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Spatial and Temporal Patterns of the Fennoscandian Seismicity - an Exercise in Explosion Monitoring

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Abstract

Fennoscandian stations and arrays detect daily numerous seismic events at local and regional distances. Almost all of these events stem from various kinds of explosions. Such explosion recordings are of little scientific value, but add considerably to the daily analyst workloads. Also in a test ban treaty verification context is such recordings problematic because identification between chemical and nuclear explosions is not always obvious.

In this work we report on efforts to automate detection, location and classification of seismic recordings, stemming from local mining activities and other explosions. The first steps here are that of establishing a knowledge base on mining activities such as their locations, firing times, type of mining activity and which stations are most likely to report events from a given mining area. Using the comprehensive Helsinki Bulletin for 1991, the above mentioned parameters have been extracted from various parts of Fennoscandia, Estonia and north-western Russia. Consistent diurnal, weekly and spatial patterns are typical for most of the seismic events included in the bulletin.

1. Introduction

The many recordings stemming from numerous quarry blasts, mining explosions and other man-made seismic events are a nuisance in seismograph network operations as their analyses add considerably to the daily workload of the analysts. In a nuclear test ban context an additional problem is that event classification is an important task and it is not always simple to distinguish between earthquakes and explosions. In recent years consid-

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erable progress has taken place in the field. Elaborate schemes based on so-called neural network techniques have been proved useful (*Dowla et al.* 1990; see also *Tsvang et al.* 1993). An alternative to such schemes is to look for distinct patterns and in particular whether signal attributes of associated seismic recordings are site specific. For example, *Rivière-Barbier* and *Grant* (1991) report that several Fennoscandian mines have prominent and consistent seismic signatures, although variability between even closely spaced mines (a few kilometers), could be large. The idea of using recording signatures for fast reliable event location and source type identification is not new in observational seismology and in fact is daily practiced in many observatories (e.g. see *Vesanen* 1944). Simply, a skilled analyst can easily differentiate between many mining areas just by a quick glance on the relevant wave forms. An illustrative example here is that the Institute of Seismology, University of Helsinki, more than two decades ago introduced a template system of explosion master events to ease the daily analysis workload. Essential elements were à priori knowledge of specific mining activities and which explosions produced distinct and easily recognizable recording signals. The tabulation of this coding system, including the location of mining operation is given in Table 1. In practice, an analyst wave form recognition would suffice for assuming an explosion location for the event recordings in question. There is now a desire to change this well-proven but essential manual system in a view of the upgrading of the national Fennoscandian networks to digital recording and the general need for operational cost efficiency.

Table 1. The Helsinki analyst template system; latitude and longitude of the operation. If known, the corresponding name of the mine is given.

Mines and explosion sites in Estonia and Russian Karelia					+
Latitude	Longitude	Name of mine	Latitude	Longitude	Name of mine
59.24	24.33		59.41	24.59	
59.5	25.0		59.33	27.27	
59.33	27.07		59.27	27.73	
59.24	27.83		59.31	27.63	
59.3	27.5		59.37	28.53	
59.45	26.49		60.0	29.9	
60.02	29.74		59.6	30.0	
59.37	28.43		59.36	28.37	
61.01	29.04		60.90	29.35	
60.8	29.3		60.95	29.18	
61.1	30.3		61.5	30.4	
61.4	31.6		60.7	29.0	
61.4	34.3		61.9	30.6	
61.14	29.87		62.2	34.3	
64.68	30.66	Kostamuksha open pit	60.6	29.2	
60.7	28.7		60.8	29.5	

