Short Notes Mapping and Removing Quarry Blast Events from Seismicity Catalogs

Article

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Short Notes

Mapping and Removing Quarry Blast Events from Seismicity Catalogs

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Abstract We present an algorithm to identify and remove quarry explosions from earthquake catalogs while retaining a maximum amount of data. For most seismicity studies, quarry blasts are a data contamination that obscures natural phenomena under investigation. Based on the fact that most quarry blasts are performed during daytime hours, we spatially map out the ratio of daytime to nighttime events, *Rq*. This type of map clearly identifies regions of high quarry activity. A grid search identifies the highest *Rq* volume, which is subsequently removed from the data. This process is repeated until no volume with an anomalous ratio of daytime to nighttime events with significance greater than 99% remains. Examples for Switzerland, Alaska, and the western United States demonstrate the capabilities of the algorithm, where the algorithm removes 20%, 6%, and 0.75% of the events, respectively. We suggest that computing maps of *Rq* should be a routine part of any microseismicity study

Introduction

Seismologists analyzing microseismicity are frequently faced with the challenge of how to identify and eventually exclude quarry and mine blasts from seismicity catalogs. These artificial seismic sources contaminate the natural signal under investigation. For example, in studies of seismic quiescence (e.g., Reasenberg and Simpson, 1992; Dieterich and Okubo, 1996; Wyss and Martyrosian, 1998), quarry blast contamination is a major potential source of error, along with artificially introduced seismicity rate changes (Habermann, 1987; Zúñiga and Wyss, 1995; Zúñiga and Wiemer, 1999). Studies that attempt to relate seismicity rate changes to static stress changes caused by mainshocks (e.g., Toda *et al.*, 1998) need to pay careful attention to the quarry blast problem. The same is true for studies of the frequency-magnitude distribution (e.g., Wiemer and Wyss, 1997; Wiemer and Katsumata, 1999). Commonly, quarry blasts display an artificially high *b*-value ($b > 1.5$) because they represent repeating events of mostly similar and small size.

Identifying quarry blasts is not a simple task. Most seismic networks endeavor to identify and mark quarry blasts during their routine data analysis, yet it is a well-established fact that only a variable percentage of events are removed by this screening. A careful analysis of waveforms and their spectra can often find telltale signs of explosion characteristics (Hedlin *et al.,* 1990; Su *et al.,* 1991; Wuster, 1993; Musil and Plesinger, 1996), but such detailed analysis is impractical when dealing with large volumes of data on a daily basis or when reexamining existing seismicity data sets. Hypocentral depths may give an indication; however, hypocenter accuracy, particularly for small events, is such that this cannot be used as a reliable discriminator. A commonly applied statistical identification criterion makes use of the fact that explosions are generally performed exclusively during the daytime hours (e.g., Rydylek and Sacks, 1989, 1992). A histogram of the number of events as a function of hour of the day (e.g., Figure 1a) clearly shows a peak during daytime hours in regions where quarries exist. Because the detection threshold is generally lower during daytime, due to the higher ambient noise, regions not containing quarries generally show just the opposite, a decrease in the number of detected events in these hours. One obvious method to remove all daytime quarry explosions is to limit seismicity analysis to nighttime events for the entire region under investigation (e.g., Wyss and Wiemer, 1997). However, this approach reduces the amount of available data by about 50%.

The objective of this short note is to demonstrate that by spatially mapping the ratio *Rq* of daytime to nighttime events, likely quarry locations can be identified. The algorithm then proceeds to remove daytime events that are likely quarry blasts from regions with an elevated *Rq* only, thus maximizing the amount of data available for microseismicity studies. At the same time a list of likely quarry explosions can be extracted.

Data Sets and Method

Three data sets were analyzed: the catalogs of events in Switzerland, produced by the Swiss Seismological Service, the Alaska Earthquake Information Center catalog, and the Council of the National Seismic System (CNSS) catalog for

