Centre Européen de Géodynamique et de Séismologie
European Center for Geodynamics and Seismology
Grand-Duché de Luxembourg

Président d'honneur: Son Altesse Royale Le Grand Duc Henri

Président: M. Feider
Secrétaire: E. Buttini

Report prepared by Dr. J. Barrière
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Seismic studies based on data from the Luxembourg National Seismic Network

Report 2019

As stated in the 2018 report, we have pursued the development of the seismic monitoring of the Luxembourgish territory by combining high-quality, broadband seismic instrumentation with appropriate data processing and analysis.

The main improvements with respect to the past year are:

- The addition of real-time data from 5 additional stations belonging to other networks into the processing chain in order to increase the confidence of the earthquake location procedure.
- The implementation of a picking-free, cross-correlation-based algorithm adapted to the detection and location of small earthquakes in Luxembourg into the SeisComP3 software, thus providing a complete solution for detecting, locating and archiving seismic events in real-time. For the moment, this result is achieved through the interfacing between Seiscomp and the computing platform where the location program is running (Matlab). A more efficient alternative, which could be further envisaged, would be the development of a dedicated module to Seiscomp based on the same algorithm.
- The analysis of the ambient seismic noise properties in Luxembourg in order to gauge the feasibility of high-resolution (crustal images) surface wave tomography studies in the future.

We show in Figure 1 how adding several stations from neighbouring networks (Belgium, Germany) dramatically improves the location accuracy of nearby seismic events just outside the national network. The ellipse around each event (called the 2D error ellipse) represents the uncertainty of the location for the considered earthquake and is significantly reduced in regions where the station coverage has been improved (especially on the Belgian side). The addition of seismic stations also allows to improve the network detection threshold (234 events in one year against 194 in two years without using the additional stations). As already observed from the previous analysis (Sept. 2016 – Sept. 2018, Figure 1a), most of the seismicity in and around Luxembourg comes from the human activity (quarry blasts). Nonetheless, the two most energetic events (local magnitude $M_L \sim 1.7$) for the past year (Oct. 2018 – Oct

2019, Figure 1b) are tectonic earthquakes occurring at large depths (> 10-15 km). These events are numbered 2 and 3 in Figure 1b. The event 2 is located in an active seismic region (Belgian Ardennes), a few kilometers south to the city of Verviers, where one of the largest historical earthquakes known in Western Europe (M ~ 6-6.5, 18 Sept. 1692) took place only about 50 km north of the Luxembourgish border. Event 2 has also been well detected by the Belgian seismic network leading to a manual location solution similar to the one we obtained. Event 3, however, is better constrained by our network because situated on the extreme South East of the Luxembourgish territory, highlighting the usefulness of such a local deployment, which can eventually help to improve our understanding of the background seismicity in this stable tectonic context. Figure 2 shows the screenshot of the SeisComp window associated to this earthquake, recalling the main information (map, arrival times of seismic phases, time residuals, etc.).

The first natural event (in contrast to human-induced) accurately located on the Luxembourgish territory with this new network was detected two years ago (18 Nov. 2017) close to the ECGS with a focal depth around 10 km (numbered 1 in Figure 1a). This seismic event of very low magnitude (<1) clearly illustrates the capability of this local network to monitor efficiently the micro-seismicity in this area. We decided to study this particular earthquake by applying a matched-filter technique in order to check if similar events occurred in the past in the same source region. This method is notably routinely employed at ECGS at volcanic settings (Virunga volcanoes) where similar seismic source processes close to each other in space are often repeated in time due to magma movements at depth. Using the recordings of this earthquake at Walferdange as template (called thereafter master event, see Figure 3a), we can scan the entire available database at this station (roughly the past 10 years) for retrieving similar waveforms using a standard moving cross-correlation approach. This way we can retrieve similar past earthquakes not detectable and/or not locatable at that time due to an insufficient station coverage or a too low SNR (i.e., signal-to-noise ratio, indicating how the event emerges above the noise level).

