Historical Earthquakes, Paleoseismology,
Neotectonics and Seismic Hazard:
New Insights and Suggested Procedures

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# How well does known seismicity between the Lower Rhine Graben and southern North Sea reflect future earthquake activity?

*Thierry Camelbeeck[1], Kris Vanneste[1], Koen Verbeek[1], David Garcia-Moreno[1,2], Koen van Noten[1] & Thomas Lecocq[1]*

[1] Royal Observatory of Belgium: thierry.camelbeeck@oma.be, kris.vanneste@oma.be, koen.verbeeck@oma.be, koen.vannoten@oma.be, thomas.lecocq@oma.be

[2] University of Ghent: David.garciaMoreno@Ugent.be

## Abstract

Since the 14th century, moderate seismic activity with 14 earthquakes of magnitude $M_W \geq 5.0$ occurred in Western Europe in a region extending from the Lower Rhine Graben (LRG) to the southern North Sea. In this paper, we investigate how well this seismic activity could reflect that of the future.

The observed earthquake activity in the LRG is continuous and concentrates on the Quaternary normal faults delimiting the LRG, which are also the source of large surface rupturing Holocene and Late Pleistocene earthquakes. The estimated magnitude of these past earthquakes ranges from 6.3±0.3 to 7.0±0.3 while their average recurrence on individual faults varies from ten thousand to a few ten thousand years, which makes foreseeing future activity over the long-term possible.

Three of the largest historical earthquakes with $M_W \geq 5.5$ occurred outside the LRG. Late Quaternary activity along the fault zones suspected to be the source of two of these earthquakes, i.e. the 1580 Strait of Dover and 1692 northern Belgian Ardennes earthquakes, is very elusive if it exists. Hence, similar earthquakes would be very infrequent at these locations suggesting that the seismicity outside of the LRG would be episodic and clustered on some faults during periods of a few hundreds of years interrupted by long periods of inactivity typically lasting for some tens to hundreds of thousand years. Seismic moment release estimation and its comparison between recent geological and historical seismicity periods lead us to suggest that the high seismicity level observed between AD 1350 and AD 1700 west of the LRG would be uncommon.

## 1. Introduction

Moderate and rare large historical earthquakes in Western Europe in the region north of the Pyrenees and the Alpine arc are sparsely located (Figure 1). Nevertheless, they occurred clustered in patches of activity separated from regions where seismicity is absent. At first sight, this observation could indicate that some regions would be more susceptible than other ones to generate moderate to large earthquakes. Moreover, the observation that most of these earthquakes occurred at different locations inside the active patches suggests an apparent random spatial distribution of seismicity at different spatial scales.

However, recent studies of plate interior seismic activity suggest that such apparent concentrations and gaps in seismicity likely reflect the short earthquake record compared to the long and variable recurrence interval of large earthquakes (Swafford and Stein, 2007). Therefore, to evaluate whether persistent or absent seismicity in current active or inactive regions, respectively, is simply a consequence of the short duration of the observation period or is more permanent in the current tectonic context are important issues for seismic hazard evaluation (Stein et al., 2015). Answering these questions needs an identification and collection of information on large earthquakes that occurred before the period when written earthquake eyewitnesses began. Retrieving traces of past large earthquakes in the geomorphology and the recent geologic record is the subject of the disciplines active tectonics and paleoseismology.

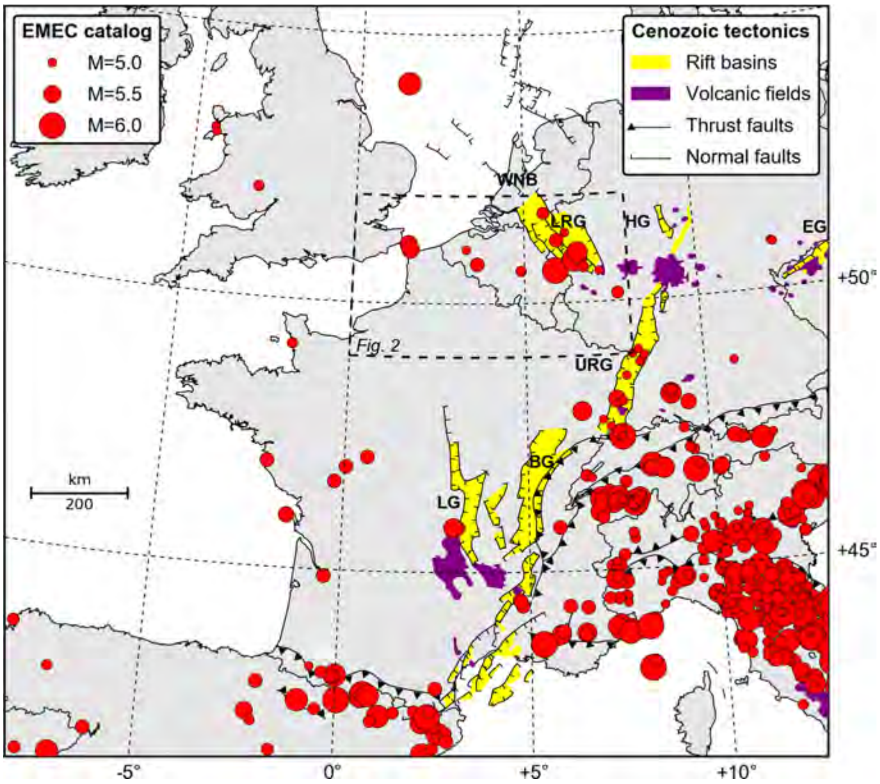

**Figure 1**. Seismic activity in Western Europe. Epicenters of earthquakes with estimated $M_W \geq 5.0$ as reported in the European Mediterranean Earthquake Catalogue (EMEC) (Grünthal and Wahlström, 2012). WNB for West Netherlands Basin, LRG for Lower Rhine Graben, HG for Hessian Graben, URG for Upper Rhine Graben, BG for Bresse Graben and LG for Limagne Graben. The small rectangle with black dotted line shows the limits of figure 2.

In this paper, we discuss the contribution of the seismology team of the Royal Observatory of Belgium to the study of this issue in the region extending from the Lower Rhine Graben (LRG) to the southern North Sea (dotted rectangle in figure 1). First, we provide the background information on the seismicity in the studied area. Second, we discuss the results of our studies on Holocene and Pleistocene activity of the faults bordering the LRG and their relationship to large earthquakes. Third, we focus on our investigations to evaluate whether tectonic activity is persistent on the geological structures that generated the large 6 April 1580 Strait of Dover and 18 September 1692 Verviers (eastern Belgian Ardennes) historical earthquakes (Figure 2). Finally, we explain some aspects of the seismicity in and outside the LRG based on the comparison of the recent geological seismic moment release with the one released by historical earthquake activity, and we emphasize the need to develop research strategies that allow improving our knowledge on inherited faults that could generate future large earthquakes outside the LRG.

## 2. Historical seismicity between the Lower Rhine Embayment and southern North Sea

The region extending from the Lower Rhine Graben (LRG) to the Strait of Dover and the southern North Sea is one of the most seismically active areas in Western Europe. Since the 14th century, 14 earthquakes with estimated or measured magnitude $M_W\geq5.0$ occurred in this area (Figures 1 and 2, Table 1). There is no observed seismic activity to the south of this active cluster in the Paris Basin, nor in the northern prolongation of the LRG in the northwest of the Netherlands and in the southern North Sea.