Norwegian mines					+
Latitude	Longitude	Name of mine	Latitude	Longitude	Name of mine
58.30	6.40	Titania	69.6	29.9	Bjørnavattnet
Mining sites on Kola Peninsula and adjacent areas					
67.67	33.74	Kirovsk	67.63	33.84	Rasvumschorr
67.64	34.02	Koashva	67.64	33.88	Tsentralnju
69.4	33.18	Zapoljarnju	68.16	33.18	Olenogorsk
67.6	34.2		69.6	32.2	
67.7	31.4		67.56	30.44	Kovdor
69.3	34.4		69.2	34.7	
68.87	33.03	Murmansk	69.23	33.17	
Mines in Northern Sweden					+
67.18	20.67	Malmberget	67.12	20.90	Aitik
67.8	20.2	Kiruna	67.7	21.0	Svappavaara
Mines and explosions sites in Finland					
60.17	23.84	Mustio	61.33	23.03	Stormi
60.30	22.29	Parainen	61.9	21.5	Otamo
61.6	21.7	Kritiskeri	62.07	27.41	Ankele
63.12	27.72	Siilinjärvi	64.12	28.06	Lahnaslampi
64.1	24.7	Perkköö	62.83	29.25	Horsmanaho
63.66	26.05	Pyhäsalmi	62.8	22.9	Törnävä
63.16	27.99	Nilsiä	63.0	26.8	Talluskanava
65.78	24.70	Elijärvi	63.85	25.05	Hitura
61.64	24.26	Orivesi	61.94	29.03	Ruokojärvi

A recent approach to a non-analyst handling of the mining explosion problem is the evolutionary intelligent monitoring system (*IMS*) developed for automatic multiarrays data processing analysis (*Bache et al.* 1990, *Bratt et al.* 1990). Here satellite imagery information has been incorporated, providing information on mine locations (including quarries) and other types of large scale construction works. Such information has proved very useful in seismic bulletin work, since seismic epicenter locations at their best are accurate to the nearest 5-10 kilometers. This "spotting" method provides accurate epicenter solutions, which often are superior to these derived from conventional traveltime observations. The mining and quarry sites obtained from satellite imagery pictures and those of the old manual template system as used at the Institute of Seismology, Helsinki, are shown in Figure 1a - the sites coincide well with each other. The stations in Fennoscandian network, which contributed data to this study is shown in Figure 1b.

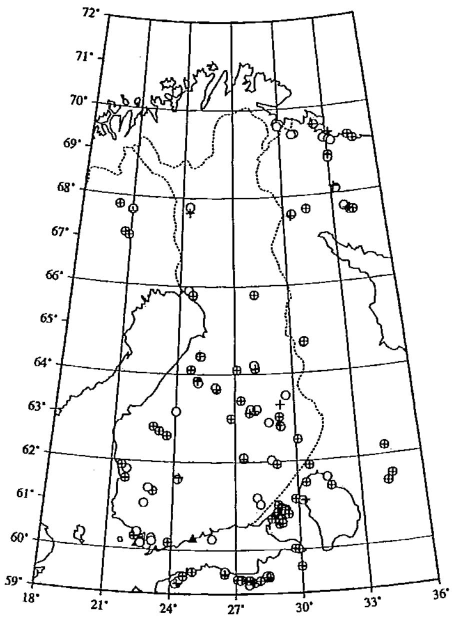

Fig. 1a .The mining sites in Fennoscandia according to the analyst template system in use at the Institute of Seismology, University of Helsinki (circles) and intelligent monitoring system (IMS) based on satellite imagery (crosses: F. Rivière-Barbier 1993a). The locations overlap nicely. The black triangle shows the location of Helsinki data center.

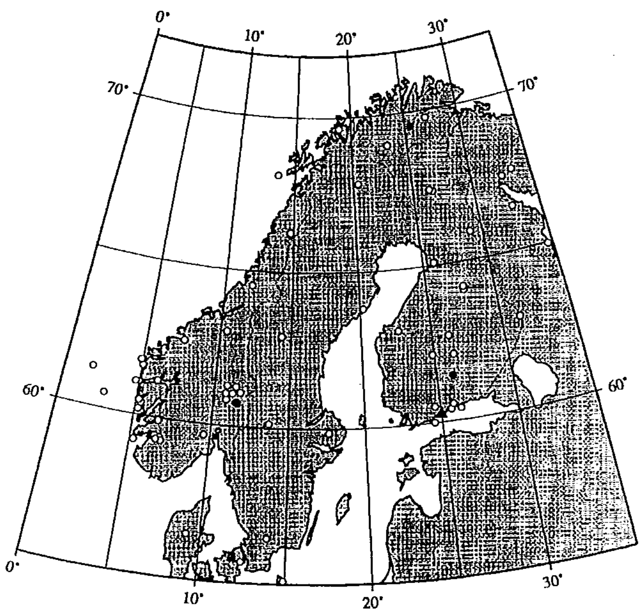

Fig. 1b. Fennoscandian seismograph stations reporting events in this study. Black dots represent arrays.

