A decade of paleoseismic research in the Roer Valley graben

VANNESTE, Kris
Royal Observatory of Belgium, kris.vanneste@oma.be

VERBEECK, Koen
Royal Observatory of Belgium, koen.verbeeck@oma.be

CAMELBEECK, Thierry
Royal Observatory of Belgium, thierry.camelbeeck@oma.be

Abstract

We present a synthesis of the paleoseismic research conducted by the Royal Observatory of Belgium in the Roer Valley graben (RVG) during the past 12 years. Our investigations along the Bree fault scarp in Belgium were the first in stable continental Europe to provide evidence that large surface-rupturing earthquakes with magnitude ranging from 6.2 to 6.7 have occurred during the Holocene and the late Pleistocene. Since 2000, we investigated also the region southeast of the Bree fault scarp where the Geleen fault transects much younger (Saalian and Late Weichselian) terraces of the Meuse River. The analysis of two paleoseismic trenches excavated in 2002 and 2005 raised the question whether or not the entire Geleen fault defines a single rupture segment.

Introduction

Studies of long-term seismic activity in any region of the world require the longest historical perspective possible. For this purpose, it is important to keep in mind that an earthquake is part of a long-term geological process. It is also an instantaneous catastrophic event in the geological history of a fault or a region. A large earthquake commonly, but not always, leaves clues about its occurrence in the geological record and the landscape morphology. Thus, geologists can retrieve these traces and interpret them. This is the purpose of active tectonics and paleoseismology. Most of the quantitative observations on active faults and their relationship with earthquake activity come from regions of the world where the seismic activity is important. In those regions where lithospheric deformation is associated with plate boundaries, the relationship between the earthquake activity, the morphology, and the geological record is well recognized.

In most intraplate regions such as northwest Europe, tectonic deformation related to earthquake activity is slow and not well expressed in the landscape, as a result of which very few geological studies have been carried out up to recently to evidence a relationship between geology and earthquake activity. In stable continental Europe, our investigations [1] [2] [3] [4] [5] along the Bree fault scarp in Belgium were the first to provide evidence that large surface-rupturing earthquakes occurred during the Holocene and late Pleistocene. The purpose of this contribution is to provide a short summary of the research done in the RVG.

Seismicity and Quaternary faults in the Roer Valley Graben

Re-evaluated historical earthquake and present-day seismological data [6] indicate that much of the known seismic activity in northwest Europe is concentrated in the RVG (figure 1). Nevertheless, the three strongest known earthquakes with estimated magnitude ≥ 6.0 occurred outside of this active structure, in the northern Ardennes (1692, M ~6 ¼), the southern North Sea (1382, M ~6.0) and the Strait of Dover (1580, M ~6.0).

