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Paleoseismology of the Geleen fault, Lower Rhine Graben

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Abstract: *We present a synthesis of the paleoseismic research conducted by the Royal Observatory of Belgium on the Geleen fault in the Lower Rhine Graben (LRG) over more than a decade. Our investigations along the Bree fault scarp section of this fault in Belgium were the first in stable continental Europe to provide evidence that large surface-rupturing earthquakes with magnitudes greater than 6.3 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 intersects much younger (Saalian and Late Weichselian) terraces of the Meuse River. The analysis of two paleoseismic trenches excavated on this fault section raised the question whether or not the entire Geleen fault defines a single rupture segment.*

Key words*: intraplate, normal fault, paleoearthquake, late Pleistocene.*

INTRODUCTION

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 (Camelbeeck & Meghraoui, 1996, 1998; Meghraoui et al., 2000; Vanneste et al., 1999, 2001) along the Bree fault scarp section of the Geleen fault 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 summary of the paleoseismic research carried out on this fault.

SEISMICITY AND QUATERNARY FAULTS IN THE LOWER RHINE GRABEN

The LRG is situated in the border area between Belgium, The Netherlands, and Germany, and is bounded by two NNW-SSE trending Quaternary normal fault systems (Fig. 1). The eastern boundary is defined by the Peelrand fault, 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.

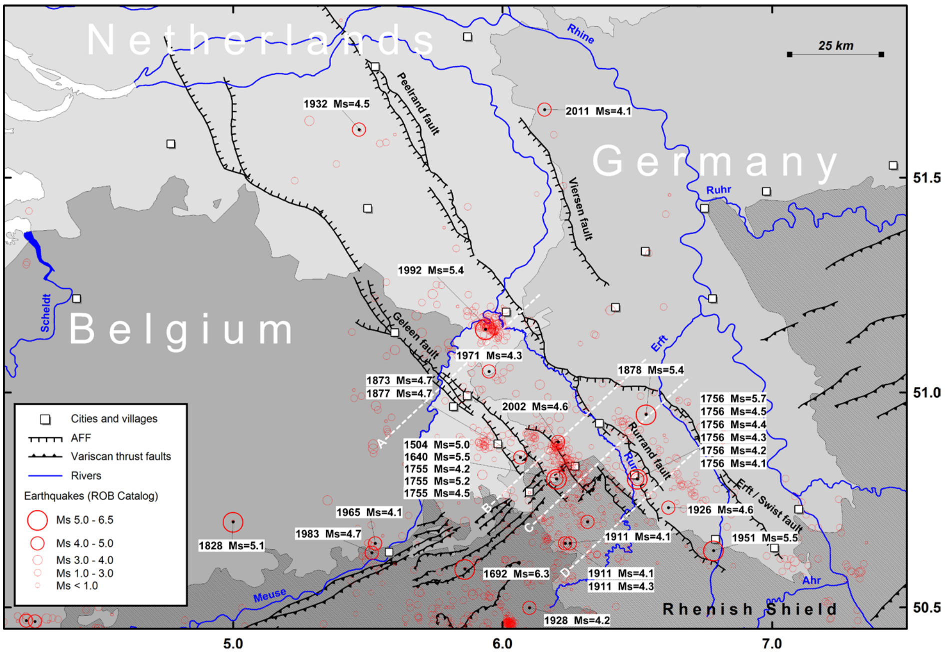

Fig. 1: Quaternary faults, seismicity and location of paleoseismic trenches in the Lower Rhine Graben. CSS: Composite Seismic Sources, AFF: Active Faults, ROB: Royal Observatory of Belgium

Re-evaluated historical earthquake and present-day seismological data (Camelbeeck et al., 2007) indicate that much of the known seismic activity in northwest Europe is concentrated in the LRG. The LRG experienced 7 earthquakes with M_S between 5.0 and 6.0 since 1350 (Fig. 1). The largest instrumentally recorded earthquake was the M_S 5.4 Roermond earthquake in 1992, and the largest historical earthquake was the 1756 Düren earthquake, with estimated M_S ~5 ¾. Focal mechanisms show mainly normal faulting. However, it is worth noting that the three strongest known earthquakes with estimated magnitude ≥ 6.0 occurred outside of the LRG, 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).

Many faults have been mapped in the LRG, but so far a model of fault hierarchy or fault segmentation was lacking. In the frame of a European database of seismogenic sources, we have devised a seismic-source model for the LRG, consisting of so-called composite seismic sources (Vanneste et al., 2013). Each composite seismic source may encompass one or more fault segments, but it is considered unlikely that a rupture segment would extend across more than one source. We distinguished 15 seismic sources based on major stepovers, bifurcations, gaps, and important changes in strike, dip direction or slip rate (Fig. 2). The sources are further subdivided into one or more informal fault sections, each with an associated surface trace. We compiled all relevant data concerning the seismic-source parameters required for the database, putting lower and upper bounds on strike, dip, rake, slip rate, and depth, and an upper bound on earthquake magnitude. We also compiled vertical displacement observations (cumulative offset and age of marker horizons), allowing us to assign minimum and maximum vertical deformation rates to each source. These vertical displacement rates range mostly between 0.01 and 0.07 mm/yr, and corresponding slip rates between 0.01 and 0.09 mm/yr. The Peelrand and Erft/Swist faults appear to be the fastest slipping faults, followed by the Geleen fault, which has a slip rate of ~0.055 mm/yr.