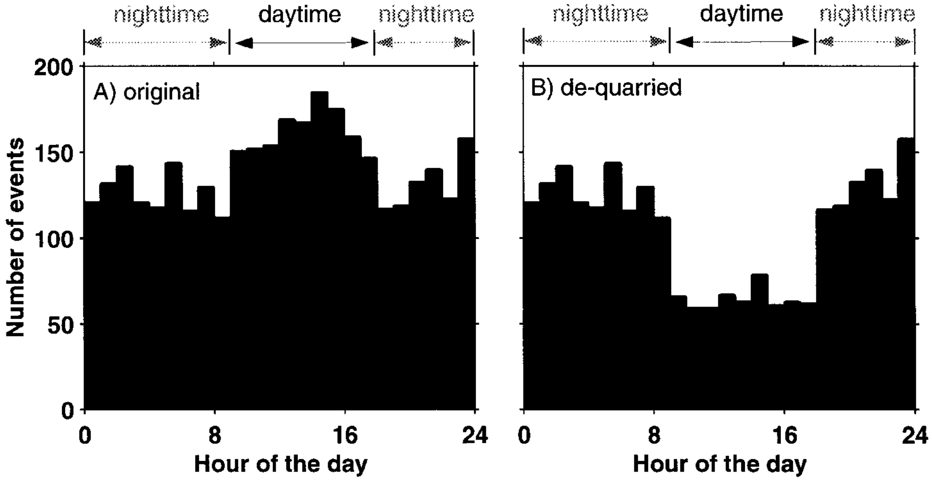

Figure 1. Histograms of the number of events per hour. The histogram is based on the Swiss seismicity catalog from January 1980 to December 1998. (a) The original distribution, with a clear increase in the number of detected events during daytime hours due to quarry explosions. (b) "De-quarried" catalog. Some tectonic events have also been removed by the de-quarrying algorithm.

the western United States. Generally, hour-based algorithms are applicable anywhere where quarry or mine explosions are performed during particular hours. We will limit our search to crustal events ($z < 30$ km), although in some catalogs we have seen quarry contamination that reached below that depth, because of large inaccuracies in hypocentral depth estimation.

We define the normalized ratio of daytime to nighttime events in the following way:

$$Rq = Nd\ Ln/(Nn\ Ld) \tag{1}$$

where Nd and Nn are the total number of events in the daytime or nighttime period, respectively, and Ln, Ld the number of hours in each period ($Ln + Ld = 24$). We then map this ratio spatially using a densely spaced grid, and sampling only the N ($N = Nd + Nn$) closest epicenters to each node from the entire catalog (Wiemer and Wyss, 1994, 1997). The sample size, N, is a free parameter of the mapping, and we perform a grid search over the N parameter space ($Nmin = 50$, $Nmax = 400$, $Nstep = 50$; i.e., 8 maps are computed) in order to identify the sample size with the highest Rq. Therefore, the parameter space spans three dimensions: latitude, longitude, and sample size N. Once this three-dimensional grid has been computed for the data set under investigation, we identify the node with the most anomalous Rq ratio. We also apply a test for aftershock sequences, because a mainshock with its largest portion of aftershocks during the daytime hours of the first day may resemble a quarry-type hour signature.

Because we want to compare Rq populations computed for different sample sizes N, Rq in itself is not a suitable measure. To establish how anomalous an observed $Rq(N)$ value is, we need to translate the ratio Rq into a probability of occurrence, using a numerical simulation. We create 10^6 randomly distributed sample data sets, each containing N numbers in the time interval $0.00 - 23.59$ h. Next we bin each sample into hourly bins and compute the ratio Rq. The 95 and 99 percentile of Rq as a function of N are shown in Figure 2. Using these results, we can directly translate each

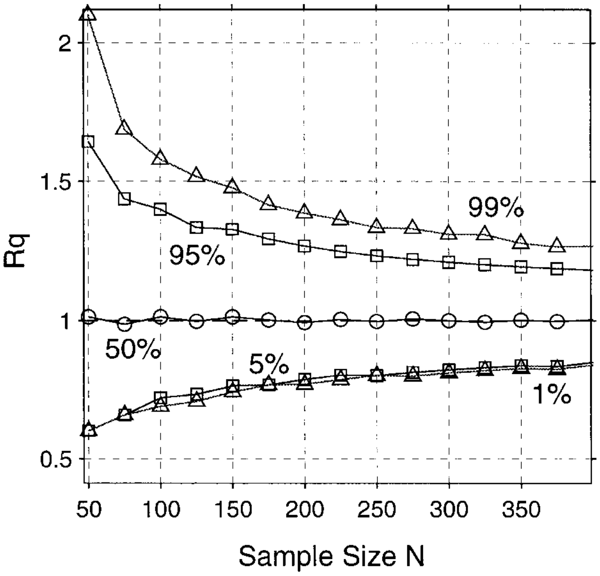

Figure 2. Randomly created day-to-nighttime events ratio Rq as a function of sample size N. A random sample of size N in the range 0–23.59 was drawn 10^6 times. Plotted are the 99 percentile of Rq (triangles), 95 percentile (squares), 50 percentile (circles) 5 percentile (squares, bottom), and 1 percentile (triangles, bottom).

