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Separation of quarry blasts from the aftershock sequence of the Oroszlány (Hungary) January 29, 2011 $\mathrm{M_L} = 4.5$

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Abstract The Vértes Hills are one of the most active seismic regions in Hungary. An $\mathrm{M_L} = 4.5$ magnitude earthquake shocked this area near to Oroszlány on January 29, 2011. The mainshock was followed by about four hundred aftershocks, and their magnitude varied from $\mathrm{M_L} = -0.6$ to $\mathrm{M_L} = 3.5$. Despite of the large number of aftershocks, the seismotectonic interpretation is very difficult because these earthquakes occurred in the vicinity of quarries. The waveform similarity analysis was proven a successful method to separate earthquakes and explosions, and revealed plus information about the aftershock sequence.

Keywords Waveform similarity · Microearthquakes · Quarry blast

1 Introduction

Seismicity of Hungary is moderate earthquakes between $\mathrm{M_L} = 4$ and $\mathrm{M_L} = 5$ measured on the Richter scale occur in every 15–20 years, while those measuring $\mathrm{M_L} > 6.0$ in every 100–150 years. One of the greatest earthquakes in Hungary ($\mathrm{M_L} = 5.4$) was occurred in the east side of Vértes Hills near to town Mór (47.32N; 18.19E) in the year 1810 about. The focal depth was about 5 km. The earthquakes occur usually in shallow depth (6–15 km) in the upper part of the crust in the entire Carpathian basin (Tóth et al. 1999). This event caused significant damage on about 3 thousands square kilometers and some people were killed (Zsíros 2004).

The Vértes Hills became seismically active region again (after 200 years) when a moderate $\mathrm{M_L} = 4.5$ earthquake occurred on January 29, 2011 17:41:38 (UT) near to town Oroszlány (47.459N; 18.361E) at depth of 9 km. This epicenter was about 15 km to the Mór earthquake occurred in 1810. The mainshock was followed by more than four hundred aftershocks. Their

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magnitude varied from $M_L = -0.6$ to $M_L = 3.5$. These aftershocks are very important for the seismology of Hungary, because it was first time when significant number of aftershocks was detected and located instrumentally. Out of the total 477 recorded seismic events (between the years 2011 and 2012), 67 were related to probable mining blasts (14 %) and 410 to earthquakes (86 %). Separation based on the hypocenter parameters could not be used because of the high location errors in this region, and the explosions were not announced, so maybe misclassified events in both groups.

The contamination of earthquakes with explosions in the case of microearthquakes has become new problem in Hungarian seismology. The artificial seismic events may complicate the seismotectonic interpretations and may modify the parameter *b* of Gutenberg Richter law (Gutenberg and Richter 1944).

2 The Vértes Hills and the seismic events

The Vértes Hills have complex geological structures; it is bounded on all sides by fault planes. It is separated from the Bakony Hills by the Mór-Székesfehérvár Line (Mór Graben) and from the Gerecse Hills by the Bicske-Galla fracture line. The Mór Graben is the result of transverse faulting with NW-SE strike. The southeast of Vértes Hills is bounded by Pleistocene loess and sand. Geologically the Vértes Hills are a karst plateau, with uplifting only very recently (Pleistocene-Holocene) and shows an example of transition from post-rift tension to neotectonic compression (Fodor et al. 2005). Using precise levelling, Joó and Csepregi (2007) performed research of vertical movements of the Vértes Hills between 1991 and 2005 and detected uplifts 4.9 mm/a, while the neighboring Bakony Mountains uplift with 2.7 mm/a. The vertical movements of Mór Graben was less 0.7 mm/a. The south side of Mór Graben at benchmark of Söréd subsided with -0.6 mm/a.

