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The 1965–1970 seismic episode in the Hainaut coal basin (Belgium): a key period to analyse the triggered nature of a century-long seismic activity

Supplementary material

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ABSTRACT

Damaging earthquakes happened in the Hainaut coal basin (Belgium) in the 19th and 20th centuries but stopped after coal mining. We relocated 54 Hainaut earthquakes of the period 1965 and 1985 by using regional and local seismic phase measurements from recordings in and around Belgium. These new results finalise the Hainaut earthquake catalogue, derived from macroseismic data for the 1887–1965 period and instrumental records after 1965. This updated database allows us to discuss the origin of this intriguing seismicity. Computed focal depths show that the strongest earthquakes before 1985 occurred inside the Upper Palaeozoic part of the Brabant Parautochton, probably below the deepest parts of the coal mines. The shallowness of this seismicity, its spatial link with the coal basin, the compressive to strike-slip focal mechanisms of the stronger earthquakes between 1965 and 1985 and the large quantity of coal mass removal all match with worldwide observations of mining-triggered earthquakes. The earthquake mechanisms agree with the local, compressive to transpressive stress regime derived from differences in upper crustal density and topography that make the Hainaut area more sensitive to fault reactivation at shallow depths, as observed in similar tectonic settings elsewhere in the world.

KEYWORDS

early-instrumental, earthquake relocation, focal mechanism, local stress analysis, triggered seismicity, coal mining, Hainaut, Belgium

Article history

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S1. Principle of the relative location method

S1.1. Basic principle

The basic principle of this method of relative location between two earthquakes, defined as an earthquake couple, is explained on Figure S1 representing a simplified crustal cross-section. Figure S1 shows the propagation path of the Pn waves for an earthquake of known epicenter E_0 and focal depth Z_0, and an earthquake, for which the epicenter E_1 and focal depth Z_1 are unknown, up to a seismic station STA.

Their arrival time T_0 and T_1 are respectively:

$$T_0 = H_0 + (2H_M - Z_0)\frac{cos(i_0)}{V_0} + \frac{X_0}{V_1} \qquad (eq.\ S1)$$

$$T_1 = H_1 + (2H_M - Z_1)\frac{cos(i_0)}{V_0} + \frac{X_1}{V_1} \qquad (eq.\ S2)$$

where $cos(i_0) = \sqrt{1 - \frac{{V_0}^2}{{V_1}^2}}$ with V_0 and V_1 respectively the P-wave velocity in the crust and the upper mantle and H_M the thickness of the crust. H_0 and H_1 are the origin times of respectively the master and unknown earthquakes. The term $(2H_M - Z_0)\frac{cos(i_0)}{V_0}$ is called the **Pn wave time term** of the E_0 earthquake. For the E_1 earthquake, the expression is similar.

The difference of arrival time Δt_i between the two earthquakes at a station STA is:

$$\Delta t_i = T_0 - T_1 = H_0 - H_1 + \frac{\Delta Z cos\ i_0}{V_0} + \frac{\Delta X}{V_1} \qquad (eq.\ S3)$$

ΔX being the difference of distance of the station to the two different seismic events and $\Delta X = X_0 - X_1$, while $\Delta Z = Z_0 - Z_1$ is the difference of focal depth between the two earthquakes.

As the distance between the station and the two earthquakes is very large compared to the epicenter distance between them ($X_0 \gg \Delta X$), the angle γ at the unknown epicenter between the directions of the master event epicenter and of the station STA can be written in function of the azimuth $\emptyset$ of the master epicenter and the azimuth Θ_i of the seismic station as $\gamma \cong (\Theta_i - \emptyset)$.