**Table 1.** $M_W\geq5.0$ earthquakes since 1350 in the regions between the LRE and southern North Sea

| N° | Date | Lat °N | Long °E | $M_W$ | | | region |
|---|---|---|---|---|---|---|---|
| | | | | BE | EM | SH | |
| 1 | 1382 05 21 | 51.30 | 2.00 | 6 | 5.5 | 5.4 | Southern North Sea |
| 2 | 1449 04 23 | 51.60 | 2.50 | 5½ | 5.0 | 4.0 | Southern North Sea |
| 3 | 1504 08 23 | 50.77 | 6.10 | 5½ | 5.0 | 4.8 | Roer Valley Graben |
| 4 | 1580 04 06 | 51.00 | 1.50 | 6 | 5.5 | 5.5 | Strait of Dover |
| 5 | 1640 04 04 | 50.77 | 6.10 | 5½ | 5.5 | 5.5 | Roer Valley Graben |
| 6 | 1692 09 18 | 50.59 | 5.86 | 6¼ | 6.1 | 5.8 | Eastern Belgian Ardenne |
| 7 | 1755 12 27 | 50.77 | 6.10 | 5¼ | 5.0 | 5.1 | Roer Valley Graben |
| 8 | 1756 02 18 | 50.80 | 6.50 | 5¾ | 5.9 | 5.7 | Roer Valley Graben |
| 9 | 1828 02 23 | 50.70 | 5.00 | 5 | 5.1 | 5.2 | Brabant Massif |
| 10 | 1846 09 27 | 50.12 | 7.68 | 5 | 5.2 | 5.2 | Middle Rhine Valley |
| 11 | 1878 08 26 | 50.95 | 6.53 | 5½ | 5.7 | 5.5 | Roer Valley Graben |
| 12 | 1938 06 11 | 50.78 | 3.58 | 5.0 | 5.3 | 5.3 | Brabant Massif |
| 13 | 1951 03 14 | 50.63 | 6.72 | 5.3 | 5.1 | 5.1 | Roer Valley Graben |
| 14 | 1992 04 13 | 51.16 | 5.95 | 5.3 | 5.3 | 5.3 | Roer Valley Graben |

Epicentre location from the earthquake catalog of the Royal Observatory of Belgium
BE: $M_W$ from the earthquake catalog of the Royal Observatory of Belgium
EM: $M_W$ from the EMEC earthquake catalog (Grünthal and Wahlström, 2012)
SH: $M_W$ from the SHEEC earthquake catalog (Stucchi et al., 2013)
In the text, we indicated information from BE, but a comparison with EMEC and SHEEC shows the variability of magnitude estimation for historical earthquakes

Looking at the last 650-700 years, a period in which historical information allows estimating earthquake location and magnitude, the Roer Valley Graben (RVG), the central graben of the LRG that crosses the border region between Belgium, Germany and The Netherlands, appears as the most active area (Hinzen and Oemisch, 2001; Hinzen and Reamer, 2007; Camelbeeck et al., 2007). In the RVG, seismicity occurred uninterrupted (Figure 2). The strongest known earthquake is the 1756 Düren event (Germany) with a magnitude estimated around 5 ¾. Six other earthquakes reached $M_W\geq5.0$. The two most recent significant events are the $M_W=5.3$ 1951 Euskirchen (Germany) and the $M_W=5.3$ 1992 Roermond earthquakes (the Netherlands) (van Eck and Davenport, 1994). The spatial pattern of earthquake hypocenters agrees with an activity associated to the NNW-SSE trending Quaternary normal fault system displacing the main terraces of the Rhine and Maas rivers, as already suggested by Ahorner (1962, 1975). Earthquake focal mechanisms of the two most recent significant earthquakes, the $M_W=5.3$ 1992 Roermond (Camelbeeck and van Eck, 1994) and the $M_W=4.6$ 2002 Alsdorf earthquake (Hinzen and Reamer, 2007) show quasi-pure normal faulting with one of the nodal planes having similar strike and dip as the faults along which they are supposed to have occurred.

Outside the LRG, the spatial distribution of the current seismic activity is heterogeneous between a large inactive area to the east and a more active area to the west and the southeast of the LRG. To the southeast of the LRG, a zone of moderate seismic activity follows the Middle Rhine Valley across the Rhenish Massif up to the northern limit of the Upper Rhine Graben (Ahorner, 1983; Hinzen and Reamer, 2007). The strongest event in this area is the $M_W\sim5$ 1846 Sankt Goar earthquake. Another area with a small level of earthquake activity is the SW-NE trending Hunsrück-Taunus zone limiting the Rhenish Massif to the south between the southern part of Grand Duchy of Luxemburg and of the Middle Rhine Valley (Ahorner, 1983).

The major Midi-Eifel thrust, which separates the Brabant parautochton from the Ardenne allochton and represents the northernmost fault zone of the Variscan front, appears as a limit separating different zones in the observed seismicity pattern to the west of the LRG. To the south of this limit and abutted to the LRG, the Ardenne consists of Devono-Carboniferous rocks folded and faulted during the Variscan orogeny (335-300 Ma) (Oncken et al., 1999). Two major units can be distinguished: the Ardenne Massif or Rhenish Shield, and more to the southwest, the Paris Basin. The Paris Basin and the western part of the Ardenne show only little seismic activity. In contrast, seismic activity is more pronounced in the northeastern part of the Belgian Ardenne and the Eifel Mountains in Germany. It is spatially more diffuse and less important than in the RVG even though the most significant event of the earthquake history of the whole region, with an estimated $M_W$ of 6 ¼, occurred here on September 18 1692 near the city of Verviers (Alexandre et al., 2008). By relocating the earthquakes that occurred between 1985 and 2010 in the Ardenne-Eifel area and RVG (Figure 3a), Lecocq (2011) evidenced a remarkable 20 km long NNW-SSE alignment of epicenters already identified by Ahorner (1983) who named it the Hockai Fault Zone (HFZ) (Figures 2 and 4B). The distribution of earthquake focal depths along a perpendicular profile suggests that the HFZ is a narrow zone in which focal depth does not exceed 10 km. To the west of the HFZ, focal depths progressively increase, reaching 25 km depth, while to the east they reach 20 km. The resulting difference of integrated shear strength, which is smaller in the HFZ than in the surrounding area, lead us to consider the HFZ as a weakness zone surrounded by a stronger crust. This is why we suggest that the 1692 earthquake occurred along the HFZ, in its northern part.

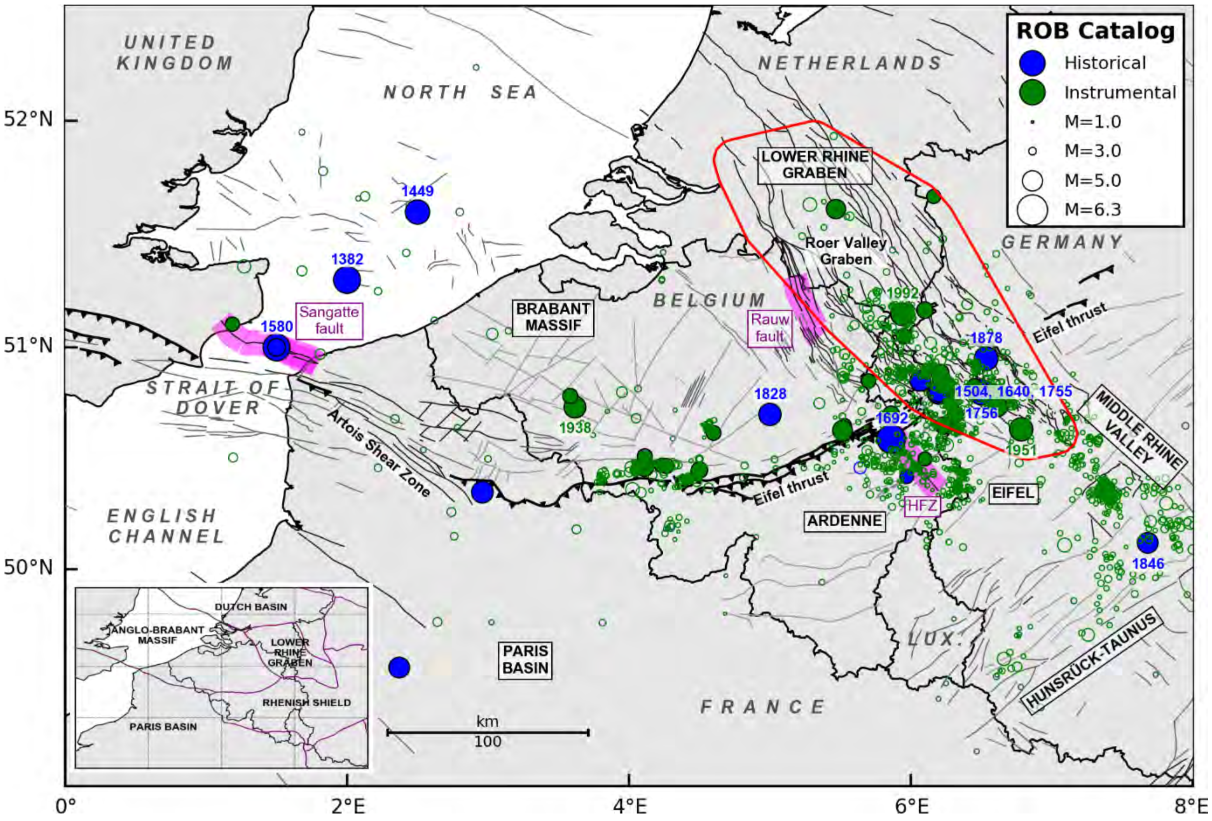

**Figure 2**. Seismic activity in the region from the Lower Rhine Graben to the southern North Sea from 1350 to 2018 (Catalogue of the Royal Observatory of Belgium). The area inside the red contour is the Lower Rhine Graben. The Sangatte and Rauw faults as well as the Hockai Fault zone (HFZ) are indicated by the magenta-coloured areas.