The epicenter map of events occurred in 2011 and 2012 showed that the epicenters of natural and artificial events are overlapped (Figs. 1, 2). The size of events was low and the number of detecting stations was limited. Only three permanent seismic stations (PKST, CSKK, PKSG) operate on the area and their location is very unfavorable. There was only a limited time interval (two month) when three other (VSOM, BOKD, SUKH) mobile stations were installed to record the aftershocks, which were operated by three institutions: Hungarian Academy of Sciences, Eötvös Loránd Geophysical Institute of Hungary (ELGI), the GeoRisk Ltd. (Table 1).The parameters of hypocenters are from the Hungarian National Seismological Bulletins (Gráczer et al. 2012, 2013) and from the Hungarian Earthquake Bulletins (Tóth et al. 2012, 2013). Most of the explosions took place at the ‘DOLOMIT’ quarry which is 3.3 km far from the PKSG and 13.3 km from the CSKK stations. The epicenter of the $M_L = 4.5$ mainshock (and most of the aftershocks) is at a distance 7 km from PKSG and 12 km from CSKK stations.

The waveforms of aftershocks showed high similarity to each other. The blasts were carried out by delay-fired technology, and the propagation path to stations was the same, so we have expected similar waveforms in case of blasts too. The waveform similarity analysis appeared to be suitable method to separate the earthquakes from explosions.

Focal mechanism solution was performed only in case of seven events despite the large number of aftershocks because of their small size (Weber and Süle 2014; Tóth et al. 2012, 2013). Three of them had strike-slip mechanism, very similar to that of the mainshock. There were thrust faulting events with some strike-slip component.

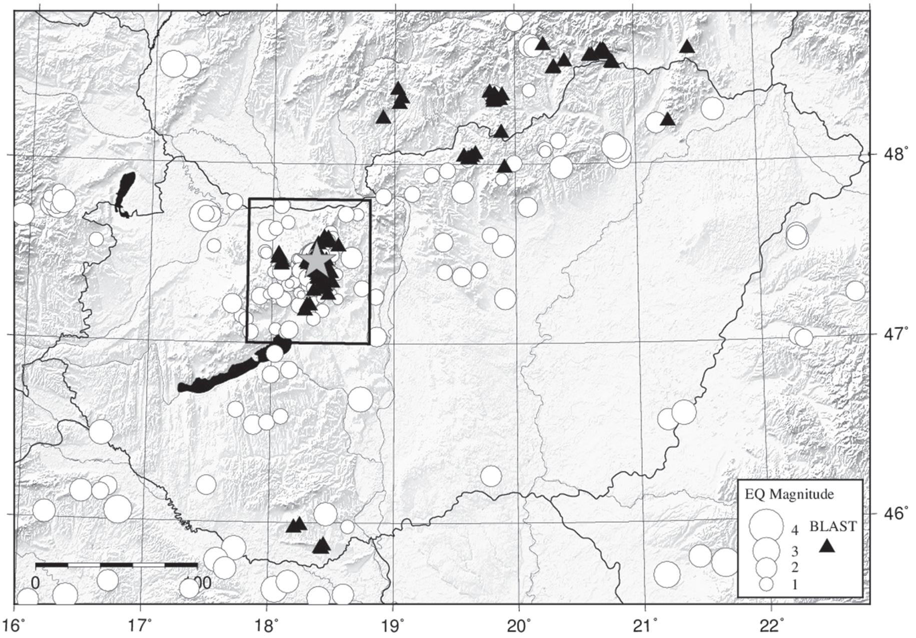

Fig. 1 Seismic activity map of Hungary and of area Vértes Hills (47° − 47.8°N – 17.8° − 18.8°E) during 2011 and 2012. The *star* indicates the mainshock $M_L = 4.5$, and the rectangle the investigated area

3 The temporal distribution of seismic events

The ambiguous identification of seismic events partly due to hypocenter inaccuracy and the times of explosions were not announced. Quarry blasts preferably take place during daytime between 8 and 12 h (Fig. 3a). The diurnal distributions of earthquakes at different magnitude bands were different. In case of $M_L < 0.2$, the events have shown a midnight maximum and a midday minimum due to the more favorable registration circumstances at night, when the cultural noise is lower (Fig. 3b). Diurnal distribution of $M_L > 0.2$ earthquakes showed slight maximum between 12 and 16 h. This midday peak may be caused by misclassified explosions.