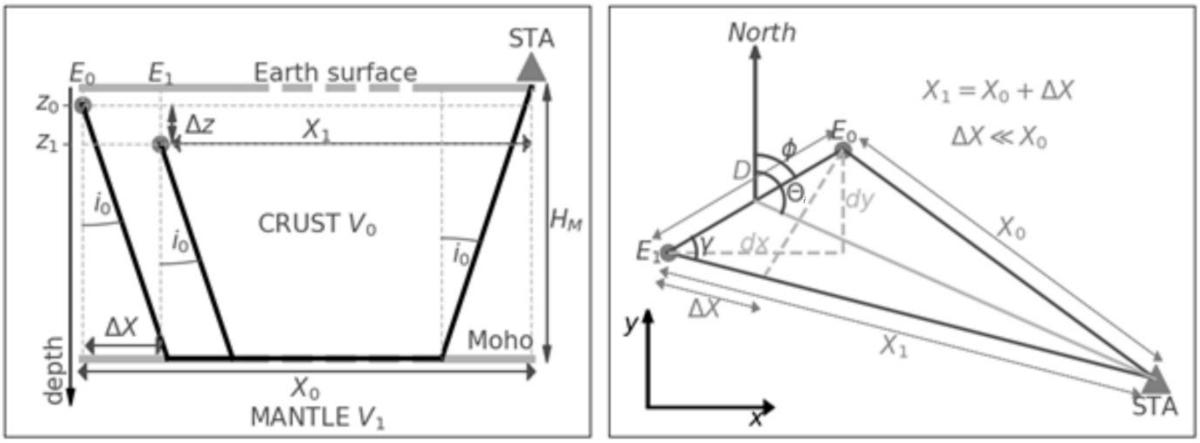

***Figure S1**. **Left** - Simplified cross section showing the propagation paths of Pn waves between an unknown and a known master earthquake and its arrivals at seismic station STA. **Right** – Planar configuration of the epicenter location E_1 of the unknown earthquake, the well-determined epicenter E_0 of a master event and the position of the seismic station STA. See text for explanation of abbreviations.*

Then:

$$\Delta X = D\cos\gamma = D(\cos\Theta_i\ \cos\emptyset + \sin\Theta_i \sin\emptyset) \qquad (eq.\ S4)$$

Hence:

$$\Delta t_i = T_0 - T_1 = H_0 - H_1 + \frac{\Delta Z \cos i_0}{V_0} + \frac{D(\cos\Theta_i\ \cos\emptyset + \sin\Theta_i \sin\emptyset)}{V_1} \qquad (eq.\ S5)$$

This relationship can be expressed as:

$$\Delta t_i = a + b\ \cos\Theta_i + c\ \sin\Theta_i \qquad (eq.\ S6)$$

In which:

$$a = H_0 - H_1 + \frac{\Delta Z \cos i_0}{V_0} \qquad (eq.\ S7)$$

$$b = \frac{D\cos\emptyset}{V_1} = \frac{\Delta y}{V_1} \qquad (eq.\ S8)$$

$$c = \frac{D\sin\emptyset}{V_1} = \frac{\Delta x}{V_1} \qquad (eq.\ S9)$$

A set of equations like equation S6 can be written by considering the difference of Pn arrival times for the same two earthquakes for all seismic stations for which the Pn phase has been measured. This system of linear equations has three unknowns a, b and c that can be reliably determined if the data number and the azimuthal coverage of seismic stations are sufficiently large.

Knowing the apparent velocity V_1 of Pn-waves, the values of b and c allow determining the epicenter E_1=(Δx, Δy) of the unknown earthquake relative to the epicenter E_0 of the master event. Based on the coordinates of the master event epicenter, the relative coordinates Δx and Δy led to establish the real epicentral coordinates of the unknown earthquake. This relative epicenter location is directly determined by the azimuthal variation of the observed difference of Pn arrival times and is completely independent of the origin time and focal depth of the two earthquakes that are included in the parameter a.

The estimation of "a" allows evaluating the difference in origin time or focal depth of the two events if one of these two parameters can be determined independently. If the origin time of the E_1 earthquake is known, evaluating focal depth by equation S7 requires an evaluation of V_0, the apparent velocity of the P wave in the crust (see Supplement S2 below).

We also added Pg and Sg direct waves time measured at stations located at less than 170 km from Hainaut. Pg and Sg waves propagate in a way like Pn waves for shallow seismic events as the Hainaut earthquakes, but with the difference that Pg and Sg waves are critically refracted at an intermediate crustal level whereas Pn waves refract at crust-mantle interface. Therefore, equation S6 can also be used to model the time arrival difference of Pg and Sg "direct waves" measured at those shorter distances.