The dominant frequency content of the master event is relatively high (5-20Hz) and matching similar waveforms on the three seismic components (one vertical, two horizontals – North/East) would be only possible if highly similar source processes repeat in time. Using this technique, we have surprisingly detected a "family" of 4 other micro-earthquakes characterized by correlation coefficient higher than 0.66 for the three components (Figure 3b). These events occurred between March 2013 and March 2019 and have even lower amplitudes than the main one (Figure 3a). As a first hypothesis about the source mechanism, this result could for instance suggest a seismic source linked to fluid-driven processes in a particular zone of weakness below this central region of Luxembourg (e.g., Audin et al., 2002).

The last investigation we conducted using these data was the calculation of Noise Cross-Correlation Functions (NCFs) between all station pairs from the available continuous recordings between 1 Oct. 2018 and 1 Oct. 2019. The purpose of this technique is to use the seismic signal continuously generated at the Earth's surface as a source of surface waves for tomographic studies. The most powerful seismic noise source at low frequencies (< 1Hz) is called microseisms, which consist basically in a background tremor generated by water wave motions in oceans. Since the first applications (e.g., Shapiro et al., 2005 for Southern California), this method has proven to be very useful to image the Earth's crust with no need for well-distributed seismicity as required for local earthquake tomography. This Surface Wave tomography (SWT) approach is thus very appropriate to our low-seismicity region. We compute NCFs in the frequency band 0.05-0.2 Hz (at these frequencies, the surface waves can sample the uppermost 10-20 km of the crust and oceanic microseisms are stronger). The NCFs between two stations consist in waveforms exhibiting a maximum of correlation at time lag corresponding to the average surface wave speed between these two stations. If the station coverage is sufficiently dense, then an image of the surface wave speed can be computed by combining all station pairs information. However, in case of a strongly directive source, biased traveltime estimates can be obtained if station pairs do not align with the noise direction. As a preliminary analysis using the set of available stations (Figure 4a), we check the directivity of noise sources (Figure 4b) and we plot the NCFs for interstation distances between 10 and 120 km (Figure 4c). Being the calculation of cross-correlation between two signals, the maximum of NCFs can be obtained at positive or negative time lag depending on the chosen station as reference. In the case of perfect omni-directional noise source distribution, the NCFs should be symmetric around 0. In our case, the NCFs are asymmetric (the maximum is clearly identifiable on one side), a fact that implies a preferential directivity in the noise source. Our results show that the seismic noise is oriented toward the North Sea because NCF maxima are obtained for station pairs alignment toward the North West. By selecting NCFs satisfying some selective criteria (e.g., minimum SNR, consistent time lag) we can plot NCFs showing reasonable moveouts of surface wave arrivals with a (global) best-fit of about 2.8 km/s for the surface waves group velocity (the red line in Figure 4c fitting the maximum of NCFs envelopes). These results are promising and will further encourage the deployment of additional stations in order to image the crust of this stable tectonic area with an unprecedented high-resolution (lower-resolution, large-scale SWT tomographies for entire Europe have already been published, e.g., Lu et al., 2018).