Moderate earthquake activity also occurs in the Carboniferous basins just north of the Midi-Eifel thrust. The Liège area recently suffered from two earthquakes that occurred on 21 December 1965 ($M_W = 4.3$) and 8 November 1983 ($M_W = 4.6$). More to the west, pronounced seismic activity occurred since the end of the 19th century in the Hainaut zone. Despite the fact that none of these earthquakes exceeded magnitude 4.5, some of them were locally damaging due to their shallowness. An unresolved question about part of this activity is its possible relationship with mining works in this region that begun to be extensive in the 19th century and stopped in the years 1960-1970 (Descamps, 2009). Since the installation of a denser seismic network in Belgium in 1985, a few small earthquakes were also located just south of the Midi-Eifel thrust between the Liège area and the eastern extremity of the Hainaut seismic zone.

North of the Variscan Front, the Anglo-Brabant Massif consists of lower Cambrian to Silurian deposits deformed during the Acadian orogeny (late Llandovery to late Pragian). The Anglo-Brabant Massif witnesses a diffuse seismicity with two damaging $M_W$=5.0 earthquakes on the Belgian territory on 23 February 1828 and on 11 June 1938 (Table 1). Two other moderate earthquakes occurred below the southern North Sea in the offshore prolongation of the Brabant Massif on 21 May 1382 and 23 April 1449 (Table 1) (Melville et al., 1996). Diffuse seismic activity is also present in the nearby French and southern British territories at the limit between the Artois hills and the Flanders plain and its offshore prolongation across the Strait of Dover. A $M_W$=6.0 earthquake occurred here on 6 April 1580 (Melville et al., 1996). Camelbeeck et al. (2007) associated this seismicity to faults reactivated during an early Tertiary tectonic inversion and that cut the small Artois anticlinal flexure (Auffret and Colbeaux, 1977). These fault zones are well identified by the horizontal gradient of the gravity Bouguer anomaly (Everaerts, 2000; Camelbeeck et al., 2007).

## 3. Are the faults that generated moderate and large earthquakes geologically active?

Extending our catalogue of large earthquakes to periods preceding the first written testimonies on earthquake effects requires identifying imprints of large earthquakes in the geomorphology and in the geologic record. However, such earthquake traces are difficult to observe in continental plate interiors because the faults that generated large earthquakes are not very active, if at all, and even low rates of erosion or deposition can erase or hide their traces. Pioneering works of Crone et al. (1990, 1992, and 1997) were the first to relate seismicity with surface faulting evidence recorded in the near-surface geology in stable plate interiors. Their common thread was the clear geomorphic evidence given by the surface ruptures of the 1986 Marryat Creek and 1988 Tennant Creek earthquakes in the Australian craton, and by the fault scarps along the Meers fault in southwest Oklahoma and along the Cheraw fault in southeast Colorado. These geomorphic indicators were ideal geological targets because they precisely indicated where to undertake paleoseismic investigations. These forerunner studies were also the first to highlight past surface rupturing earthquakes by studying fault scarps with no reported seismic activity. Their analyses evidenced the episodic nature of large earthquakes in stable continental regions (SCR).

In Western Europe, there is no identified historical earthquake having ruptured the surface. Of course, the largest ones only reached magnitudes $5\frac{1}{2} \leq M_W \leq 6\frac{1}{4}$ which is at the lower limit to produce surface displacement observable without modern geodetic measurements. Furthermore, finding historical documents that mention small surface ruptures is unlikely because possible surface faulting events occurred before the 18th century, a period from which few written records are available. The lack of a historical source of a known surface rupture does not allow defining precisely where to conduct a search for recent or active faulting and to identify the source of the aforementioned earthquakes. Of course, the Quaternary faults of the LRG displace the main terraces of the Rhine and Maas Rivers and are at some places identifiable in the landscape. Nevertheless, their precise fault location needs specific geological and geophysical investigations (Demanet et al., 2001). Until the mid-1990s, as no historical events were mentioned to have ruptured the ground surface, no one would have suspected that the LRG faults could produce large surface faulting earthquakes, especially because Ahorner (1975) considered fault movements in the LRG as purely aseismic.

The $M_W$=5.3 1992 Roermond earthquake stimulated discussions between Earth scientists about the behaviour of Quaternary faults in the LRG and if earthquakes larger than the Roermond event could happen there. This is why scientists of the Royal Observatory of Belgium addressed these issues from 1995 onwards by undertaking detailed geological and geomorphological investigations of fault scarps in the RVG, searching for the slightest evidence of Holocene and late Pleistocene earthquake activity along Quaternary faults (Camelbeeck and Meghraoui, 1996, 1998). In section 3.1, we present the main quantitative results of our investigations during the last 20 years showing the active character of these border faults and their relationship with large surface rupturing earthquakes.

In parallel, improvements during the last 30 years in our knowledge about historical earthquakes suggest that three large earthquakes with $M_W$>5.5 occurred to the west of the LRG (Melville et al., 1996; Alexandre et al., 2008). In contrast with surface faulting earthquakes, for which the observed surface break identifies the fault source at the ground surface, the seismogenic source of the moderate historical earthquakes outside the LRG can only be suspected. Therefore, identifying their sources is more complex and needs to incorporate an analysis of the regional geological and geophysical background, a mechanical analysis of the current seismic activity, and the strict application of the methodologies of active faulting studies. We present in section 3.2 a synthesis of investigations on the faults that generated the large 6 April 1580 Strait of Dover and 18 September 1692 Verviers earthquakes, and that suggest that their Quaternary activity would be elusive. The Royal Observatory of Belgium led these investigations in cooperation with universities of Ghent and Liège, respectively.

### 3.1. The Roer Valley Graben: an active geological source of large earthquakes

Our investigations along the Bree fault scarp (Geleen fault) in Belgium at the western border of the RVG were the first in stable continental Europe to suggest the occurrence of large surface-rupturing earthquakes during the Holocene and the Late Pleistocene (Camelbeeck and Meghraoui, 1996; 1998; Meghraoui et al., 2000; Vanneste et al., 1999, Vanneste and Verbeeck, 2001). Paleoseismic investigations were also conducted along the eastern border faults of the RVG, on the Peel fault near Roermond in the Netherlands and the Rurrand fault near Jülich in Germany (Vanneste and Verbeeck, 2001; van den Berg et al., 2002). Along the Geleen fault, we estimated that the magnitude of the three most recent paleoearthquakes should range between 6.3±0.3 and 6.7±0.3. Evidence suggests that larger earthquakes with $M_W$ approaching 7.0±0.3 could have occurred along the Rurrand fault while the magnitude of the three paleoearthquakes identified along the Peel fault ranges from 6.0±0.3 to 6.5±0.3. Camelbeeck et al. (2007) discuss these interpretations in more detail.

The analysis of the six trenches excavated across the Geleen fault provide invaluable information on the recurrence of large earthquakes along a single seismogenic fault in the RVG. Two large earthquakes occurred during the last 20 kyr while four other similar events have been observed during the previous 80 kyr. The two trenches excavated near Rotem in the Meuse Valley suggest a timing for the most recent event dated between 2.5 ± 0.3 and 3.1 ± 0.3 kyr BP. The average return period for the two and five most recent earthquake cycles is 14 ± 8 kyr and 23 ± 4 kyr, respectively. The average fault slip for the same intervals is 0.050 ± 0.036 mm/yr and 0.031 ± 0.012 mm/yr, respectively. These results suggest significant variability in large earthquake return periods, and possibly in slip rates as well.

Vanneste et al. (2013) compiled all relevant data concerning the Quaternary faults of the LRG and associated seismicity and devised a parameterized model of composite seismic sources, which provides a base for modeling seismic hazard. This data compilation furnishes lower and upper bounds on the activity rates of all the faults in the LRG. Fault slip rates are derived from long-term vertical displacement rates estimated from the age and vertical displacement of the main terraces of the Rhine and Meuse rivers during the last 700 kyr. They range from 0.007 to 0.1 mm/yr.