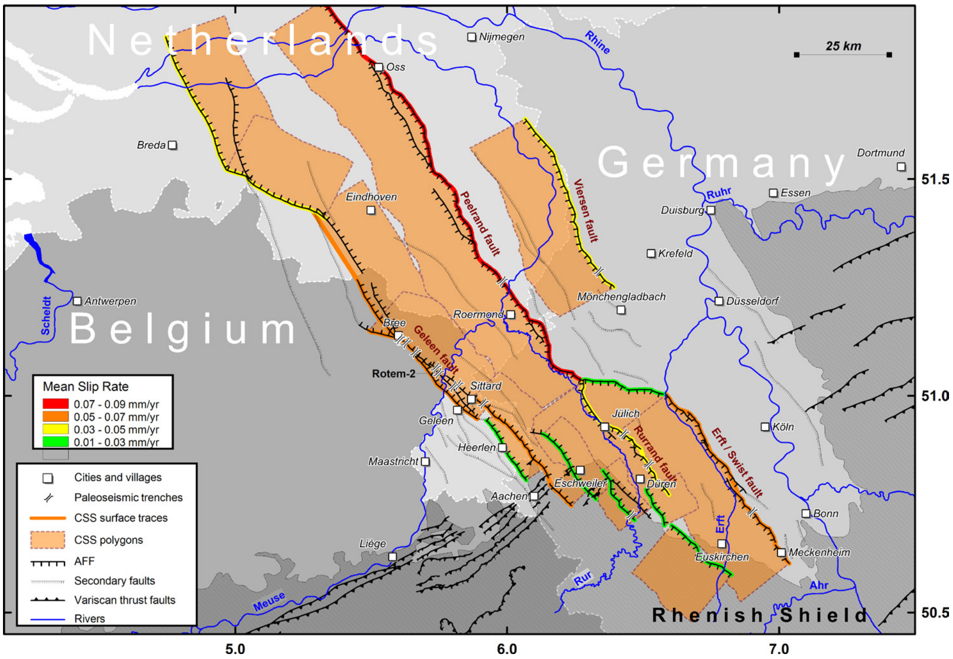

Fig. 2: Hierarchical fault model for the Lower Rhine Graben. Surface traces are colored according to the slip rate. CSS: Composite Seismic Sources, AFF: Active Faults

PALEOSEISMIC INVESTIGATION OF THE GELEEN FAULT

The Geleen Fault runs NW-SE over a distance of ~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 kyr) main terrace of the Meuse River on the Campine Plateau, against Late Weichselian (ca. 27-12 kyr) sands in the graben. Five palaeoseismic trenches have been studied here between 1996 and 2000 (Camelbeeck & Meghraoui, 1998; Meghraoui et al., 2000; Vanneste et al., 2001). 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 101.4 ± 9.6 kyr. The last three paleoearthquakes could be correlated along the entire Bree fault scarp, and caused vertical displacements of 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 surface 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 (Vanneste et al., 2008), 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 (Fig. 3). Radiocarbon and OSL dating (Vandenberghe et al., 2007) 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 (Vanneste et al., 2008) 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 11,600 – 17,200 yr.

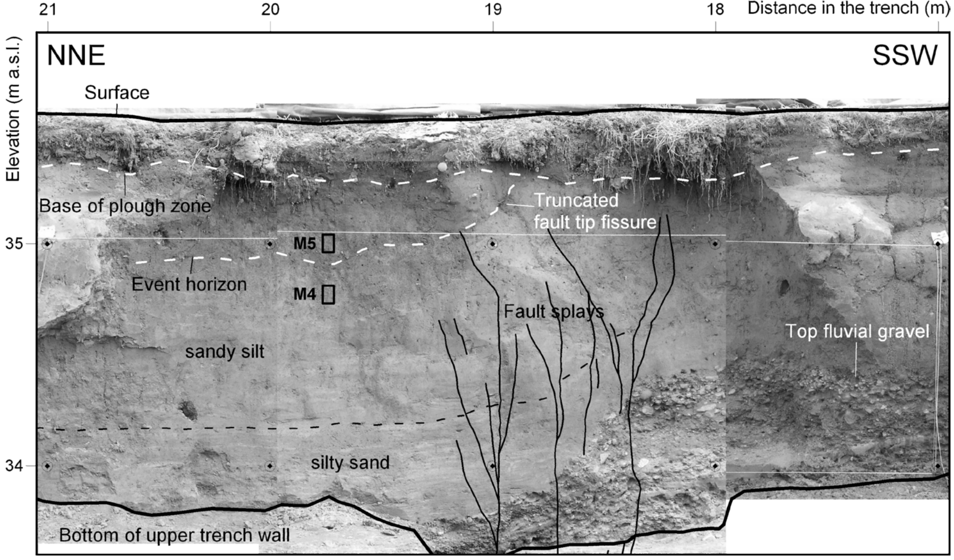

Fig. 3: Paleoseismic evidence for the most recent surface-rupturing earthquake in a trench across the Geleen fault near Rotem. Location shown in Fig. 2

Southeastern part of the Geleen fault

Our findings contradict the earlier general consensus that faulting in the LRG occurs largely aseismic. In a paleoseismic study on the southeastern portion of the Geleen fault near Born (The Netherlands), Houtgast et al. (2003) 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 kyr 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, the authors appear to have overlooked features such as fault terminations and a fault-zone unconformity. Reinterpreting their trench log, we can 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 Houtgast et al. (2003) 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 (Wesnousky, 2006). 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

Our investigations along the Geleen fault provide information on the recurrence of large earthquakes along a single seismogenic source in the LRG. 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 (Vanneste et al., 2001), 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 better constraining 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 LRG is therefore a necessity if we want to understand their mechanical behavior and the variation of strain in space and time.

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