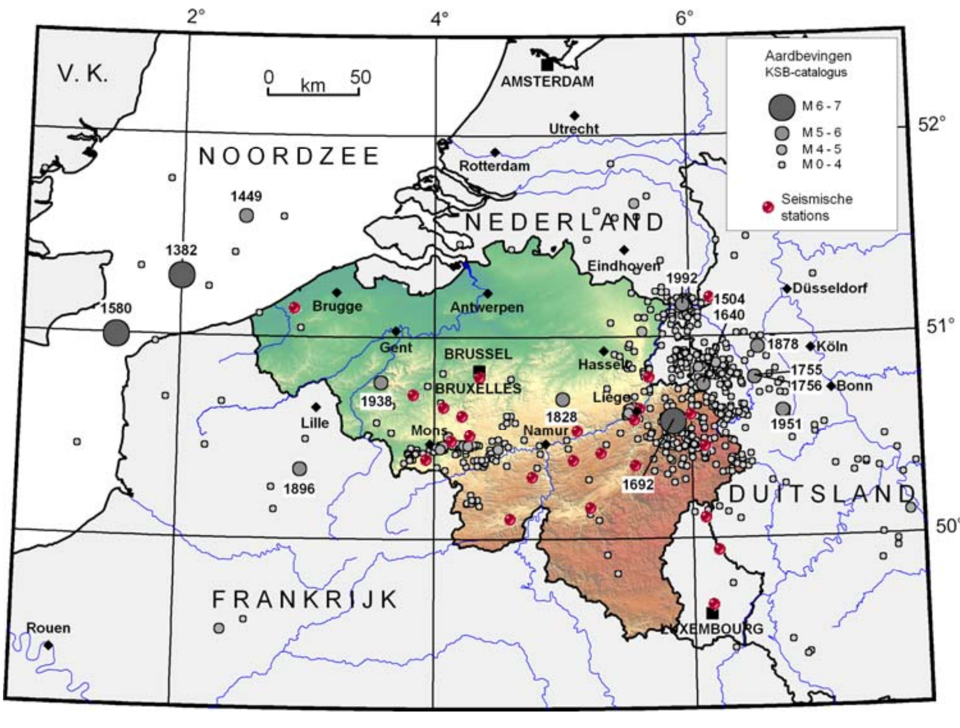
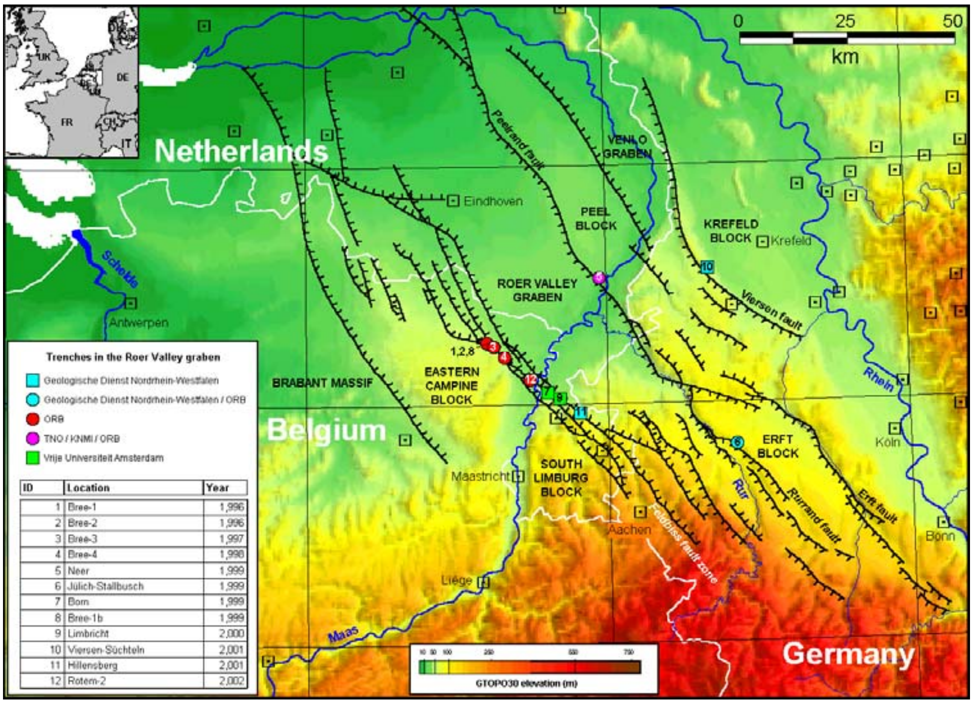


Figure 1 – Seismic activity in northwest Europe and location of the stations of the Belgian seismic network

The RVG experienced 7 earthquakes with M_S between 5.0 and 6.0 since 1350. The largest instrumentally recorded earthquake was the M_S 5.4 Roermond earthquake in 1992, and the largest historical earthquake was the M_S 5 ¾ Düren event in 1756. Focal mechanisms show mainly normal faulting [7].

The RVG is situated in the border area between Belgium, The Netherlands, and Germany, and is bounded by two NNW-SSE trending Quaternary normal fault systems (figure 2). The eastern boundary is defined by the Peelrand fault, along which the 1992 Roermond earthquake occurred, bifurcating SE-ward into the Rurrand and Erft faults. The western border is defined by the Feldbiss fault zone, which consists of a bundle of en échelon faults, among which the Geleen fault. We addressed the question of the capability of these faults to produce large earthquakes by undertaking paleoseismic investigations along the western border of the graben since 1996.