4 The waveform similarity method

The waveform similarity method is based on correlation analysis which detects and associates events with similar waveforms that are the clusters. Earthquake clusters occur as aftershocks, foreshocks and swarms. There are also clusters that do no fit readily into any of these categories, because of the long time period spanned by the events. The spatial and temporal extent of these clusters is highly variable. Ellsworth and Dietz (1987) have reported nearly identical earthquakes occurring up to 47 years apart on a creeping section of the San Andreas Fault. Doublets have nearly identical waveforms; same hypocenter and magnitude are the expression of stress release on the same part of fault. Cheng et al. (2007) have applied a waveform cross-correlation technique to study the similarity and the repeatability of more than 21.000 microearthquakes between 1995 and 2001 in the aftershock zone of the 1984

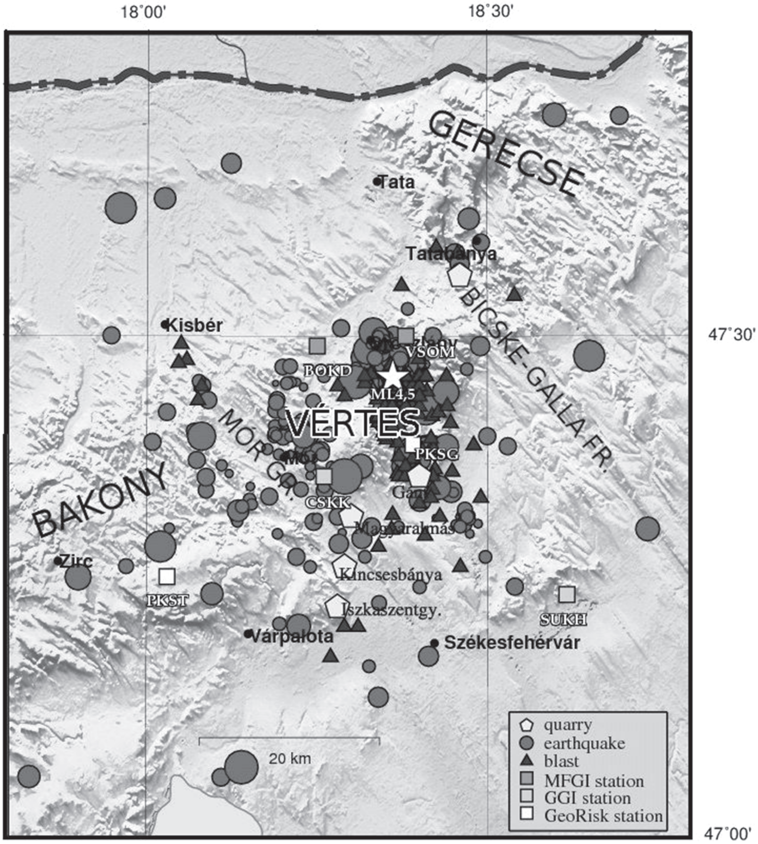

Fig. 2 Seismic activity map of Vértes Hills with seismological stations and quarries

Table 1 The parameters of the seismological stations

Code	Latitude (N)	Longitude (E)	Elevation (m)	Status	Org.
BOKD	47.4889	18.2517	150	Temporal	ELGI
CSKK	47.3631	18.2605	319	Permanent	GGI
PKSG	47.3918	18.3907	200	Permanent	GeoRisk
PKST	47.2590	18.0343	437	Permanent	GeoRisk
SUKH	47.2424	18.6165	100	Temporal	GGI
VSOM	47.5066	18.3757	150	Temporal	ELGI

western Nagano earthquake in central Japan. The authors identified a total 278 doublets and 62 multiplets (807 events) that occurred consecutively within second to days.