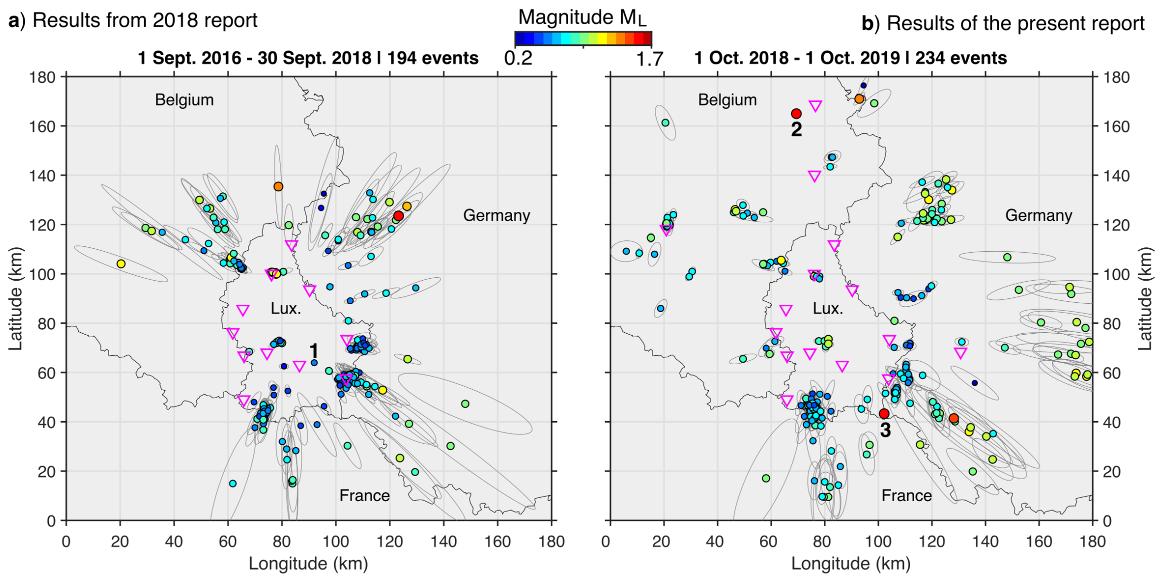

Figure 1: Local seismicity in and around Luxembourg with associated location errors (ellipses) a) between 1 Sept. 2016 and 30 Sept. 2018 (2018 report) and b) between 1 Oct. 2018 and 1 Oct. 2019. The large majority of these seismic events are of human origin (quarry

blasts) but some of them are clearly identified as tectonic earthquakes (e.g., event 1 in a and events 2,3 in b).

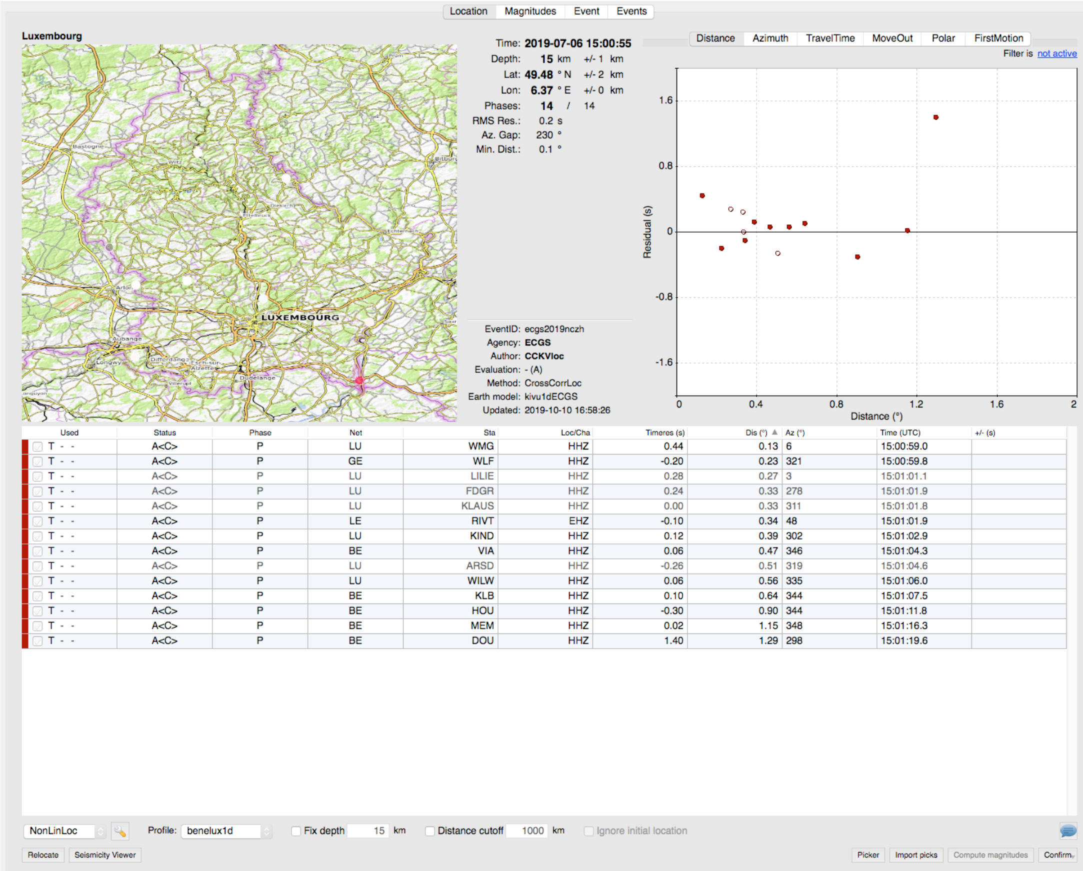

Figure 2: SeisComP3 window of the M_L1.7 seismic event occurring on 6 July 2019 at the borders of Luxembourg, France and Germany. The epicentre is identified by a red dot on the map.