S1.2. Multiple event relative location

Instead of locating each unknown earthquake relative to specific master events individually, we extended the basic principle by simultaneously inverting all pairs of unknown and master events in one single computation. The advantage of this procedure is to increase the number of equations for the x- and y-coordinates of all the unknown earthquakes, which decreases the influence of bad quality data in the location results and allows adding earthquakes with little data in the analysis. However, the resulting system of equations becomes more complex than equation S6. The equations in S10 present the case of two earthquakes i and j at unknown coordinates and one master event m at known coordinates (X_m, Y_m). In the equations in S10, we considered that N seismic stations recorded the Pn-waves of these three seismic events. Three sets of relationships are included in this system, each of them considering the relative location of the two unknown events with the master event and the relative location between the two unknown earthquakes. This linear system contains 3*N equations and allows determining a_{mi}, a_{mj}, a_{ji} equivalent to a in equation S6 and the coordinates X_i, Y_i, X_j and Y_j of the two studied seismic events. Here, we only write the equations corresponding to seismic stations 1, 1< s <N and N.

$$\Delta t_{mi}^{1} - \frac{X_m + Y_m}{V_1} = a_{mi} \qquad - \frac{X_i \sin\Theta_1}{V_1} \qquad - \frac{Y_i \cos\Theta_1}{V_1}$$

…

…

$$\Delta t_{mi}^{s} - \frac{X_m + Y_m}{V_1} = a_{mi} \qquad - \frac{X_i \sin\Theta_s}{V_1} \qquad - \frac{Y_i \cos\Theta_s}{V_1}$$

…

…

$$\Delta t_{mi}^{N} - \frac{X_m + Y_m}{V_1} = a_{mi} \qquad - \frac{X_i \sin\Theta_N}{V_1} \qquad - \frac{Y_i \cos\Theta_N}{V_1}$$

$$\Delta t_{mj}^{1} - \frac{X_m + Y_m}{V_1} = \qquad a_{mj} \qquad - \frac{X_j \sin\Theta_1}{V_1} \qquad - \frac{Y_j \cos\Theta_1}{V_1}$$

…

…

$$\Delta t_{mj}^{s} - \frac{X_m + Y_m}{V_1} = \qquad a_{mj} \qquad - \frac{X_j \sin\Theta_s}{V_1} \qquad - \frac{Y_j \cos\Theta_s}{V_1}$$

…

…

$$\Delta t_{mj}^{N} - \frac{X_m + Y_m}{V_1} = \qquad a_{mj} \qquad - \frac{X_j \sin\Theta_N}{V_1} \qquad - \frac{Y_j \cos\Theta_N}{V_1}$$

$$\Delta t_{ij}^{1} \qquad = \qquad a_{ji} - \frac{X_i \sin\Theta_1}{V_1} + \frac{X_j \sin\Theta_1}{V_1} - \frac{Y_i \cos\Theta_1}{V_1} + \frac{Y_j \cos\Theta_1}{V_1}$$

…

…

$$\Delta t_{ij}^{s} \qquad = \qquad a_{ji} - \frac{X_i \sin\Theta_s}{V_1} + \frac{X_j \sin\Theta_s}{V_1} - \frac{Y_i \cos\Theta_s}{V_1} + \frac{Y_j \cos\Theta_s}{V_1}$$

…

…

$$\Delta t_{ij}^{N} \qquad = \qquad a_{ji} - \frac{X_i \sin\Theta_N}{V_1} + \frac{X_j \sin\Theta_N}{V_1} - \frac{Y_i \cos\Theta_N}{V_1} + \frac{Y_j \cos\Theta_N}{V_1} \qquad \text{(eq. S10)}$$

S2. Seismic crustal model for Hainaut earthquakes

S2.1. Pg and Sg wave velocities

The velocity with which direct crustal seismic phases Pg and Sg propagate can be predicted by a simple linear relationship. For this modeling, we used 10 shallow Hainaut earthquakes recorded by the Belgian seismic network since 2001 (Table S1).

Table S1. Source parameters of the Hainaut earthquakes for which crustal seismic phases arrival times measured by the Belgian seismic stations are used to model their propagation time with distance, such as shown on Figure S2. Mw is determined using the Mw-M_L relationship by Camelbeeck et al. (2022) (valid for 2.6 < M_L < 4.5).