Rq into a probability of occurrence. A value $P_{Rq(N)} = 99\%$ indicates that the probability to observe such a *Rq(N)* value by chance is 1% or less. We use the 99 percentile as our significance threshold for the iterative removal of events from the data. A node with $Rq_{(x,y,N)}$ will be excluded from the data set if it exceeds this threshold. In summary, the removal of likely explosions is performed in the following steps:

1. Compute a map of *Rq* for 8 different *N*, ranging from $N = 50$ to $N = 400$.
2. Translate each $Rq_{(x,y,N)}$ value into a probability of occurrence $P_{Rq(x,y,N)}$
3. Find the most significant $P_{Rq(x,y,N)}$ node. If this value exceeds the 99% confidence level, and the events are not mostly aftershocks, remove all daytime events for that particular node from the seismicity catalog.
4. Iterate steps 1–3 using the modified data set until no node with $P_{Rq(x,y,N)} \geq 99\%$ can be found.

To eliminate aftershock sequences in step 3 we require that no more than 20% the daytime events occur on one day. The software to spatially map and eventually remove blast events is part of the Matlab-based software package ZMAP and can be downloaded via anonymous ftp (*http://www.seismo.ethz.ch/staff/stefan/*).

First Case Study: Switzerland

The earthquake catalog compiled by the Swiss Seismological Survey contains approximately 5500 earthquakes during the period January 1980–December 1998 (Deichmann, 1992; Baer *et al.,* 1997). Standard operating procedure suggests to mark and eventually exclude identified explosions from the catalog, yet the network operators are well aware that numerous quarry blasts remain in the catalog (N. Deichmann, personal comm., 1999). The overall hourly distribution (see Figure 1a) suggests that quarry explosions are performed during the hours of 8:00 to 17:59 h (therefore, $Ld = 10$; $Ln = 14$), with an approximate excess of at least 400 events, or 10% of the total number of events. Figure 3 shows a map of Switzerland; gray-shaded is the ratio *Rq*. This map was computed for events with $M \geq 1.5$, using a sampling size of $N = 100$ earthquakes and a node spacing of 10 km. High *Rq* ($Rq > 1.5$) plotted in dark indicates quarry-rich areas. Comparison with the location of known quarries confirms that dark areas indeed are likely locations for quarry blasts. The hourly distribution of events is shown for two subvolumes (Fig. 3b,c), identified as 1 and 2 in Figure 3a. We now apply the aforementioned iterative removal of events. After 13 iteration steps, no volume with $Rq > 1.5$ remains (Fig. 3d). The total hourly distribution of the cleaned catalog is shown in Figure 1b. This distribution shows reduced seismicity levels during day hours. A total of 891 out of 4477 events, or about 20%, were removed from the data set. By removing the entire daylight times, 2091 events would have been removed.