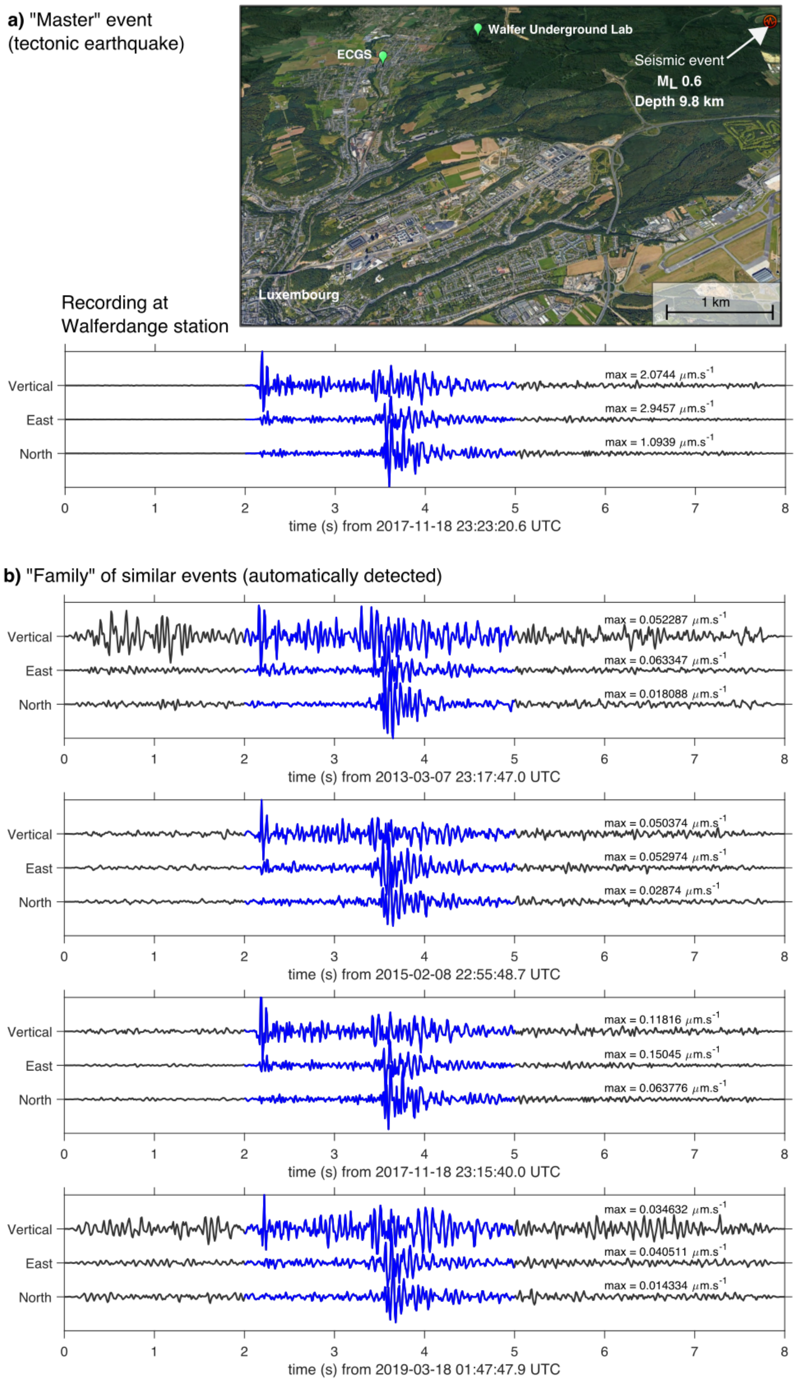

Figure 3: a) Map and 3-component records of the tectonic event occurring on 18 Nov. 2017 recorded at Walferdange station b) 4 highly similar events detected using a matched-filter technique. The maximum absolute amplitude is indicated above each trace. The waveforms highlighted in blue correspond to the 3-s event detected at the same closest station (Walferdange). Even though of very low amplitudes, the P-wave and S-wave arrivals are clearly detectable for each event.