DATE	TIME	LAT	LON	Z	ERT	ERH	ERZ	Mw
23-02-2018	23h07m00.64s	50.462	4.159	2.9	0.39	1.2	1.9	1.7
05-06-2009	06h56m55.18s	50.585	4.306	6.8	0.23	0.8	2.0	2.1
24-02-2009	00h45m39.31s	50.399	4.402	5.6	0.33	0.7	1.6	2.0
13-08-2008	22h47m34.21s	50.442	4.052	1.5	0.32	0.8	1.7	2.2
08-08-2008	16h52m22.77s	50.419	3.799	3.0	0.47	2.3	3.9	2.1
14-07-2008	01h33m58.80s	50.403	3.786	3.4	0.35	1.0	1.2	2.9
20-02-2003	05h13m30.04s	50.418	4.400	5.8	0.34	0.9	2.2	2.2
14-11-2002	03h09m45.67s	50.419	4.379	6.5	0.41	0.9	1.7	2.4
30-04-2002	21h49m59.32s	50.449	4.058	4.4	0.40	1.1	2.5	2.6
04-09-2001	02h45m55.09s	50.430	4.494	3.2	0.32	1.0	3.9	2.7

The solution of the numerical inversions and the associated uncertainties at a 0.95 confidence level are (Fig. S1):

For Pg wave: $T_{Pg} = a_0 + \frac{\Delta}{Vp}$ with a_0 = 0.61 ± 0.54 s and V_P = 5.92 ± 0.32 km/s

For Sg wave: $T_{Sg} = a_1 + \frac{\Delta}{V_S}$ with a_1 = 0.96 ± 0.78 s and V_S = 3.47 ± 0.10 km/s

These velocities correspond to upper crust velocities typical of this part of Western Europe, which is also coherent with the fact that all the earthquakes are shallow and that the waves are diving into the upper crust. The time terms a_0 and a_1 would correspond to a focal depth around 3 km, which agrees well with the computed depth for these events (Table 1).

S2.2. Pn propagation velocity

To model Pn-wave propagation time versus distance, we used 306 measurements collected for the 12 best documented earthquakes in the Hainaut region between 1965 and 1985. The method is based on the equation describing the variation of Pn wave arrival time with distance from a single earthquake source:

$$T_0 = H_0 + a_0 + \frac{X_0}{V_1} \qquad (S11)$$

where the Pn wave time term for the earthquake is now simply expressed by the parameter a_0.

To determine the mean velocity V_1 of Pn wave from equation (S1), it is necessary to evaluate the location and the origin time H_0 of the different earthquakes involved in the computation. The more reliable evaluation of H_0 for the different earthquakes is obtained by using the measured arrival times of direct Pg and Sg waves at UCC and DOU. These stations are the closest to the Hainaut area, which minimized errors on the computation of propagation times due to uncertainties on the crustal velocity model.

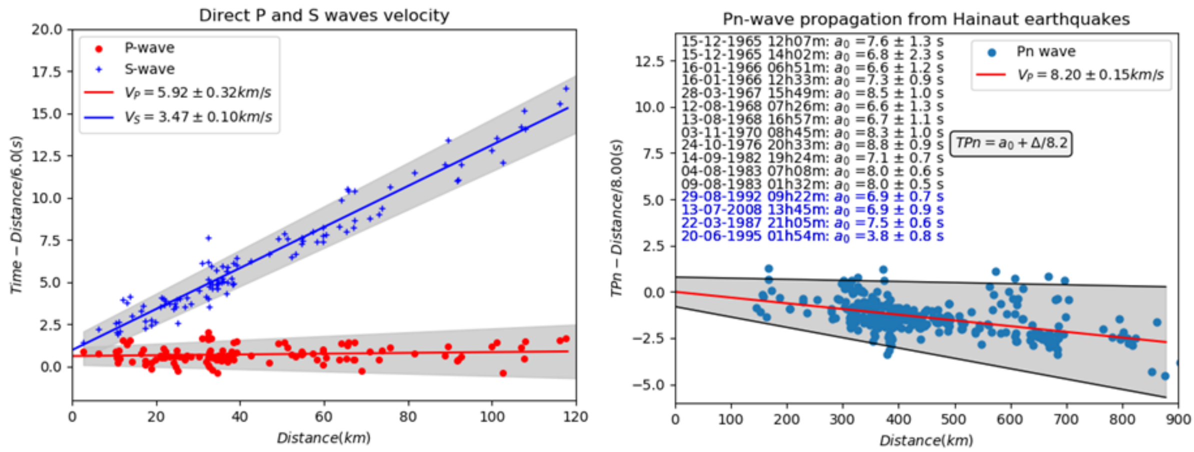

Figure S2*. <u>Left</u>: Direct Pg and Sg waves velocities in the crust (data from Hainaut earthquakes since 2002). <u>Right</u>: Pn-wave velocity (data from Hainaut earthquakes reported on the figure and the four master earthquakes).*