In this paper the aim is to track the Fennoscandian mining and other explosion activity both in time and space on the basis of available bulletin data for the year 1991. The distribution of those events is shown in Fig. 2. Also, this is the first step in a larger research strategy, to discriminate and locate automatically and accurately regional seismic events from digital Fennoscandian seismograph stations.

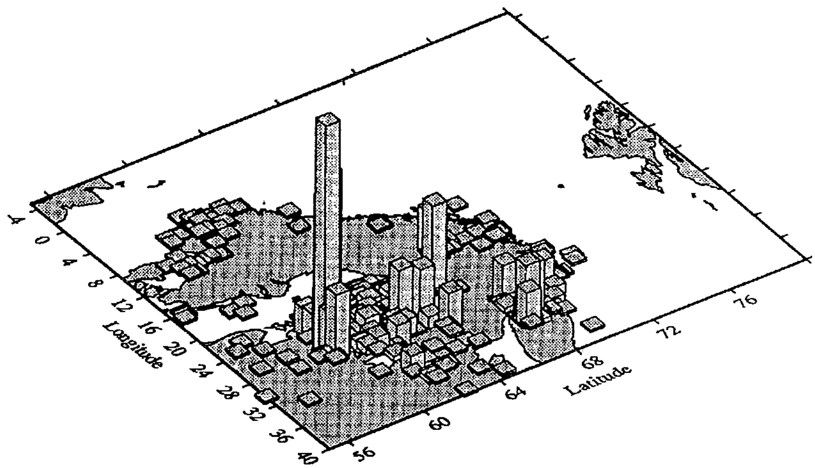

Fig. 2. Seismic events of presumed explosion origin in Fennoscandia in 1991 according to the Nordic Bulletin issued by the Finnish National Data Center (FNDC). The size of a column is 1° x 1°. The highest activity is on the Estonian coast, where many oil shale quarries are located. The highest column in the area represents 145 events. The total number of explosions for the Estonian mining operations was 1419 in 1991. Also, in northern Sweden, western Norway, Russian Karelia and Kola the explosion activities are high. Most events in Finland stem from mines, quarries and construction work sites.

2. *Observational data and dominant mining areas*

The data used in this study are event listings from Finnish seismological bulletins and from the so-called Nordic Seismological Data Base. The latter may be considered a regional bulletin as these event listings represent a merging of reports from the seismological observatories in Helsinki (Finland), NORSAR (Kjeller, Norway), Bergen (Norway) and the Russian Academy of Sciences, Kola Branch (Apatity). The Nordic data base at present is seemingly somewhat incomplete as numerous weak events detected and automatically located by the NORESS and ARCESS arrays are often missing. The epicenter solutions from these arrays are seemingly not officially released unless checked by the local analysts. Rather comprehensive listings for ARCESS and NORESS arrays are given by *Rivière-Barbier* (1993a, 1993b). Anyway, for the year 1991 altogether 4446 event reports were found in Helsinki bulletins (*Uski et al.* 1992), within the geographical region as defined in Fig. 2. Before plotting the events listings were prescreened for removing earthquakes and duplicate events. The latter are defined as events with an origin time difference less than 30 s and epicenter locations within 50 km of each other, but different reporting agencies. In the figure, the most striking feature is the numerous explosions in the Estonian oil shale quarries, from which 1419 events were reported in 1991. Other, prominent mining areas are Kiruna-Malmberget (northern Sweden), Russian Karelia, and the Kola district (NW Russia). Explosion activity at west-coast of Norway (Bergen) is tied to road and construction works, and hence has a more dispersed epicenter pattern. The prominent explosion areas were subject to more detailed analysis, presented below.

2.1. Kiruna-Malmberget northern Sweden (Figures 3 - 6)

The high columns in Figure 3 coincide with the Malmberget mine. There is also high mining activity in Kiruna. The explosion activity is relatively high and the shooting times are mainly in the afternoon and late evenings (Fig. 4). These are two distinct shooting intervals (Fig. 4), which may reflect different shooting practice at different mines. To see, if we could resolve this problem, the explosion locations were plotted for specific time intervals (Fig. 5). The majority of events occurring in afternoons can be connected to the Malmberget and Aitik mines while very early morning events are evidently explosions in the Kiruna mine.