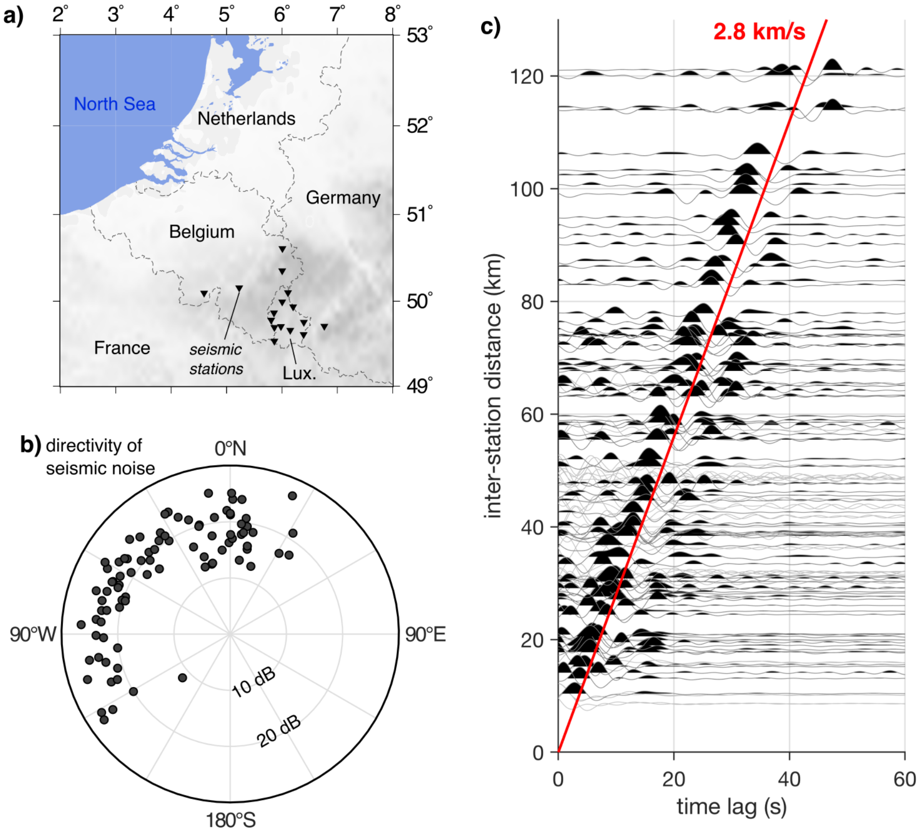

Figure 4: a) Map of seismic stations used for the calculation of NCFs. b) Each dot in the polar plot correspond to the preferential azimuth and SNR value (radial axis) of the NCFs displayed in c) Wiggle traces of the NCFs showing a moveout of surface wave arrivals corresponding to a group velocity of about 2.8 km/s (a reasonable value for the continental crust and this kind of seismic waves).

References

Audin, L., Avouac, J. P., Flouzat, M., and Plantet, J. L., Fluid-driven seismicity in a stable tectonic context: The Remiremont fault zone, Vosges, France, *Geophys. Res. Lett.*, 29, doi:10.1029/2001GL012988, 2002.

Lu Y., Stehly L., Paul A. and AlpArray Working Group, High-resolution surface wave tomography of the European crust and uppermost mantle from ambient seismic noise, *Geophys. J. Int. 214*, doi: 10.1093/gji/ggy188, 2018.

Shapiro N.M., Campillo M., Stehly, L., Ritzwoller, M.H., High resolution surface wave tomography from ambient seismic noise. *Science* 307, 1615–1618. 2005.