Other trench exposures provided additional convincing evidence for earthquake surface rupture in the LRG (Skupin et al., 2008, Grützner et al., 2016, Kuebler et al., 2016). Moreover, Gold et al. (2017) evidence an apparent Late Quaternary fault-slip rate increase in the southern LRG by using new main terrace vertical offset measurements.

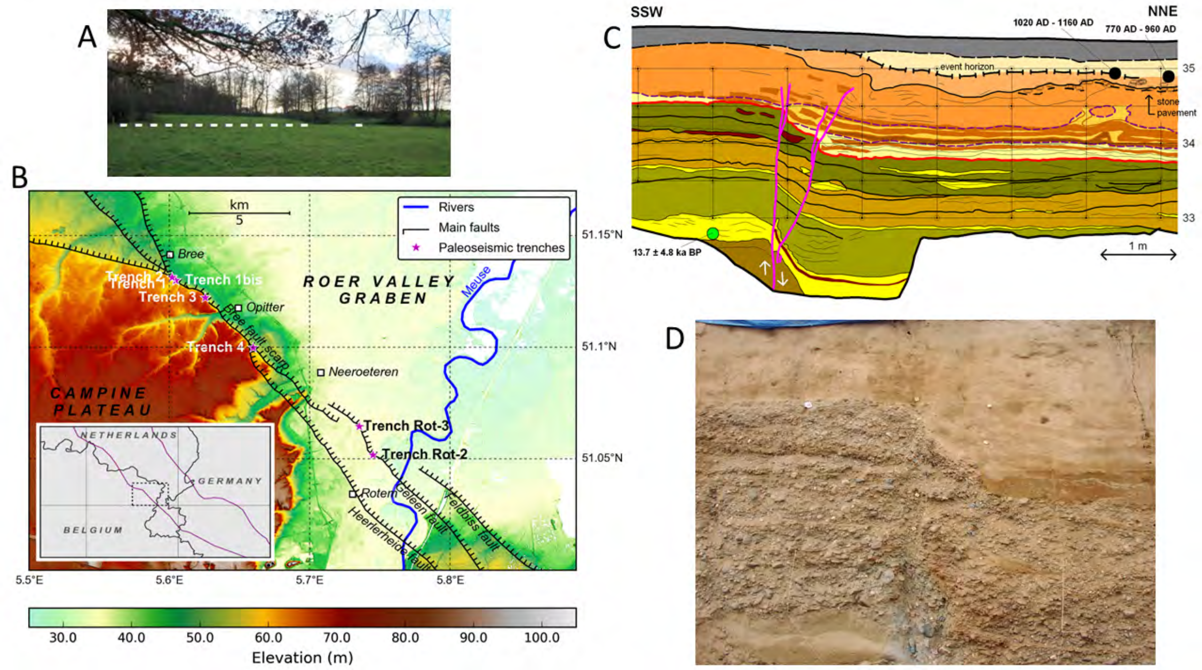

**Figure 3**. The Geleen fault at the western border of the Roer Valley Graben. (A) Photograph of the frontal scarp - underlined by the white dotted line - near Bree at the trenches 1 and 1bis location and corresponding to the Holocene slip of the fault; (B) Digital Elevation Model of the western border of the RVG in Belgium and location of the excavated paleoseismic trenches; (C) Geological logging of the northwestern wall of the Rotem-2 trench; and (D) photograph in this trench showing the Geleen fault displacing the top of the late Weichselian terrace and overlying eolian sands and silts by 0.75-1 m.

## 3.2. The stable continental region bordering the Roer Valley Graben

The six moderate and large historical earthquakes located to the west of the RVG occurred on fault zones for which the most recent prolonged activity occurred during the Meso-Cenozoic period. The 1382 and 1449 earthquakes (Table 1) occurred in the offshore extension of the Brabant Massif that contains a sequence of troughs and faults in the Mesozoic and Early Cenozoic cover (Henriet and De Batist, 1989). Such faults and troughs are absent in the sedimentary cover of the onshore Lower Paleozoic Brabant Massif where the 1828 and 1938 earthquakes are located (Table 1), leading to suggest that these onshore earthquakes could result from fault reactivation within the core of the Massif. The 1580 Dover Strait earthquake (Table 1) occurred in the offshore prolongation of an anticlinal flexure defining the limit between the Artois hills and the Flemish Plain onshore, and which is cut by faults resulting from an early Tertiary tectonic inversion phase. The $M_W$=6 ¼ 18 September 1692 earthquake, which is the largest known earthquake in Western Europe (Alexandre et al., 2008), occurred on a Variscan structure reactivated at different periods during the Mesozoic and the Cenozoic.

As the most recent known tectonic activity of the geological structures associated to the largest known earthquakes is contemporaneous with or older than the early Cenozoicum, we can conclude that the occurrence of large earthquakes is not sufficiently frequent to generate visible imprints of faulting in the geomorphology and in the geologic record. Until recently there were no specific investigations to evaluate whether this assumption was correct. Therefore, we investigated the epicentral areas of the 6 April 1580 and 18 September 1692 earthquakes. Our objectives were to identify the fault zones that generated these historical earthquakes and to evaluate their most recent activity.

### *3.2.1. The Hockai Fault Zone and the 18 September 1692 earthquake*

The Hockai fault zone (HFZ) corresponds to a SSE-NNW oriented fault zone in the northeast Ardenne and its northern foreland (Figures 2 and 4). Its name comes from an alignment of earthquakes identified by Ahorner (1983). Demoulin (1988) reported geomorphological anomalies associated to a

Carboniferous-Permian fault zone nearby and parallel to this seismic alignment. He therefore designated this fault zone as the HFZ, implicitly establishing a link between the seismic events and this inherited fault zone.

The HFZ originated at the end of the Variscan orogeny during the late Carboniferous and early Permian and moved episodically during the Mesozoic and the Cenozoic. Demoulin (2006) mapped the HFZ from geomorphological evidences related to this activity. He succeeded to evidence geomorphological features over a total length of around 40 km, with gaps of several km. Vanneste et al. (2018) furnish a synthesis of the geological background and geomorphological observations along the HFZ.

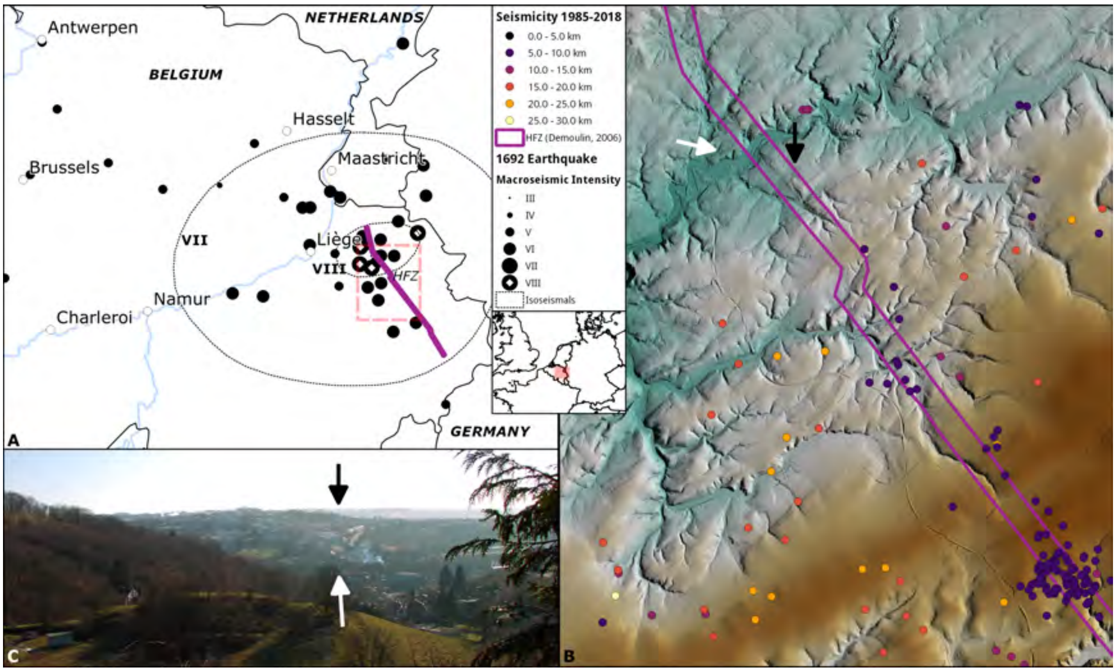

**Figure 4.** The Hockai fault zone (HFZ). (A) Macroseismic intensities in the epicentral area of the 18 September 1692 Verviers earthquake (Alexandre et al., 2008). The smallest doted curve shows the area with intensities VIII and VII-VIII, the largest is the area with intensity ≥ VII. The mauve line indicates the HFZ (from Demoulin, 2006); (B) Epicenters of earthquakes between 1985 and 2018 in the area indicated by the orange color in (A). The colors differentiate earthquake focal depths. The background map is the new LIDAR Digital Terrain Model of the area where the 7 km long bedrock fault scarp associated with the northern part of the HFZ is well visible. The white and black arrows indicate the position in the DEM of the fault scarp view in the photo (C).