The question why earthquake clustering occurs is of fundamental importance to reveal earthquake mechanics. Various authors have proposed that spatial clustering of earthquakes is a consequence of the heterogeneous distribution of strength along faults. The earthquake cluster represents the progressive failure of a strong locked portion of a fault on which stress

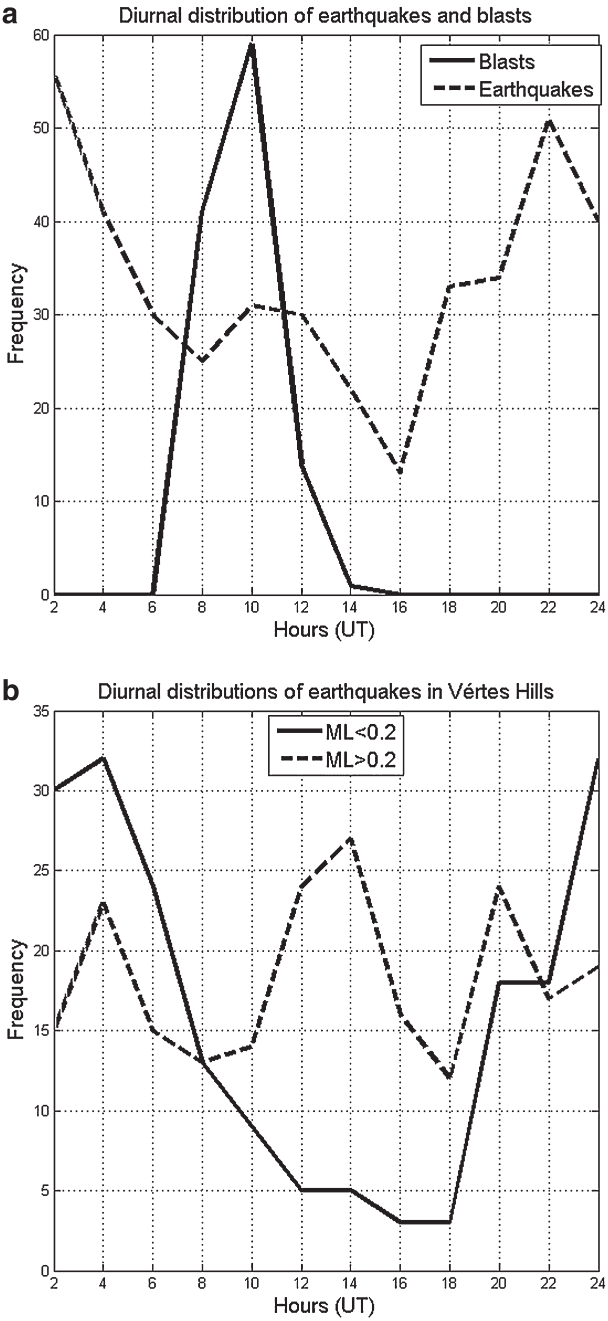

Fig. 3 Diurnal distribution **a** of earthquakes and blasts and **b** of earthquakes in case of $M_L < 0.2$ and $M_L > 0.2$ magnitude values

has become concentrated due to seismic or aseismic slip on the surrounding weaker sections of the fault (Pechmann and Thorbjarnardottir 1990).

Some clusters of small earthquakes are distinguished by high similarity in waveform among the events in clusters. Geller and Mueller (1980) hypothesized that earthquakes within these groups have similar focal mechanisms and occur within a distance of one quarter of the wavelength corresponding to the high frequency limit of the waveform similarity. The one quarter wavelength argument ($\lambda/4$ criterion) appears to provide a reasonable guide to maximum source separation distances. For example if the P-wave velocity is 5.9 km/s, and the waveform is well correlated at frequency up to 16 Hz, the maximum events separation should be approximately 90 m, up to 8 Hz is 180 m, and up to 4 Hz is 370 m. The ray trajectories from source to receivers are about the same (within much less than one wavelength) so the spatial gap between sources is smaller than the source-receiver distance, about few meters to several km. Baisch et al. (2008) have found that the $\lambda/4$ criterion does not sufficiently constrain the hypocenter location due to the lack of high-frequency information. Thorbjarnardottir and Pechmann (1987) used the cross-correlation technique to analyze the similarity of short period digital seismograms from groups of closely spaced explosions with known locations. These works demonstrated that the degree of similarity between waveforms of two different seismic events recorded at the same station is a function of the source separation distance as well as the properties of the source. Highly similar waveforms of different earthquakes are due to similar focal mechanisms and common propagation paths. The relative hypocenter locations of events in clusters of similar earthquakes can provide useful insights into geometry and style of faulting at depth within the crust. The multiples are considered to be related to identical shear slip on a fracture or neighboring sub-parallel fractures. In this case their hypocenters are spatially near, and their sources are equivalent, despite different origin times, and it is likely that the expression of stress released on the same structure.