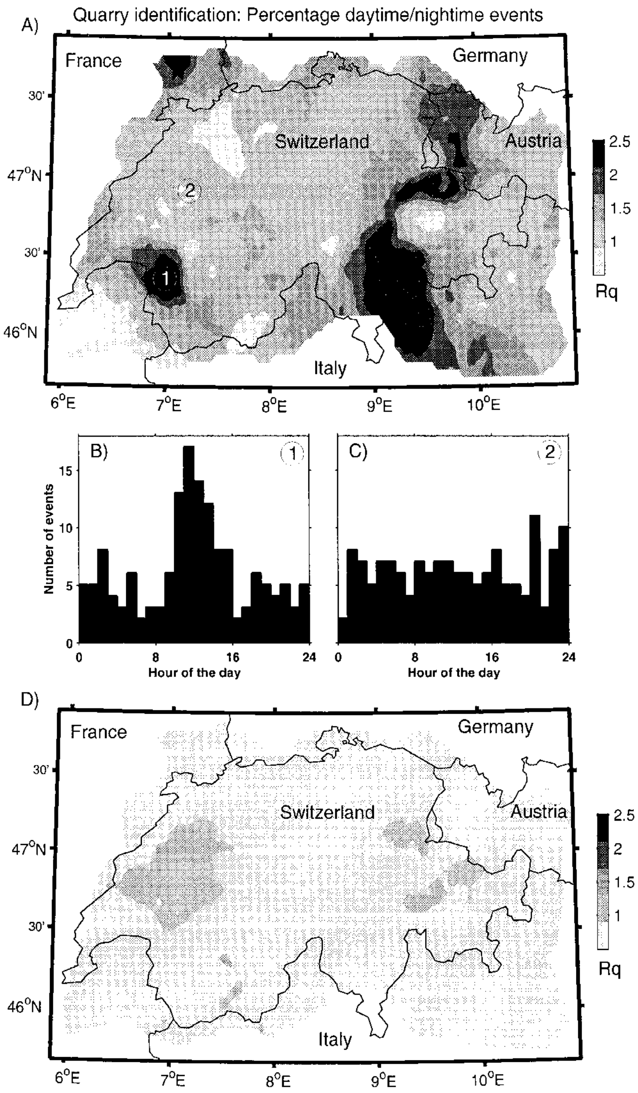

Figure 3. (a) Map of Switzerland. Gray-shaded is *Rq,* the ratio of daytime to nighttime events (equation 1). This map was produced by gridding the seismicity, using a 10 km node spacing, and sampling the 100 nearest events to each node. *Rq* values greater than 1 shown in dark indicate the presence of quarries. White areas were not sampled. (b, c) Hourly histogram of the number of events for two selected regions, marked (1) and (2) on the map. (d) Same as (a) after removing explosions from the catalog.

Second Case Study: Alaska

The seismicity catalog compiled by the Alaska Earthquake Information center (AEIC) for the period January 1990–December 1998 contains a total of about 25,000 events for Central and Interior Alaska with a depth less than 30 km and $M > 0.5$. We mapped the ratio *Rq* using a sample size of $N = 200$ and a node spacing of 10 km (Fig. 4a). Values of Rq greater than 1.4 and up to 2.5 indicate the presence of explosions in the data set. Quarries and mines are mostly located near and north of the Denali fault, where quarries and the Usibelli coal mine are located. The iterative removal of quarry events identifies a total of 1570 possible explosions, or 6% of the total data volume.

To investigate if indeed removing quarry blasts area can make a significant difference, we computed two spatial maps of the b-value for Central Alaska: one using the original data set, the second using the de-quarried data set produced using our algorithm. The b-value was mapped using sample sizes of $N = 500$ and a node spacing of 25 km. Differences in b of up to $+0.25$ units between the two catalogs can be found near the Denali fault, coinciding in location with the quarry rich areas identified in Figure 4. Without de-quarrying the earthquake catalog one would reach the erroneous conclusion that the b-values for crustal earthquakes in Central Alaska are unusual high ($b > 1.4$) compared to surrounding areas.

Third Case Study: CNSS Combined Catalog for the Western United States

We analyze the CNSS combined catalog for the western United States, concentrating on the most recent portion of the data, from January 1995 to April 1999. To identify the likely time of quarry explosions, we analyze events marked as such in the CNSS data. The hourly distribution of these events shows a clear peak during the hours of 17:00 to 01:00 h (UTC). A total of about 6000 blast events were identified by the network operators within the study area. We now ask the question if remaining likely blast events can be found in the explosion-free portion of the catalog. The spatial map of Rq ($N = 200$; Fig. 5) shows a largely homogeneous distribution for California with only two areas reaching Rq above 1.5 (Fig. 5). This suggests that relatively few explosions exist in the data. One sample population from southern California (volume 2) is shown in Figure 5c (converted to local time). Increased explosion contamination can be found in Utah, south of Salt Lake City (Fig. 5b), as well as in western Washington. The iterative removal identifies 690 events (0.75%) as possible explosions in California, and 480 (3%) in the remainder of the data set.