As explained in section 2, compared to other rigid parts of the Ardennes, the HFZ is a weak crustal zone that is more prone to be the source of a more significant seismic activity than the rest of the Massif. The $M_W$=6 ¼ 18 September 1692 earthquake is the largest known earthquake in Western Europe (Alexandre et al., 2008). It occurred near the city of Verviers and caused important damage corresponding to intensity VIII (EMS-92) in the northeastern part of the Belgian Ardennes (Camelbeeck et al., 2014). The observation that the HFZ crosses the central part of the most affected area suggests that the 1692 earthquake ruptured this fault zone (Figure 4). Suspected Holocene – Late Pleistocene tectonic movements in the northern part of the HFZ corroborate this hypothesis. Indeed, Graulich (1959) observed a 1.7 m vertical displacement of Late Pleistocene loess along a fault associated to the HFZ. Moreover, the LIDAR Digital Terrain Model of the Walloon region evidences a ~ 1-2 m high scarplet in the main scarp prolongation where the HFZ crosses the floodplain of the Vesdre River (Vanneste et al., 2018).

The presence of the Paleozoic bedrock at or near the ground surface explains the long preservation of the Meso-Cenozoic vertical and horizontal fault movements in the landscape along the HFZ. The main geomorphological feature in the northern part of the HFZ is a well-visible 7-km-long linear scarp corresponding to a fault displacing the basement up to 300 m horizontally and 48 m vertically, while the Mesozoic cover is vertically displaced by 23 m (Ancion and Evrard, 1957) (Figure 4). The main question in terms of seismic hazard is to evaluate the part of these movements that could be associated to the current tectonic context and then evaluate the long-term perspectives for large earthquake occurrence. Regional tectonic stresses and current deformation mechanisms are not straightforward to evaluate because the largest earthquakes along the HFZ occurred during the historical period, and their mechanism is unknown. Hence, the only available information comes from the current activity, particularly a seismic sequence that occurred in 1989-1990 during which we deployed mobile instruments. Fault-plane solutions range from sinistral strike-slip to pure normal faulting mechanisms (Camelbeeck, 1993). These mechanisms are compatible with the Meso-Cenozoic vertical and horizontal fault movements observed in the geomorphology, but it remains challenging to evaluate current and recent deformation rates from this long-term geological information.

We evaluated the Quaternary slip rate of the HFZ from geomorphic measurements in the northern portion of the fault, mainly from the terrace levels of the Vesdre River. Petermans et al. (2004) and Demoulin et al. (2007) evaluated a 10 to 20 m vertical displacement of the 2-2.5-Ma-old highest terrace level by the HFZ. This would correspond to an average vertical slip rate around 0.005 mm/yr. Demoulin (2006) suggests a vertical displacement of ~ 1 to 2 m since the deposition of the Weichselian gravels of the Vesdre River, leading to a vertical rate of the order of 0.01 mm/yr. Moreover, Petermans et al. (2004) concluded that the most recent terrace [from 61.5 to 106 kyr BP] was not displaced at the level of the resolution of the observations [a few meters], which suggests a maximum possible slip rate of 0.01 mm/yr.

### *3.2.2. The fault system across the Strait of Dover and the 6 April 1580 earthquake*

To identify the source of the $M_W \geq 5.5$ April 1580 earthquake and evaluate the recent tectonic activity in that area, Garcia-Moreno et al. (2015) collected a large set of bathymetric data and seismic reflection profiles across the width of the Dover Strait.

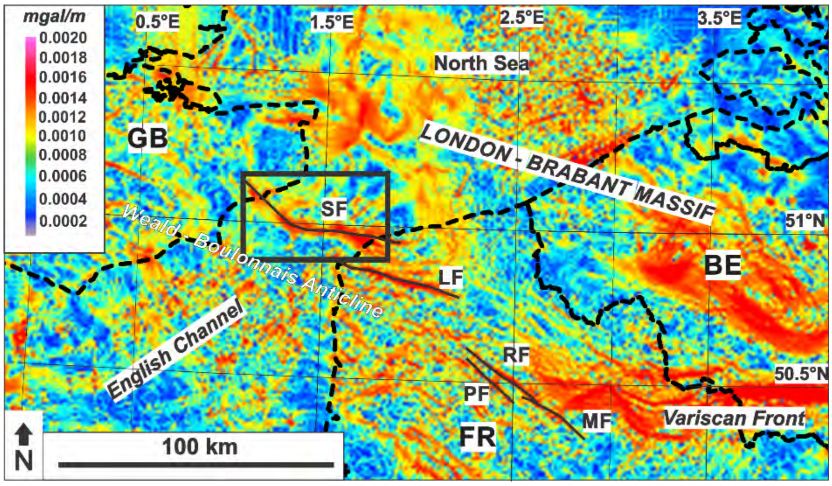

**Figure 5**. Interpreted horizontal derivative of the Bouguer gravity anomaly (see García-Moreno et al., 2015). Black rectangle: area shown in figure 6; LF: Landrethun Fault; SF: Sangatte fault; RF: Ruitz fault; PF: Pernes fault and MF: Marqueffles fault.

Geophysical data show a broad zone of subparallel WNW-ESE trending faults and folds that offset a series of Cretaceous formations. This zone, named the Sangatte Fault system, is part of the regional North Artois Shear zone (Figure 2). The largest deformations/offsets associated with this fault system correspond to reverse faulting and folding. Offsets along reverse faults reach up to a hundred meters in the center of the Strait of Dover. Normal and strike-slip faulting appears to be also significant.

Importantly, extensional and strike-slip deformations seem to be younger than compressional ones, suggesting the latest tectonic activity of these faults was due to extensional tectonic inversion/reactivation of old compressional structures (Garcia-Moreno et al., 2015).

In the submarine Dover Strait, Quaternary offsets associated with the Sangatte Fault system are poorly constrained. Quaternary erosional and depositional features in this area are limited to: (1) a set of buried deeps known as the Fosse Dangeard, (2) a prominent palaeovalley imprinted on the seafloor known as the Lobourg Channel, and (3) some scattered Holocene sand ridges and sand waves (Garcia-Moreno et al., 2015, 2019). The geophysical data collected from the Strait of Dover show that faults only reach the surface at the top of the Cretaceous bedrock, forming minor scarps. Faults do not seem to extend across the sediment infilling any of the paleo-depressions composing the Fosse Dangeard. They did not produce any deformation or offset exceeding the resolution of 1 m in the bathymetric data across the Lobourg Channel or across the scours carved within it (Figure 6).