Low cross correlation values do not necessarily imply differences in source location, because waveform differences can also be caused by differences in focal mechanism or source properties (Thorbjarnardottir and Pechmann 1987). Pechmann and Thorbjarnardottir (1990) analysed forehocks and found—with the use the $\lambda/4$ wavelength method—that the elements of clusters occurred at a distance 80 m away from each other and had similar focal mechanisms. They revealed the spatial migration of aftershocks too.

The value of correlation coefficients is a robust measure of the similarity of two seismograms. This provides a strong estimation of the maximum distance between the hypocenters. The c_{xy} correlation coefficient can be defined as

$$c_{xy} = \frac{\sum_{i=1}^{N} Wx(t_i)Wy(t_i + \tau_{xy})}{\sqrt{\sum_{i=1}^{N} Wx(t_i)^2}\sqrt{\sum_{i=1}^{N} Wy(t_i + \tau_{xy})^2}} \tag{1}$$

The $Wx(t_i)$ and $Wy(t_i)$ denote the seismograms, N is the number of samples. The aim is to estimate the time shift τ_{xy}, that maximizes c_{xy} for a given time window.

5 The results of waveform similarity analysis

The seismogram correlation analysis was performed using MATLAB toolboxes written and maintained by Reyes et al. (2009), and Reyes and West (2011). The PKSG station was closest to the mainshock, and worked all the time. Some aftershocks occurred only 5–10 km from

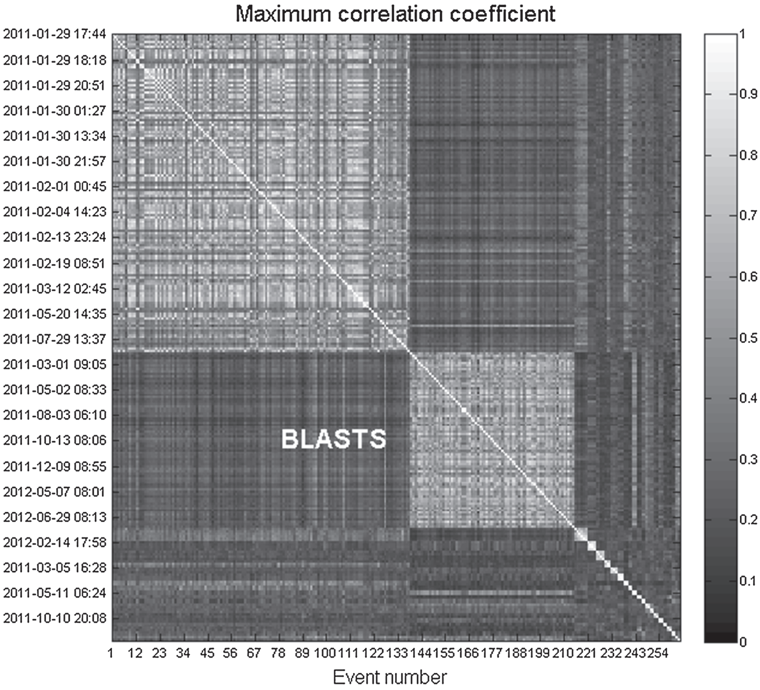

Fig. 4 Correlation matrix in case of $c_{xy} > 0.65$. The largest cluster consists of 138 aftershocks; the second largest cluster indicated “BLASTS” originated from quarry ‘DOLOMIT’ in Gánt

this station, so a lot of $M_L < 0.2$ aftershocks have also been observed clearly, and were suitable for the waveform analysis. The seismograms of explosions and earthquakes recorded by this station had been studied together, because we wanted to filter out the misclassified events. Because earthquakes generate larger S waves than compressional P waves we have preferred the records of horizontal N–S channel. The cross correlation value between each 8 s long seismograms was calculated. This correlation window has contained the P phase onset and S coda waves too. The waveforms of 216 earthquakes and 114 explosions were studied by this technique.