ID	Location	Year
1	Bree-1	1,996
2	Bree-2	1,996
3	Bree-3	1,997
4	Bree-4	1,998
5	Neer	1,999
6	Jülich-Stallbusch	1,999
7	Born	1,999
8	Bree-1b	1,999
9	Limbricht	2,000
10	Viersen-Süchteln	2,001
11	Hillensberg	2,001
12	Rotem-2	2,002

Figure 2 – The Roer Valley Graben – Quaternary faults and location of paleoseismic trenches

Palaeoseismology aims to identify and determine the size and timing of past large earthquakes through the study of co-seismic deformation of landforms and near-surface sediments. Identification of palaeoearthquakes in fault-zone exposures generally relies on the recognition of "event horizons" and "colluvial wedges".

The event horizon marks the ground surface at the time of the surface-rupturing earthquake [8]. It separates layers that have been faulted in the event from unfaulted layers that were deposited afterward. Colluvial wedges are wedge-shaped units of slope-derived material formed next to a fault by degradation of a fault scarp created in a surface-rupturing event with vertical offset. They form over a more or less long period of time following the earthquake. Event horizons and colluvial wedges are considered as primary evidence for a surface-rupturing palaeoearthquake, as they are related to instantaneous fault displacement at the surface [9]. Few non-seismic processes can create such features.

Paleoseismic investigation of the Geleen fault

The Geleen Fault runs NW-SE over a distance of ca. 27 km between the cities of Bree (Belgium) and Geleen (The Netherlands). The northern and southern sections of this fault are well expressed in the topography, in contrast to the central section, which traverses the Meuse River valley. The first paleoseismic trenches were excavated across the northern section of the fault (the "Bree fault scarp"). Later studies focused on the central section.

Bree fault scarp

The Bree fault scarp is a linear, 10-km-long and 15-to-20-m-high scarp, juxtaposing gravel of the middle Pleistocene (> 300 ka) main terrace of the Meuse River on the Campine Plateau, against Late Weichselian (ca. 27-12 ka) sands in the RVG. Five palaeoseismic trenches have been studied here between 1996 and 2000 [2][3][5]. These trenches provided evidence for the occurrence of large, surface-rupturing earthquakes on this fault in the recent geological past. In one trench, six paleoearthquakes were identified, five of which occurred in the past 100 kyr. The last three paleoearthquakes could be correlated along the entire Bree fault scarp, and caused vertical displacements of ca. 0.5–1.0 m. The most recent event (MRE) was shown to have a Holocene, most likely even late Holocene, age. The return period was found to range between ca. 14 and 23 kyr. Strong 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. However, the paleoseismic studies were also faced with some problems that are directly or indirectly related to the slow rate of deformation: evidence for the MRE is situated at shallow depth and obscured by soil development, as a result of which the MRE remained poorly dated; the tectonic signal is overprinted by a strong climatic signal (transition from periglacial to temperate conditions); dating resolution rapidly decreases for older events, etc.

Meuse River Valley

In more recent years, we extended the investigation 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, one close to this stepover, and another one 2 km SE. We found evidence for a late Holocene paleoearthquake in both trenches (figure 3). Radiocarbon and OSL dating [10] constrain the event between 2.5 ± 0.3 and 3.1 ± 0.3 kyr. BP, and between 2790 ± 20 and 3770 ± 50 calibrated years before AD 2005, respectively. Thin-section analysis [11] confirmed our identification of the pre-faulting soil and the overlying scarp-derived colluvium, which are primary coseismic evidence. In both trenches this event is associated with liquefaction, including various sand blows and a gravel dike. These features are unmistakable 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 kyr BP. The interval between both events has a two-sigma range of 11,800 – 16,800 yr.