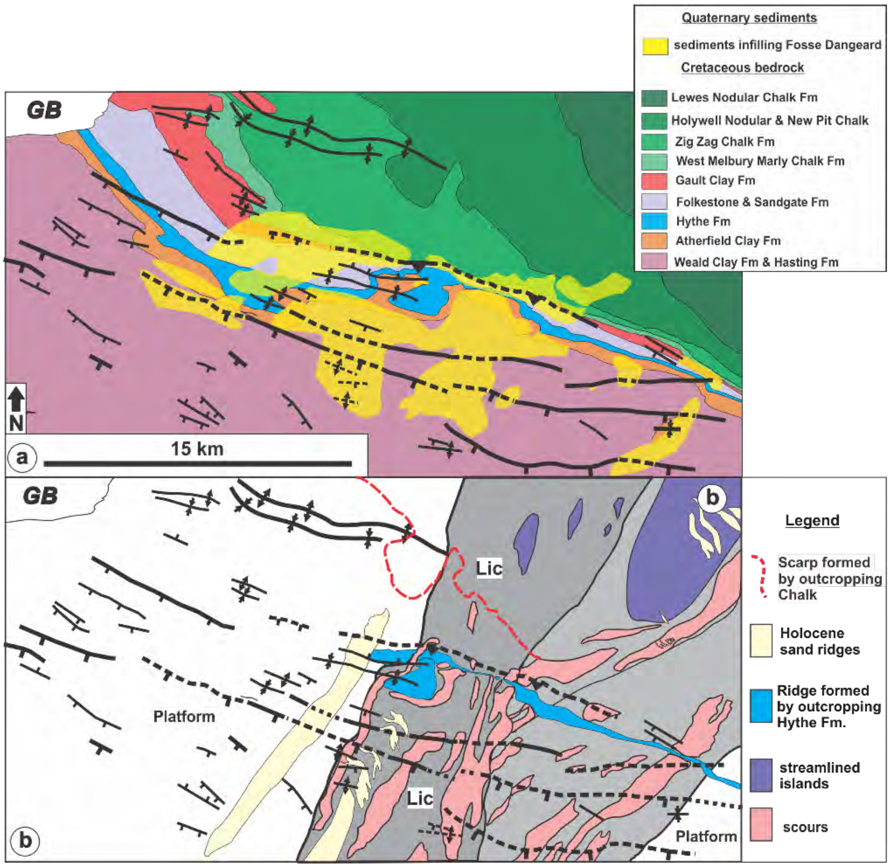

**Figure 6.** (a) Geological/structural map of the Dover Strait, including Middle–Late Pleistocene buried palaeo-depressions known as "Fosse Dangeard" (modified from García-Moreno et al., 2015, 2019). (b) structural map of the Dover Strait superimposed on geomorphological interpretation of the Lobourg Channel (modified from García-Moreno et al., 2015, 2019). Lic: inner channel formed during the last phase of major fluvial/flood erosion along the Lobourg Channel. Note that fault planes outcrop at the seafloor only across unfilled scours. Note also that neither the morphology of the Lobourg inner channel nor the fluvial/flood scours eroded within it show any distinct deformation/offset along fault planes.

Minor possible offsets (< 5 m) have been identified along some of the faults traversing the paleo-depressions composing the Fosse Dangeard. These are however limited to the lower infill and the basal erosional surfaces of these paleo-depressions. The fact that the possible offsets affect only the basal erosional surfaces of these paleo-depressions precludes to unambiguously assess whether they were formed by tectonic forcing or due to erosional processes or by a combination both (Garcia-Moreno et al., 2015). In any case, this indicates that the cumulated offset along the Sangatte Fault since the formation of the Fosses Dangeard cannot be greater than 5 m.

The absolute age of the formation and infilling of the Fosse Dangeard and the incision of the Lobourg Channel are currently unknown, precluding accurate estimations of possible Quaternary slip rates along the Sangatte Fault. Present consensus holds that the Fosse Dangeard were most likely formed during the Elsterian glacial maximum (i.e., 450,000 years ago). The age of the various seismic units composing their infill is however unknown. Gupta et al. (2017) and Garcia-Moreno et al. (2019) demonstrated that the sediment infilling the Fosse Dangeard are younger than the last phase of major fluvial/flood erosion that imprinted the Lobourg Channel. Indeed, the prominent inner channel and scours excavated into bedrock during that erosional episode truncate the uppermost layers of the Fosse Dangeard's infill. Unfortunately, the time when those erosional features were carved remains unknown. Sedimentary data suggest that the Lobourg Channel may have channelled rivers and flood flows during each of the last three Pleistocene glacial stages, at least until 16,700 year BP (Toucanne et al.,2010; 2015). However, the Dover Strait appears to have remained emerged until early Holocene, which started 12,000 years ago. Consequently, we cannot rule out the occurrence of intense flood and/or fluvial erosion along the Lobourg Channel between 16,700 and 12,000 years ago.

In conclusion, the geophysical investigations undertaken in the Dover Strait demonstrate the existence of a ~40-km-long fault zone traversing the Dover Strait. This study suggests possible maximum tectonic offsets along this fault system of max. 5 m since 450,000 years ago and less than 1 m, the resolution of bathymetric data, since the Holocene, if they exist. An earthquake that would rupture the whole length of the fault zone across the Strait of Dover would reach a $M_W$=7.0 magnitude, which corresponds to a maximum and average slip of around 2.6 m and 1.2 m respectively (Wells and Coppersmith, 1994). Therefore, if an earthquake of this importance would have occurred during the Holocene, we should find traces of its occurrence in the geomorphology of the Strait of Dover. Moreover, extrapolating the possible maximum 5 m offset of the last 450,000 years to the Holocene gives an offset of the order of 0.1 m, which corresponds to displacements caused by a $M_W$=6.0 earthquake, similar to the estimated magnitude for the 1580 event, on a fault length of around 10 km. This extrapolation from the longer-term observation is certainly closer to the real tectonic context in the Strait of Dover than the maximum value imposed for the Holocene by the resolution of the observation methods. This analysis enhances the difficulties to assess fault activity rates in this kind of offshore context. In the present case, it is not possible to identify any fault movement at the level of 0.01 mm/year.

# 4. Seismic strain and moment release

## 4.1. Seismic moment release at the geological scale

The absence of evidence of tectonic activity on the inherited faults that moved during moderate and large earthquakes in the area surrounding the LRG suggests that the seismic moment released at the geological scale essentially occurred in the LRG. We evaluated the average annual seismic moment release at the geological scale considering that earthquake activity is responsible for the total slip along the LRG faults. Schmedes et al. (2005) suggest such an almost complete seismic coupling in the LRG by combining the earthquake frequency-magnitude distribution over the last 250 years with an upper bound magnitude probability distribution obtained from the integration of seismological and geological information. Moreover, morphometric analyses along the Bree fault scarp and the Peel fault near Roermond suggest that the height of the Holocene scarps of respectively 1.0 and 1.3 m corresponds to slips related to large surface rupturing earthquakes observed in trenches (Camelbeeck et al., 2001). However, we cannot exclude that post-seismic relaxation processes could have also contributed to the total slip.

For these computations, we used the lower and upper bounds of fault slip rates, and surface source lengths of the composite seismic source model of Vanneste et al. (2013). We considered that the thickness of the seismogenic layer is 15 km. Hence, the annual rate of seismic moment in the LRG ranges from 9.0 $10^{+15}$ N.m/yr to 1.7 $10^{+16}$ N.m/yr. Moreover, horizontal rates of extension along the

LRG faults range from 0.07 to 0.13 mm/yr, which corresponds to a long-term horizontal strain rate in the range of 9 $10^{-10}$ /yr – 17 $10^{-10}$ /yr for an average LRG width of 75 km.

Our investigations on the fault zones that generated the 1580 Strait of Dover and 1692 Verviers earthquakes evidence the difficulties to evaluate recent geological activity of faults outside the LRG. However, the most often encountered observation on these faults is the absence of identifiable offset on available geomorphic and young geologic markers. Hence, the information often only provides an upper limit of fault slip rates. As better resolution in terms of slip-rate evaluation corresponds to observed offsets averaged over longer periods, no information can currently be attributed to the most recent periods (Holocene and Late Pleistocene), which is highly problematic due to the episodic character of plate interiors faults. Moreover, we do not know the existence and location of most of the faults that slipped during large earthquakes before the historical period. These different reasons prevent the evaluation of long-term cumulative seismic moment rate outside the LRG.

### 4.2. Seismic moment release by historical earthquakes

We also evaluated the cumulated released seismic moment in the studied region since 1350. To take into account the uncertainties in the magnitude evaluation for historical earthquakes, we conducted three different estimations using the earthquake catalogs of the Royal Observatory of Belgium (ROB), of the European Mediterranean Earthquakes (EMEC) (Grünthal and Wahlström, 2012), and the SHARE European Earthquake catalog (SHEEC) (Stucchi et al., 2012). In the computation, we simply added the contribution of all the earthquakes in the different catalogs without lower limit of magnitude or completeness analysis. Table 2 reports the results, indicating the cumulated seismic moment in the LRG and the large single zone (SLZ) outside the LRG for the periods 1350-2006 and 1910-2006. For the instrumental period (1910-2006), we present the contributions to the seismic moment release in three magnitude ranges ($3 \leq M_W < 4$, $4 \leq M_W < 5$ and $M_W \geq 5$) with the purpose of estimating their contribution to the total moment release and to verify that the most important contribution comes from the largest earthquakes. As is well evidenced in figure 6, earthquakes with $M_W \geq 5.0$ released most of the seismic moment.