Correlation coefficients of 0.65 or greater were defined as “well correlated” or “similar”. Pechmann and Kanamori (1982) used lower value of 0.6 for this criterion. The result of our correlation analysis was visualized as “cross correlation matrices” on Fig. 4. The events were sorted according to the cross-correlation values between each pair of traces on this picture. The diagonal elements represent the autocorrelations, where the $c_{xy} = 1$. The earthquakes and the quarry blasts did not mixed up, were arranged into different clusters. Beside of four main clusters other smaller groups and were doublets it can be seen in the bottom right side of the cross correlation matrix.

The largest cluster #1 time span was more than 1 year, and contained 138 events with magnitude between $M_L = -0.4$ and $M_L = 2.0$. The number of aftershocks decreased with time, in opposite to the blasts #2 that occurred regularly (Fig. 5). The typical waveforms of four main clusters are shown on Fig. 6.

The high number of similar aftershocks indicates that their sources and focal mechanisms were almost the same. The blasts were not mixed with the clusters of aftershocks, in spite of

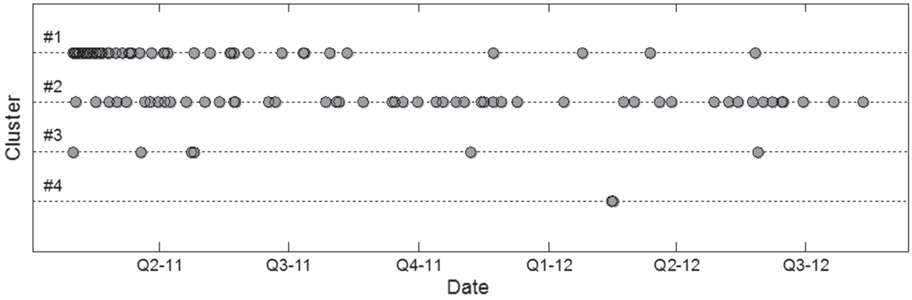

Fig. 5 Time spans of the four largest clusters ($c_{xy} > 0.65$)

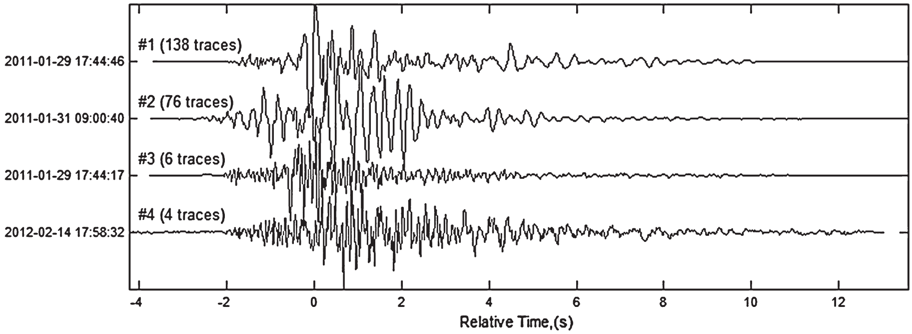

Fig. 6 Typical seismograms of main clusters ($c_{xy} > 0.65$). The cluster #2 contains only blasts

Table 2 The rate of similar earthquakes and blasts

	Similar EQs (%)	Similar blasts (%)
$c_{xy} > 0.65$	87	66
$c_{xy} > 0.75$	80	34
$c_{xy} > 0.85$	59	10

their similarity in epicenter distances. The number of similar earthquakes and blasts in case of different correlation coefficients are listed in Table 2.

In case of more severe condition ($c_{xy} > 0.85$) most of the events of the previous #1 cluster has fallen into three sub clusters, these were indicated (#1; #2; #3) on the cross correlation matrix (Fig. 7). The cluster #1 contained 51 events with magnitudes between $M_L = 0.4$ and $M_L = 1.8$. The time span and their typical waveforms are shown Figs. 8 and 9.