The Kiruna-Malmberget mining operations are unique in the sense that reportings from the Swedish seismograph stations are lacking as shown in Fig. 6. This does not reflect poor station performances but instead a general lack of economical resources for daily analyst analysis of local (mining) seismic events. The mentioned non-reportings of the NORESS and ARCESS arrays are also obvious from the figure. In other words, the local event reporting practice between Nordic seismological observatories still vary considerably. As a rule of thumb the stations closest to seismic source areas should report many more events than far away stations, say along the west coast of Norway where besides the background noise is relatively high. So far, we have not tried to establish sort of seismic recording attributes (*Joswig* and *Schulte-Theis* 1993) differentiating between the various mining operations in the Kiruna-Malmberget, because the incomplete bulletin data are not convenient for doing so. However, the importance of this issue is obvious from Fig. 5.; the conventional epicenter locations are not always close to the known mining locations.

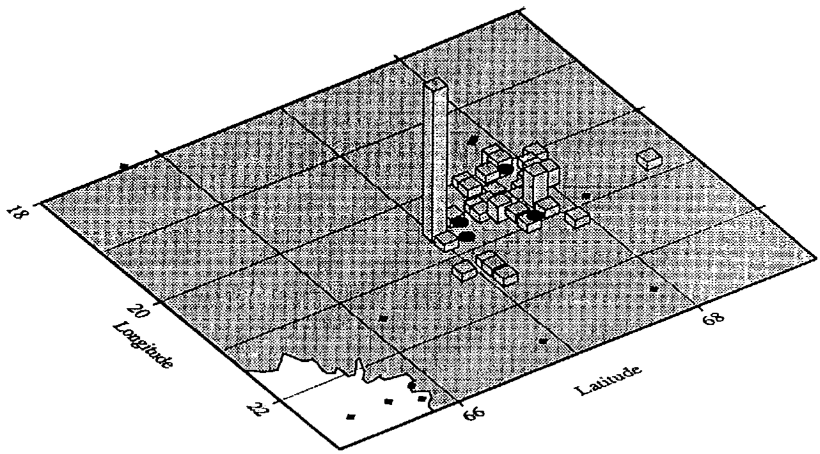

Fig. 3. Events in Kiruna-Malmberget region northern Sweden, in 1991. The mine sites are shown by black dots. The black diamonds signify small earthquakes. The column size is 0.1° x 0.1° and the highest column represents 26 events. The total number of events in the area was 212 including 11 earthquakes.

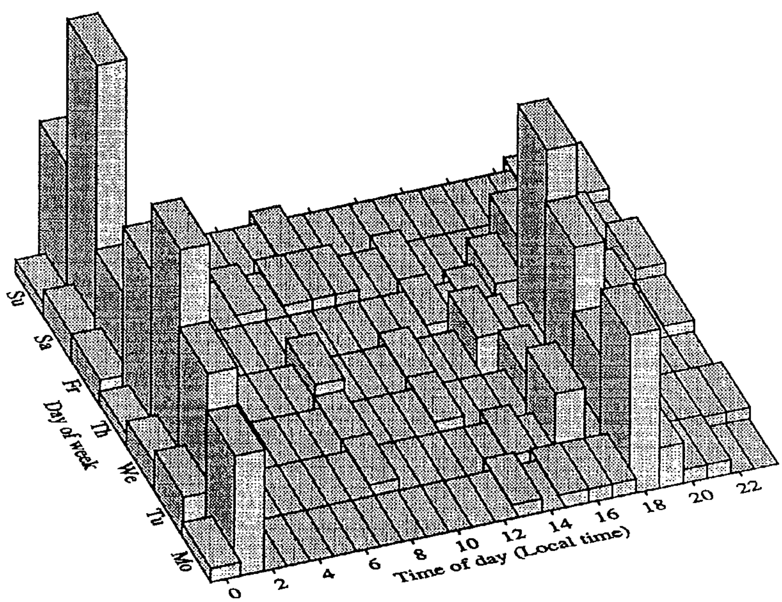

Fig. 4. Daily and weekly distribution of seismic events in northern Sweden. The majority of events occurs on working days early in the morning (local time). Daytime saving time from spring to early autumn is taken into account. Afternoon is the time of mining explosions in Aitik and Malmberget. The Kiruna mining explosions occur daily (peak on Saturday mornings). The highest column is equivalent to 22 events.