**Table 2. Cumulated seismic moment in the region extending from the LRG to southern North Sea**

| ROB Catalog | EMEC Catalog | SHEEC Catalog |
|---|---|---|
| SLZ<br>1350 - 2006: 3.76 E+18 N.m<br>1910 - 2006: 1.71 E+17 N.m<br>3 <= M < 4: 1.85 E+16 N.m<br>4 <= M < 5: 7.59 E+16 N.m<br>M >= 5: 7.67 E+16 N.m | SLZ<br>1350 - 2006: 2.71 E+18 N.m<br>1910 - 2006: 2.38 E+17 N.m<br>3 <= M < 4: 1.30 E+16 N.m<br>4 <= M < 5: 7.61 E+16 N.m<br>M >= 5: 1.49 E+17 N.m | SLZ<br>1350 - 2006: 2.14 E+18 N.m<br>1910 - 2006: 2.32 E+17 N.m<br>3 <= M < 4: 1.11 E+16 N.m<br>4 <= M < 5: 7.27 E+16 N.m<br>M >= 5: 1.49 E+17 N.m |
| LRG<br>1350 - 2006: 1.60 E+18 N.m<br>1910 - 2006: 3.52 E+17 N.m<br>3 <= M < 4: 8.40 E+15 N.m<br>4 <= M < 5: 8.08 E+16 N.m<br>M >= 5: 2.62 E+17 N.m | LRG<br>1350 - 2006: 2.08 E+18 N.m<br>1910 - 2006: 2.93 E+17 N.m<br>3 <= M < 4: 5.17 E+15 N.m<br>4 <= M < 5: 4.35 E+16 N.m<br>M >= 5: 2.42 E+17 N.m | LRG<br>1350 - 2006: 1.24 E+18 N.m<br>1910 - 2006: 2.90 E+17 N.m<br>3 <= M < 4: 4.56 E+15 N.m<br>4 <= M < 5: 4.35 E+16 N.m<br>M >= 5: 2.42 E+17 N.m |

Figure 6 reports the cumulated released seismic moment for the whole region in the map of figure 2 (Total curves), outside the LRG (SLZ curves), and inside the LRG (LRG curves). The total released seismic moment varies from 3.4 to 5.4 $10^{+18}$ N.m. Using the ROB catalogue furnishes the largest value, while the smallest corresponds to the computation with SHEEC. Hence, the annual rate of the seismic moment release ranges between 0.5 and 0.8 $10^{+16}$ N.m/yr, which is about half of the estimated long-term geological annual rate. By considering a 15 km average thickness of the seismogenic layer, it would correspond to an average strain rate released by earthquake activity between 3 and 6 $10^{-11}$/yr for the whole area.

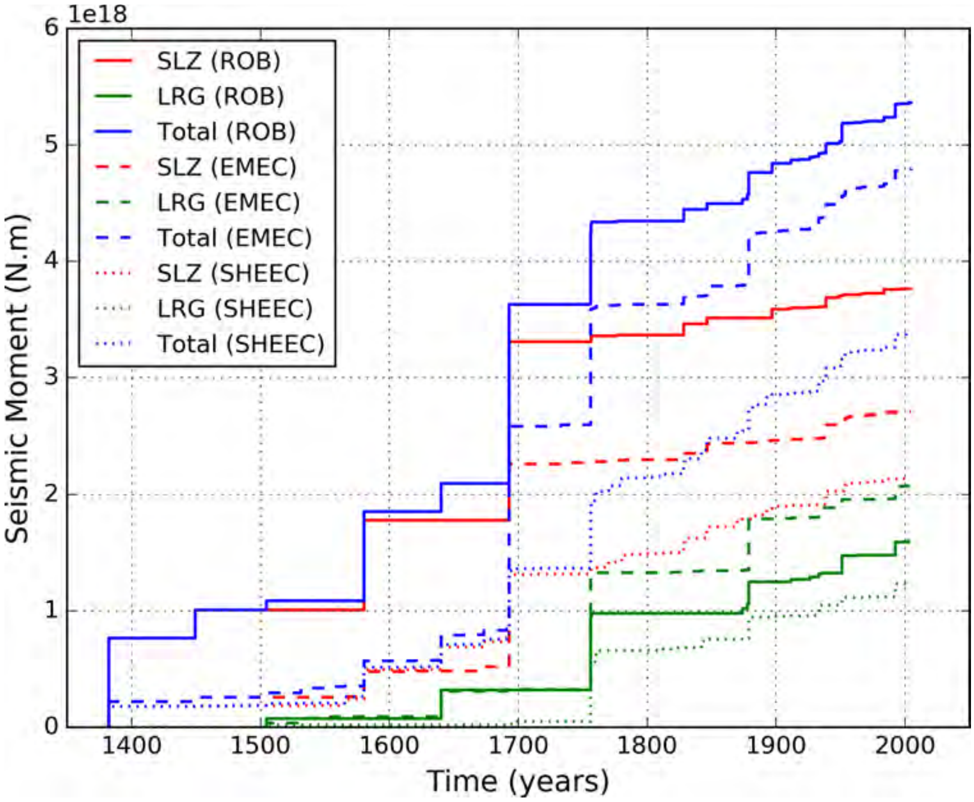

**Figure 6**. Cumulative released seismic moment since AD 1350 for the whole region mapped in figure 2 (Total curves), outside the LRG (SLZ curves), and inside the LRG (LRG curves) using the earthquake catalogue of the Royal Observatory of Belgium (ROB), the European Mediterranean Earthquake Catalogue (EMEC) (Grünthal and Wahlström, 2012) and the SHARE European Earthquake Catalogue (SHEEC) (Stucchi et al., 2012).

During the period 1350-2006, the seismic moment release in the SLZ is more or less twice the one released in the LRG. Evaluations range from 2.1 to 3.8 $10^{+18}$ N.m in the SLZ and between 1.2 and 2.1 $10^{+18}$ in the LRG, corresponding to respective annual release between 0.3 and 0.6 $10^{+16}$ N.m and 0.17 and 0.3 $10^{+16}$ N.m. The largest discrepancies between the results obtained with the different catalogs concern the period between 1350 and 1700. Table 1 shows that the difference in the magnitude evaluation of four of the largest earthquakes outside the LRG (events 1, 2, 4 and 6 in table 1) is the main factor explaining these differences in moment rates. The SHEEC catalog provides the lowest magnitude estimations for earthquakes in the SLZ, but also in the LRG. Therefore, even if the cumulated moment release between 1350 and 1700 scale differently by using the three catalogs, the region outside the LRG contributes most to the seismic moment release. During this period of 350 years, the moment release rate outside the LRG is 0.94, 0.63 and 0.37 $10^{+16}$ N.m/yr using the ROB, EMEC and SHEEC catalogs respectively, and is comparable to the geological rate ranging from 0.9 to 1.7 $10^{+16}$ N.m/yr resulting from the fault activity in the LRG.

Since 1700, the contribution of the LRG is predominant with moment release rates of 0.5, 0.67 and 0.4 $10^{+16}$ N.m/yr using the ROB, EMEC and SHEEC catalogs respectively. During this period, the differences between the magnitude estimates for the strongest earthquakes strongly diminish (Table 1). It is at the level of the instrumental magnitude uncertainty for events since 1910.

## 5. Discussion

This fragmented information on the time variation of seismic moment release provides the basis for discussing hypotheses on spatial and temporal distributions of the long-term earthquake activity in the studied area.

In this analysis, we compare seismic moment release in the LRG corresponding to its Late Quaternary WSW-ENE extension with the sum of scalar seismic moments from historical seismicity west of and inside the LRG. This comparison makes sense because despite the lack of information on focal mechanisms for the moderate and large historical earthquakes in that area, Camelbeeck et al. (2007) and Van Noten et al. (2015) determined that many recent earthquakes with $M_L \geq 3.0$ have strike-slip motions coherent with the direction of extension in the LRG.

Seismicity models should take into consideration the following observational facts presented in the previous sections:

- At the geological scale, most of the seismic moment in the whole area would be released along the active faults of the LRG because inherited faults that generated moderate and large historical earthquakes outside the LRG release little cumulative seismic moment over the long-term.

- Depending on the considered earthquake catalogue, 56 to 70 % of the seismic moment released between 1350 and 2006 occurred west of the LRG, while less than 30 to 44 % occurred in the LRG.

- The annual seismic moment release by earthquake activity in the whole area between 1350 and 1700, during which the three largest earthquakes with $M_W \geq 5.5$ occurred to the west of the LRG, is comparable to that release at the recent geological scale in the LRG.