Discussion and Conclusions

Understanding the quality of seismicity catalogs is a crucial issue for seismicity studies. To be able to identify, and eventually remove, quarry blasts from seismicity catalogs is one important aspect of data quality control, unfor-

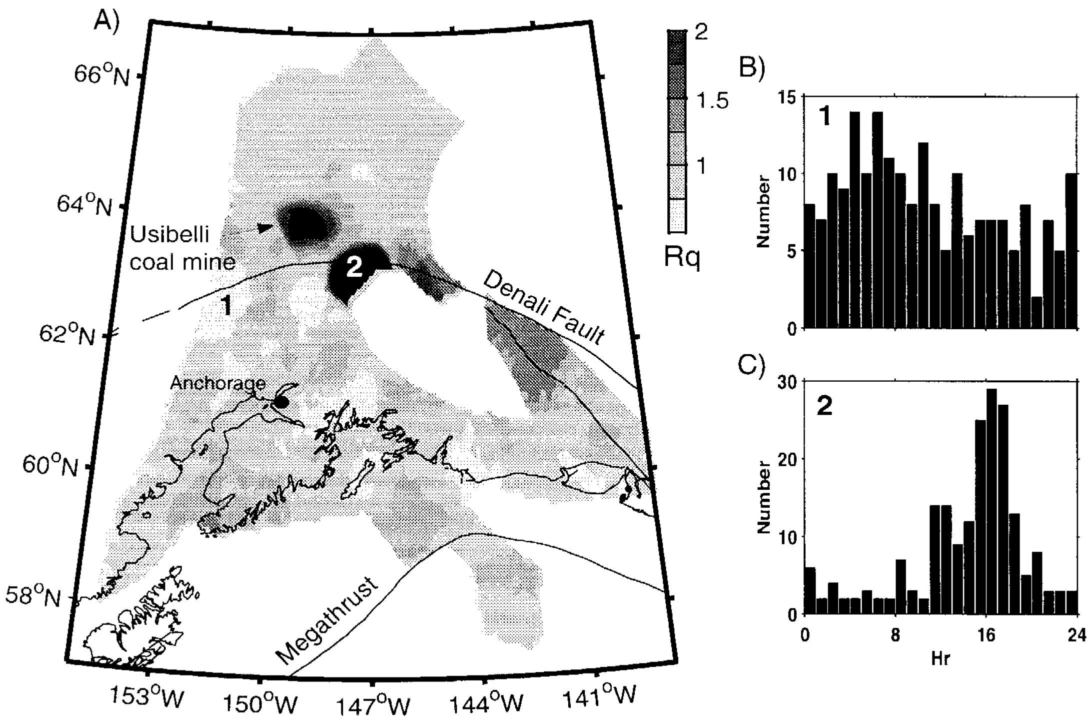

Figure 4. (a) Map of Central and Interior Alaska, gray-shaded is the ratio Rq. Dark regions indicate the presence of quarries and mines, active mainly during daytime hours. The data used were provided by the AEIC for the period 1989–1998, the sample size $N = 200$ earthquakes. (b, c) Histogram of the hourly distribution (in local time) of the seismicity for two selected regions: an explosion rich volume (1) and a normal volume (2).