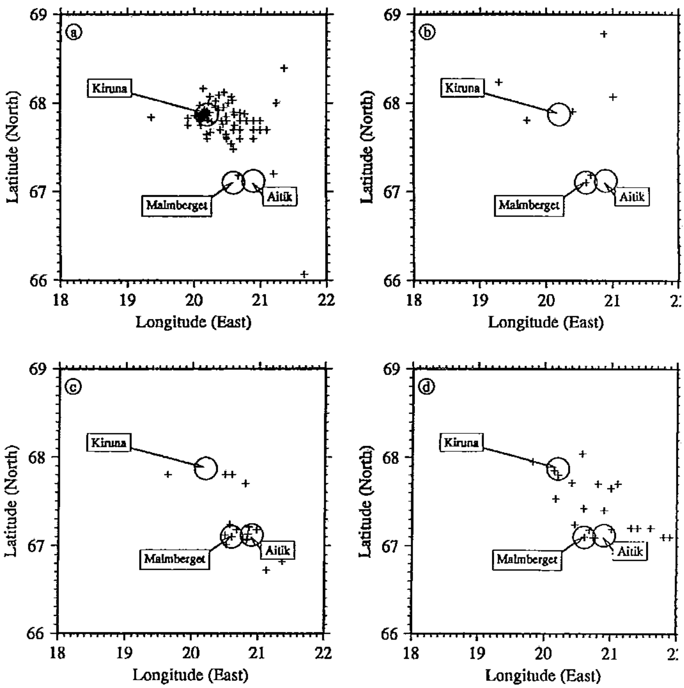

Fig. 5. Distribution of explosions in northern Sweden for different diurnal time intervals. The day is divided into four intervals of six hours. The shooting practice in the Kiruna mine (Fig 5a) is clearly different from that in the other mines of the area.

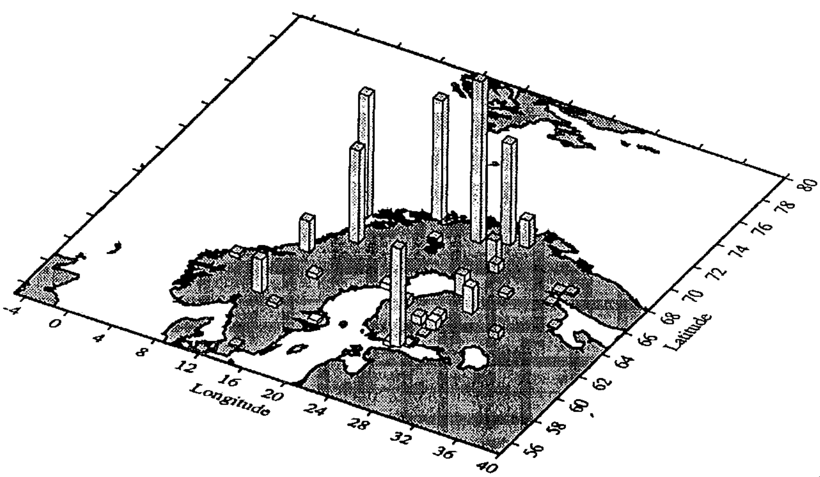

Fig. 6. Event reporting frequencies for agencies and stations in Fennoscandia and Russia of explosions in northern Sweden. The Helsinki Data Center and stations in northern Norway had the highest reporting rates of the events, but without identifying individual detecting stations. The mine locations are plotted as black dots.

2.2 *The Russian Karelia and adjacent areas (Figures 7 -10)*

The mining activity here is large as demonstrated in Figure 7 and 8, where also Estonian oil shale quarry explosions are included. The seismic activity has been subject to special studies, e.g. Tarvainen (1992) concluded that on the basis of event locations tied to nearby 3-component station recordings it was impossible to separate individual mining operations (see also *Bache et al.* 1990). Mines identified via SPOT satellite images were found to be close to the epicenters (Fig. 8).

The diurnal shooting pattern for this area is rather distinct with a strong concentration in the afternoon hours on working days (Fig. 9). Explosion charges appear to be small since the reporting frequency map in Figure 10 is dominated by Finnish stations (Helsinki agency). A few reports stem from Norwegian arrays and Russian stations.