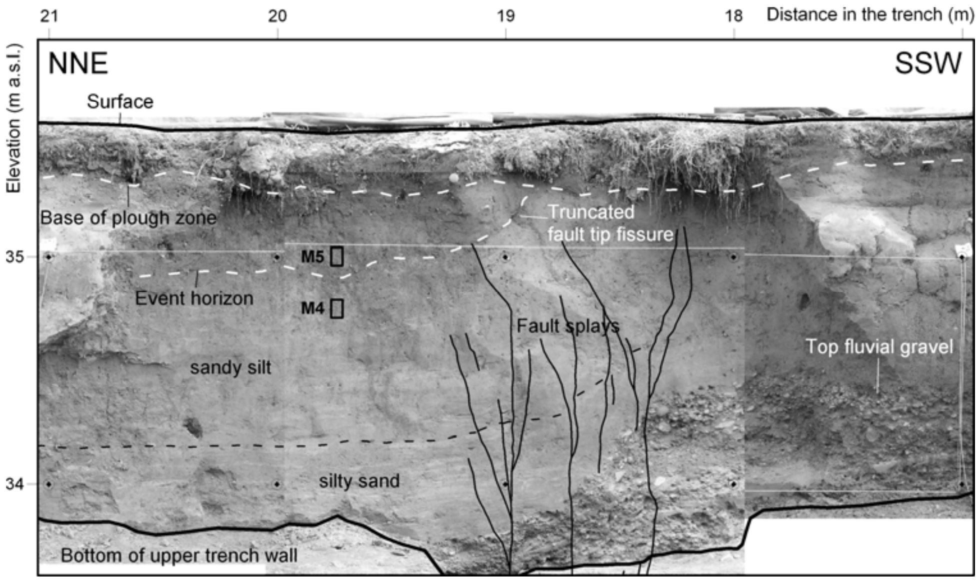


Figure 3 – Stratigraphic evidence for the most recent surface-rupturing earthquake in a paleoseismic trench across the Geleen fault near Rotem.

Southeastern part of the Geleen fault

Our findings contradict the earlier general consensus that faulting in the RVG occurs largely aseismic. Even in a recent paleoseismic study on the southeastern portion of the Geleen fault near Born (The Netherlands) [12], the authors concluded that there is no evidence for large, surface-rupturing earthquakes. Their main argument concerns the observation, at some distance from the fault, of a liquefaction feature which is attributed to a moderate earthquake around 15 ka BP, but does not seem to be directly linked with displacement on the fault itself. The offset they observe follows a short period (max. 2700 years) of erosion, separating both events in time. From this, it is inferred that this offset was created by post-seismic relaxation creep as a delayed response at the surface to the earthquake that triggered the liquefaction. However, their descriptions are conflicting, while they also appear to have overlooked features such as fault terminations and a fault-zone unconformity. Reinterpreting their trench log, we demonstrate that the stratigraphic boundary truncating the liquefaction feature in the hanging wall does correspond with an event horizon in the fault zone, and that it is associated with a small, but significant amount of fault offset. We also show that the later offset interpreted by [12] as post-seismic creep resulting from the earthquake that caused the liquefaction, is in fact much younger (post-dating post-depositional soil development), and thus unrelated to the liquefaction event. The event horizon for the event associated with liquefaction corresponds to a well-known and widespread gravel pavement, known as the Beuningen horizon, which is the same stratigraphic horizon as the event horizon for the second event in one of our trenches in the Meuse River valley.

Possible linkage of fault segments

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 M 6.7 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. It is not likely that additional trenches will provide the definitive answer to this question.

Discussion and conclusions

Paleoseismic studies provide new information on the long-term seismic activity of faults in the RVG that extends our historical and instrumental earthquake catalogs, and that is of great value for assessment and mitigation of seismic risk.

Our investigations along the Geleen fault provide information on the recurrence of large earthquakes *along a single seismogenic* source in the RVG. The synthesis of data collected in the four trenches excavated on the Bree fault scarp allows us to calculate the fault slip rate and return period for large earthquakes. If we consider the two most recent complete earthquake cycles (between event 3 and event 1), which are best constrained in time and can be correlated across the entire fault scarp, we obtain an average return period of 13.7 ± 7.8 kyr. The average fault slip rate for the same interval, averaging the displacements of events 1 and 3, is 0.050 ± 0.036 mm/yr. Using the longer faulting record from Bree trench 4 [5], we can make the same calculations for the last 100 kyr. Considering that 5 paleoearthquakes are recorded in trench 4 since 101.4 ± 9.6 kyr. BP, corresponding to 4 or 5 complete earthquake cycles, we calculate an average return period of 22.7 ± 4.3 kyr. The corresponding average fault slip rate is 0.031 ± 0.012 mm/yr., which is in good agreement with the values obtained for the two last earthquake cycles. The trenches in the Meuse River valley allowed to better constrain the timing of the MRE, between 2.5 ± 0.3 and 3.1 ± 0.3 kyr. BP. However, even in this case, the information is not sufficient to define the rupture length with certainty. Investigating the other Quaternary faults of the RVG is therefore a necessity if we want to better understand their mechanical behavior and the variation of strain in space and time.