Unfortunately, the waveform of mainshock was unsuitable for similarity analysis, because the PKSG station was unable to record its high signals. Three aftershocks—with known focal mechanisms— have been grouped in different clusters ($c_{xy} > 0.85$). We assume that the rest members of the cluster have similar focal mechanism to the well-known possessed. But proof of this requires further analysis of other stations and channels.

The elements of strict clusters—according to the similarity theory—must be in close proximity, within few kilometers. The epicenter map of the largest aftershocks in case of $c_{xy} > 0.85$ showed that the distances between the epicenters of the elements of the same cluster were sometimes quite large (Fig. 10). This suggested that the error in the determina-

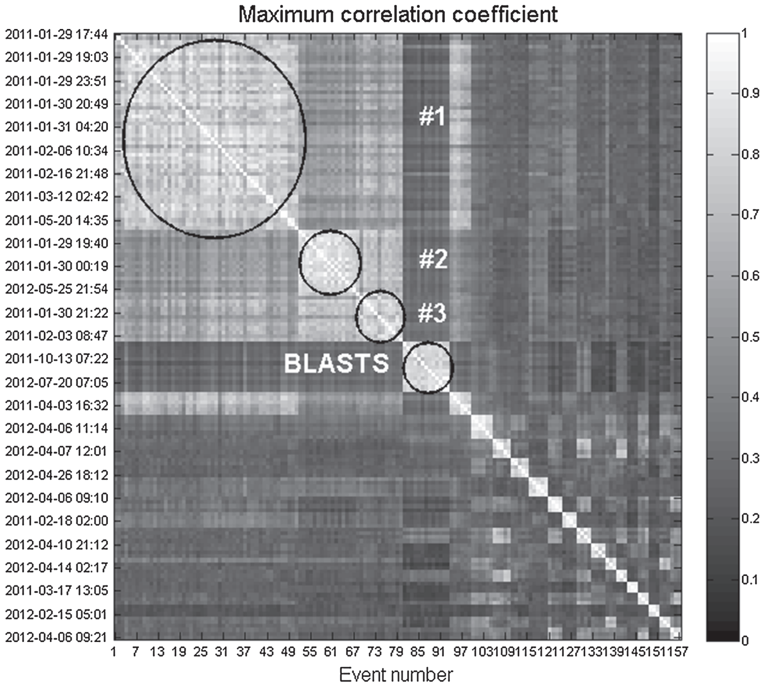

Fig. 7 Correlation matrix ($c_{xy} > 0.85$). The previous cluster #1 ($c_{xy} > 0.65$) is separated into three parts (signed #1; #2; #3). The cluster blast consists of 11 elements

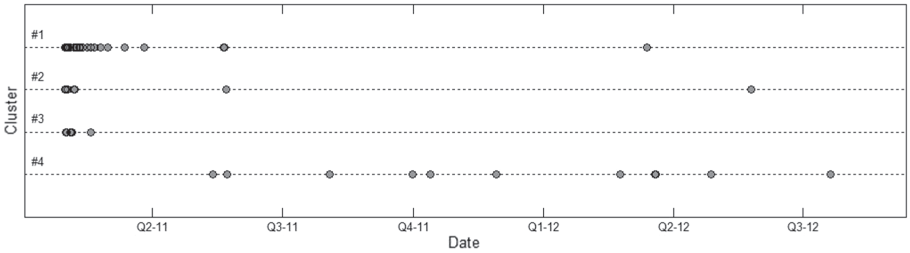

Fig. 8 Time span of the four largest clusters ($c_{xy} > 0.85$)