### 5.1. The clustered and migrating nature of large earthquakes outside the LRG

The lack of large earthquake persistence on the seismogenic sources of the large 1580 and 1692 earthquakes supports the absence of identifiable geological activity of the existing or potential sources of large earthquakes outside the LRG. To explain the observed small moment release at the geological scale ouside the LRG by comparison to the LRG, large earthquakes need to be clustered on some geological structures during limited periods of time, and then need to migrate to other structures. This clustered and migrating character of seismicity is well evidenced by the spatial and temporal pattern of historical seismicity. Indeed, all the earthquakes with $M_W \geq 5.0$ that occurred since 1350 have their epicentre at different places (Figure 2, table 1). Outside of the LRG, they are clustered during relatively short periods of less than a few hundred years and then migrated to other regions. A first group is located in the southern North Sea and the Strait of Dover in 1382, 1449 and 1580. The largest earthquake occurred along the HFZ in 1692, and two earthquakes occurred in the Belgian onshore part of the Brabant Massif in 1828 and 1938.

### 5.2. Earthquake strain is released along slow active faults in the LRG

Geological information implies that the LRG behaves as a steady-state system, which is predictable over the long-term. Of course, it is difficult to evaluate details of its shorter-term variability. This is well illustrated by historical seismicity during which the average annual seismic moment release in the LRG is five to ten times less important than the average geological release. Moreover, Vanneste and Verbeeck (2001), van den Berg et al. (2002), and Camelbeeck et al. (2007) suggest that the recurrence of large earthquakes during recent geological times along specific faults in the LRG is irregular as observed on the Geleen, Peel and Rurrand faults (Figure 7). This high variability of large earthquake recurrences is associated to the fact that slip rates are less than 0.1 mm/yr, which highlights the role of transient variations of regional crustal stress field or fault strength, compared to the tectonic strain accrual, in the triggering of large earthquakes (Calais et al., 2016).

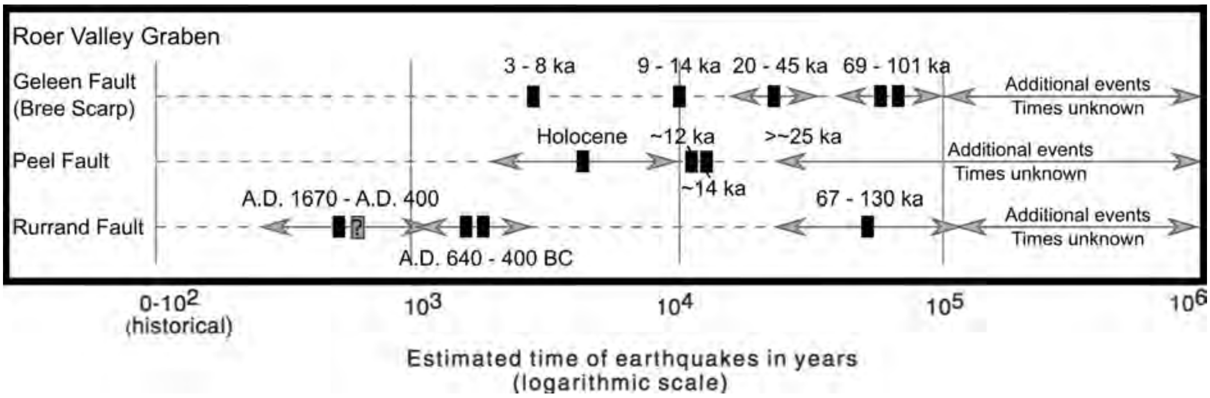

**Figure 7.** Identified paleoearthquakes and their timing along the Geleen, Peel and Rurrand faults (Vanneste and Verbeeck 2001; van den Berg et al., 2002; and Camelbeeck et al.,2007)

### 5.3. Large earthquake occurrence would be highly variable over the long-term outside the LRG

The seismic activity outside the LRG during the historical period appears as particularly important in comparison to its weak observed recent geological activity. Hence, during the period between 1350 and 1700, annual seismic moment release is similar to the average geological release rate in the LRG. As the LRG and the region outside the LRG have surfaces of 14,300 and 140,400 km$^2$, respectively (Figure 2), a similar long-term moment release would represent average activity rates ten times lower outside the LRG than inside the LRG for similar concentrations of seismogenic faults. Geological observations outside the LRG suggest slip rates smaller than 0.01 mm/yr and less dense spatial density of inherited faults capable of generating large earthquakes. Therefore, the geological seismic moment release outside the LRG should only be a small fraction of that in the LRG. Then, if we consider that a maximum of 10% of the geological seismic moment release occurs outside the LRG, the moment release between 1350 and 1700 would correspond to strain accumulation outside the LRG during a few thousand years. Actually, the real accumulation could be of the order of ten or a few tens of thousand years. Therefore, the seismic moment release and the associated occurrence of large earthquakes outside the LRG appear as highly variable with time. This includes few short periods of a high level of seismicity like that observed between 1350 and 1700 with three $M_W$~5.5-6.0 earthquakes, followed by long periods with a very low seismic moment release comparable to that observed since 1700.

### 5.4. Earthquake strain release outside the LRG is typical of SCR

As the seismic moment release during the historical period outside the LRG appears as exceptionnally elevated, it is not representative of the real long-term tectonic strain rate, which should be at least an order of magnitude less than the estimated value of 3 to 6 $10^{-11}$/yr from historical seismicity data. This also suggests that outside the LRG, large historical earthquakes released elastic strain stored in the crust during several thousand to ten thousand years as already discussed in the previous section. In this aspect, seismicity outside the LRG is similar to that observed in typical SCR (Craig et al., 2016; Calais et al., 2016).

### 5.5. Location of the next moderate and large earthquakes outside the LRG

We presented in section 3.2 our studies on the fault zones that generated the 1580 Strait of Dover and the 1692 Verviers earthquakes. An important conclusion of these investigations is the difficulty of observing fault movements and discriminating between zero and very weak movements. Hence, due to the lack or the very small imprint of their recent geological activity, identifying fault zones west of the LRG where large unknown earthquakes occurred before 1350 is challenging.

Identifying recent geological offsets on inherited faults with no earthquake activity is even more complicated. The fault presenting the largest vertical offset of Late Pliocene sediments to the west of the LRG is the 55-km-long normal Rauw fault (Figure 3). There is no instrumental or historical seismic activity associated to this fault, which also lacks geomorphological expression. Based on high-resolution geological, geotechnical and geophysical investigations finalized by a trench excavation, Verbeeck et al. (2017) provided evidence that the observed 7 m offset occurred between 2.59 Ma and 45 ka. Moreover, the regional observation of alluvial deposits in the hanging wall of the fault suggests that most of the recent fault activity was likely concentrated between 1.0 Ma and 0.5 Ma. This fault is likely one of the rare faults west of the LRG for which applying methodologies of active faulting will furnish information on its episodic activity.

Therefore, to identify structures where large earthquakes could occur in the future, scientists need to develop an understanding of the reasons why specific inherited fault zones are the source of current or historical seismicity. An example west of the LRG is the study of a shallow seismic swarm with 239 low-magnitude ($M_L$<3.2) earthquakes that occurred 20 km southeast of Brussels between 2008 and 2010. By relocating the earthquakes of the sequence and applying a matched filtering on aeromagnetic data, Van Noten et al. (2015) linked the seismic activity to a limited-size fault, corresponding to an inherited isolated fault structure in the already weakened crust of the Brabant Massif.

## 6. Conclusions

The only area in the region between the LRG and the southern North Sea where faults present a continuous activity during the Holocene – Late Pleistocene periods and an established relationship with large surface rupturing earthquakes is the LRG. Despite the fact that more research would be necessary to assess the recent geological activity on most of these faults and to evaluate the part of their slippage caused by large earthquake ruptures, the available information briefly presented in this publication make foreseeing future activity over the long-term possible. It allows inferring activity rates and observation-based hypotheses on possible maximum magnitude values for the computation of probabilistic seismic hazard assessment.

Outside the LRG, earthquake activity appears as typical of SCR. Large and moderate earthquakes occur on inherited fault zones presenting little Quaternary activity at best. Large earthquakes and associated seismicity appear episodic and clustered in some areas during periods of a few hundreds of years and then migrate to other regions. Our analysis suggests that historical seismicity data, with the occurrence of several large earthquakes to the west of the LRG between 1350 and 1700, give a false perspective of the real long-term seismicity in this region. On average, seismic moment release in the area would be less important and likely closer to that observed since the 18th century.

Future research should be concentrated on studying the mechanical and structural differences between active faults at plate boundaries or in active intraplate regions and those representing reactivated old structures that survived several tectonic and erosional cycles.

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