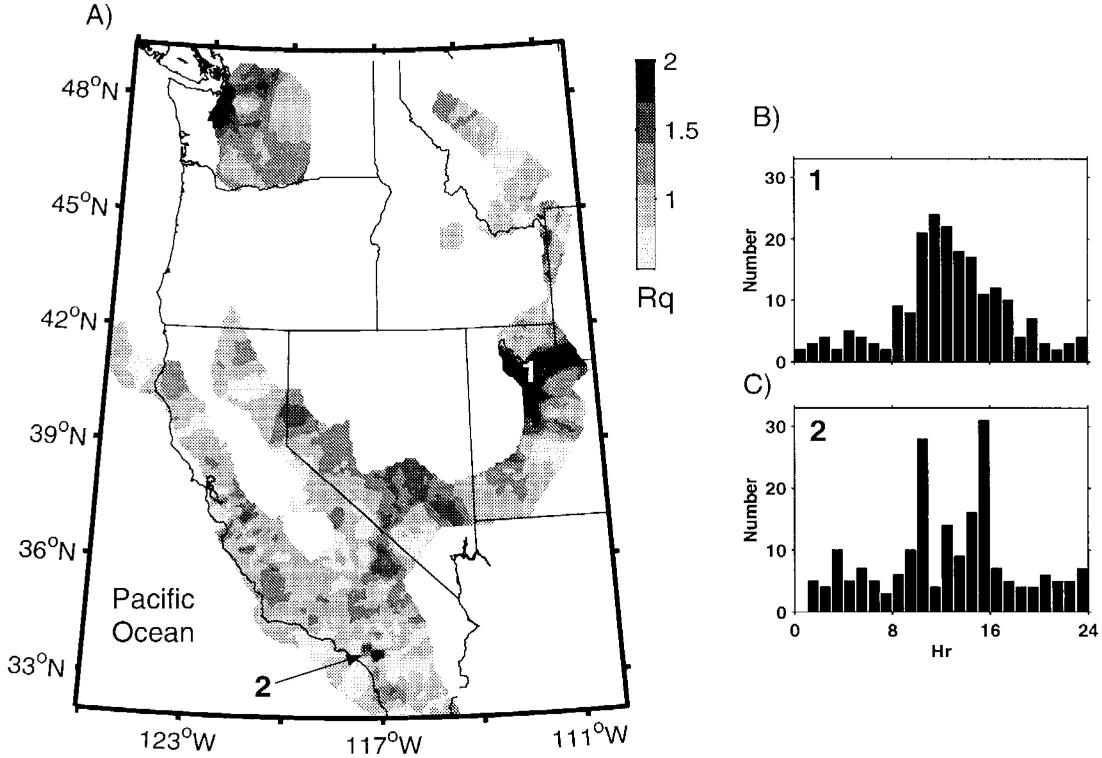

Figure 5. (a) Map of the western United States; gray-shaded is the ratio Rq for a sample size of $N = 200$ earthquakes. Dark regions indicate the presence of quarries and mines active mainly during daytime hours. The data used were provided by the CNSS for the period January 1995–December 1998. (b, c) Histogram of the hourly distribution (in local time) of the seismicity for two selected explosion rich regions in Utah (1) and southern California (2).

tunately often neglected or brushed aside in seismicity studies. Removing blast events is, for example, often required before a meaningful analysis of seismicity rate changes or earthquake size distribution can be performed. By spatially mapping the daytime to nighttime ratio of events, *Rq*, we are able to identify quarry rich areas, or individual quarries (Figs. 3–5). This is useful for network operators as well as researchers interested in tectonic studies, because it highlights areas where caution or special attention is advisable. Identifying explosions also has relevance for the monitoring of the continental test ban treaty (CTBT; e.g., van der Vink, 1995). By removing all daytime events, roughly 50% of all data are excluded. Our method of identifying areas of high *Rq*, on the other hand, removes a much smaller fraction of the data, since areas with no quarry explosions are not altered. The CNSS catalog in California contains with 0.75% the smallest percentage of likely quarry explosions, indicating that the network operators have done an excellent job identifying these events. However, regional differences between seismic networks contributing to the CNSS catalog exist. A higher percentage of explosions remain in the catalog contributed by the Utah and Washington networks than the California networks.

The list of possible quarry explosions could be investigated further using waveform based techniques (Hedlin *et al.,* 1990; Su *et al.,* 1991; Wuster, 1993; Musil and Plesinger, 1996). This would allow reinserting into the catalog tectonic events in quarry-rich areas that the presented algorithm excludes. If a complete data set is required for analysis, it would also be feasible to reinsert events into the catalog by simulating the nighttime and/or weekend distribution of seismicity rates and the earthquake size distribution. To explore recreating a complete data set, however, is beyond the scope of this study.

Quarry removal could, in principal, be achieved manually, using interactively selected polygons based on maps such as the ones shown in Figures 3–5 or based on external information about quarries. Advantages of the presented algorithm to exclude quarry blasts are that (1) an objective criteria is applied and (2) the process is automated. Using a random number generator, we can translate *Rq* into a probability of observation (see Figure 2), thus giving us the means to only exclude areas above a certain significance threshold. Having an automated and objective criteria designed is important, for example, for testing earthquake forecasting hypotheses in real-time, because interactive data manipulation should be reduced to a minimum. The basic method presented in this short note is by no means new, although little has been published in this subject (e.g., Rydelek and Sacks, 1989, 1992). New, however, is the use of a spatial grid to map *Rq*, and the introduction of a probability criterion to decide which parts of the data should be excluded.

The presented algorithm, based on a purely statistical criterion, cannot be perfect in the identification of quarry blasts. Some tectonic events during daytime hours, including rock-bursts triggered by the quarry activity, will be removed along with the blasts. Some blasts will remain in the cleaned data in areas where few blasts occur. In areas with a high percentage of blast events or many quarries, it might be preferable to exclude all daytime events. Nighttime explosions, naturally, are not identifiable with the algorithm. Generally it is recommendable to compare the results of a specific microseismicity study, using all three data sets: (1) the original data, (2) the de-quarried data, and (3) the nighttime events only. Results of a particular seismicity study should be independent of the data set of choice.

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