Outside of the RVG, strong historical earthquakes have occurred as well. These earthquakes occurred at different locations, and are generally not associated with any present-day activity. This demonstrates the incompleteness of our earthquake catalogue. Thus, the present earthquake activity, reflected by the historical and instrumental seismicity, concerns in reality a very small part of the regional deformation at the geological time scale because the tectonic processes generating them are very slow. To date, it has not been possible to identify any active fault in this area, and thus to gain any insight in the seismic-cycle characteristics of the possible seismogenic sources. It is likely that seismogenic sources exist that we don't know at present. Evaluating when and where the next large earthquake will occur in northwest Europe is an impossible task in this context.

References

[1] Camelbeeck, T., and Meghraoui, M. (1996) Large earthquakes in northern Europe more likely than once thought. *EOS, Transactions, American Geophysical Union* 77, 405-409.

[2] Camelbeeck, T., and Meghraoui, M. (1998) Geological and geophysical evidence for large palaeoearthquakes with surface faulting in the Roer Graben (northwestern Europe). *Geophysical Journal International* 132, 347-362.

[3] Meghraoui, M., Camelbeeck, T., Vanneste K., Brondeel M., and Jongmans, D. (2000) Active faulting and paleoseismology along the Bree fault zone, Lower Rhine graben (Belgium). *J. Geophys. Res.* 105, 13,809-13,841.

[4] Vanneste, K., Meghraoui, M., and Camelbeeck, T. (1999) Late Quaternary earthquake-related soft-sediment deformation along the Belgian portion of the Feldbiss fault, Lower Rhine Graben system. *Tectonophysics* 309, 57-79.

[5] Vanneste, K., Verbeeck, K., Camelbeeck, T., Renardy, F., Meghraoui, M., Jongmans, D., Paulissen, E., and Frechen, M. **(**2001) Surface rupturing history of the Bree fault escarpment, Roer Valley Graben : new trench evidence for at least six successive events during the last 150 to 185 kyr. *Journal of Seismology* 5, 329-359.

[6] Camelbeeck, T., Vanneste, K., Alexandre, P., Verbeeck, K., Petermans, T., Rosset, P., Everaerts, M., Warnant, R. and Van Camp, M. (2007) Relevance of active faulting and seismicity studies to assess long term earthquake activity in Northwest Europe In: Stein S. and Mazzotti S. (eds.), Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues. Geological Society of America Special Paper 425, 193-224.

[7] Camelbeeck, T. (1993) Mécanisme au foyer des tremblements de terre et contraintes tectoniques: le cas de la zone intraplaque belge. *Ph.D. thesis*, Université Catholique de Louvain, 295 p.

[8] Pantosti, D., Schwartz, D.P. & Valensise, G. (1993) Paleoseismology along the 1980 surface rupture of the Irpinia fault: implications for earthquake recurrence in the southern Apennines, Italy, *J. Geophys. Res.* 98, 6561-6577.

[9] McCalpin, J.P. (1996) *Paleoseismology*. Academic Press, Inc., San Diego.

[10] Vandenberghe, D., Vanneste, K., Verbeeck, K., Paulissen, E., Buylaert, J.-P., De Corte, F. & Van den haute, P. (2007). Late Weichselian and Holocene earthquake events along the Geleen fault in NE Belgium: OSL age constraints. *Quaternary International*, doi: 10.1016/j.quaint.2007.11.017.

[11] Vanneste, K., Mees, F. & Verbeeck, K. (2008). Thin-section analysis as a tool to aid identification of palaeoearthquakes on the “slow”, active Geleen Fault, Roer Valley Graben. *Tectonophysics* 453, 94-109.

[12] Houtgast, R.F., Van Balen, R.T., Kasse, C. & Vandenberghe, J. (2003) Late Quaternary tectonic evolution and postseismic near surface fault displacements along the Geleen Fault (Feldbiss Fault Zone - Roer Valley Rift System, the Netherlands), based on trenching, *Netherlands Journal of Geosciences* 82, 177-196.