However, the equations corresponding to one specific earthquake are characterized by a specific a_0 value. Therefore, the system of equation to solve contains 306 equations with 13 unknowns: V_1 and the individual a_0 value for each of the 12 earthquakes. To evaluate the optimal Pn velocity for the Hainaut area, we first invert our full dataset to obtain a preliminary location and a value of the parameter a_0 for each event. The result returns a Pn-wave velocity of 8.20 ± 0.15 km/s (Fig. S2).

S3. Camelbeecketal2025-S3-Relative location python program.zip

Supplementary material 3 contains a zip file in which the jupyter ipython notebook

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is included that applies the multiple event location method (see section 3.3) developed in this study using station phase arrival times. This notebook works as follows:

S3.1. Code 1: Transforming the data of the unknown events

The first code transforms the data of the station phase arrivals "Hainaut65-85_phase_arrivals.txt" into single data text files for all the unknown earthquakes couples (ex: "relative_loc_28-03-1967_14-09-1982b.txt"). These files are stored in the Hainaut65-85_relative_locs folder.

"Hainaut65-85_phase_arrivals.txt"

This text file contains phase arrival time measurements of 26 relocated earthquakes in the 1965-1985 period in the Hainaut basin and the four master events, measured at all seismic stations used in the study. Each station line presents the name of the station (STA), the approximate azimuth of the centre of the Hainaut zone relative to the station (AZI), corresponding seismic phase (Phase), followed by the arrival times (hh mm ss.xx) for each earthquake date at that station.

S3.2. Code 2: Transforming the data of the master events

This second code transforms the data in the file "Hainaut65-85_phase_arrivals.txt" into single data files for all the couples containing master events. (ex: "relative_loc_24-10-1976_20-03-1966.txt"), these files are also stored in the folder relative locs.

S3.3. Code 3: Computation of location of unknown earthquakes

This third code computes the locations of the 26 unknown earthquakes and the relative time-terms for all the earthquakes couples. This code generates several products:

Hainaut65-85_relocations.txt

Final relocation results for 26 earthquakes in the 1965-1985 period in the Hainaut basin. For each earthquake, the first row gives the longitude and latitude, each followed by their uncertainty in kilometre. The second row gives the Easting and Northing Belgian Lambert72 coordinates, each followed by their uncertainty in kilometre. Each of the following 1000 rows presents, in Easting and Northing Belgian Lambert72 coordinates, the 1000 different solutions of the system of equations obtained by using (i) 1000 different locations of the master events based on their associated mean and 1σ values and (ii) 1000 different arrival times of each phase measurement using a normal distribution centred on the corresponding measurement with a sigma of 1 second. The solution in the first two rows hence present the mean of these 1000 locations and the uncertainty corresponds to the 1σ of the distribution.

The output file contains the absolute location of each unknown earthquake and its uncertainty, which are the mean coordinates and their 1σ from the 1000 computed different locations and is structured as follows:

EARTHQUAKE:15 December 1965 12h07m

4.095	1.06	50.446	1.42	(*Longitude*	*σLong*	*Latitude*	*σLat)*
130.61	1.06	126.09	1.42	(*X*	*σX*	*Y*	*σY)*
131.14	127.98			(*X1 Y1)*			
130.79	127.07			(*X2 Y2)*			
129.56	126.09			(*X3 Y3)*			
***.**	***.**			(*X* Y**	** rows 4 to 1000)*		

X and Y are given in Lambert72 coordinates.

time_residuals_by_pairs.txt

Output file containing station time residuals using the final location of each earthquake couple.

time_term between event pairs.txt

Output file containing relative time-term and equivalent focal depth between the earthquakes of each couple.

Hainaut65-85_earthquake_couple_relative_locations folder

A folder with each figure representing the azimuthal difference of the seismic phase propagation times (converted to distance using the corresponding phase velocity) for all stations that recorded the two mentioned earthquakes in the title of the figure (like Figure 10 in this study).