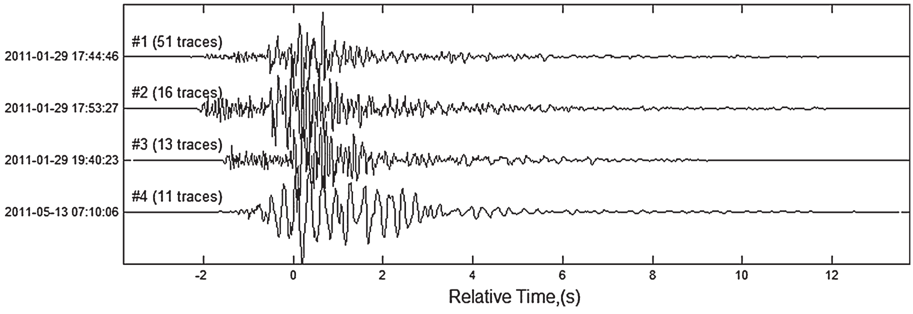

Fig. 9 Typical seismograms of aftershocks (#1; #2; #3) and blasts (#4) ($c_{xy} > 0.85$)

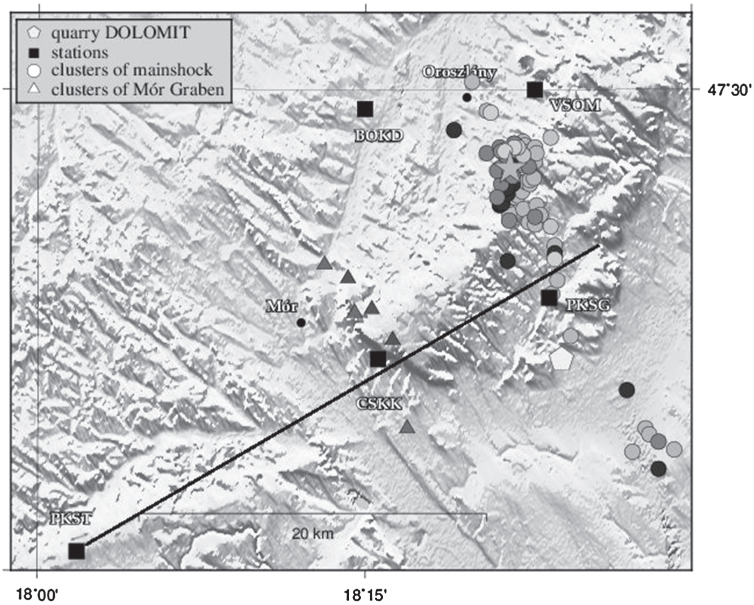

Fig. 10 Epicenter map of the largest clusters ($c_{xy} > 0.85$). The different *shades of circles* and *triangles* mean the elements of different clusters. The *star* indicated the epicenter of Oroszlány mainshock $M_L = 4.5$

tion of epicenters could be up to 15 km. Waveform correlation analysis revealed additional information about the accuracy of the epicenters.

It can be observed, that the elements of the clusters were stretched into a band which is perpendicular to the straight line that was determined by the location of permanent seismic stations PKST, CSKK, PKSG (the straight line on Fig. 10). We can see two clusters close to Mór Graben that were not belonged to aftershocks of Oroszlány mainshock $M_L = 4.5$.

The waveform correlation analysis has resulted grouping of several small events into different clusters that had no hypocenter parameters. Connecting these events to the aftershocks sequence could reveal more accurate time distribution. Waveform correlation analysis—in case of strict clusters—provides additional information about the spatial distributions of the hypocenters.

6 Conclusions

The waveform similarity analysis was proven a successful method to separate earthquakes and explosions in case of Oroszlány aftershocks. The waveform correlation analysis resulted that 10 % of explosions and 59 % of earthquakes similar using the correlation threshold value of 0.85 in the Vértes Hills region between the years 2011 and 2012. The largest cluster contained 51 aftershocks—magnitudes between $M_L = 0.4$ and $M_L = 1.8$—with very similar waveforms. The high similarity indicated that their hypocenters must be very close to each other and their focal mechanisms could be similar also. The epicenter map of these clusters showed that the distances between the elements of the same cluster were stretched into a band which was perpendicular to the straight line that was due to the unfavorable location of seismic stations PKST, CSKK, PKSG.

The waveforms of quarry blasts have never mixed with the clusters of aftershocks—in the condition of $c_{xy} > 0.65$—in spite of their epicenter distances were similar to each other.

The waveform correlation analysis has resulted grouping several small events into different clusters that had no hypocenter parameters.

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