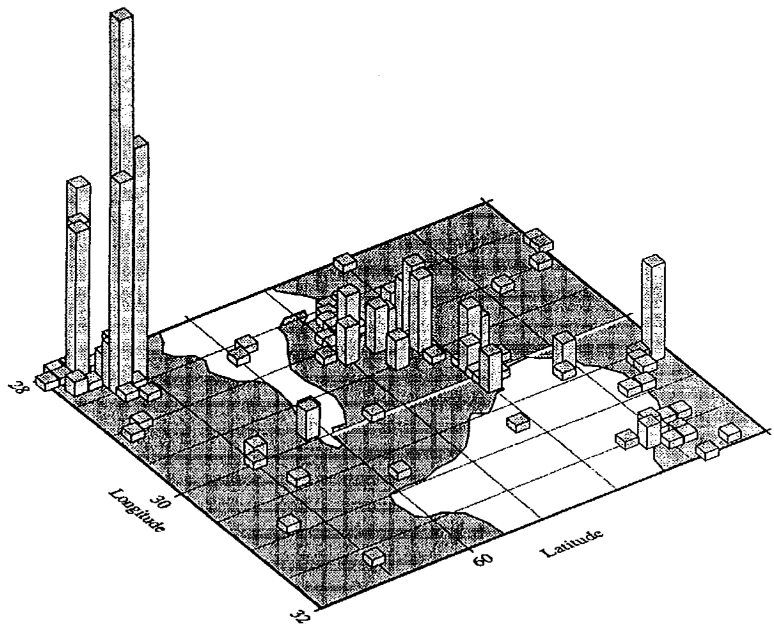

Fig. 7. Events in Russian Karelia in 1991 and adjacent areas. The column size is 0.1 0.1. The sites of highest activities match well with mining locations seen on satellite imagery data (GSE/US/73). The outstanding feature is the many explosions in the oil shale mines in eastern Estonia, which for purpose of comparison were included. The highest column here represents 51 events. The number of events within the mapping area was 488.

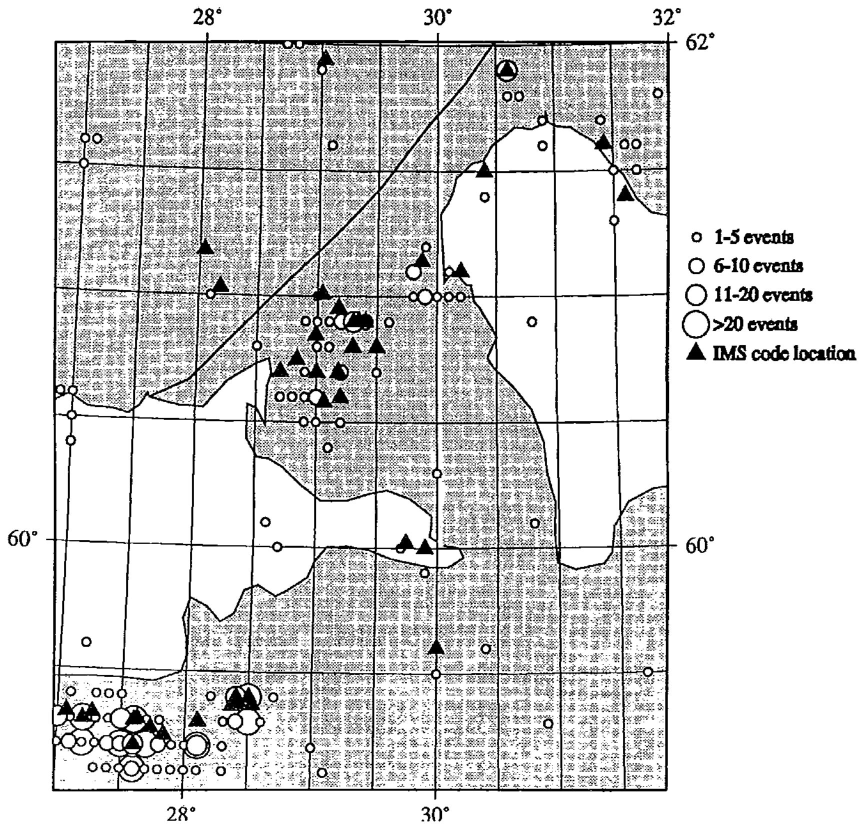

Fig. 8. The events of Fig. 7 shown together with SPOT located mining sites.

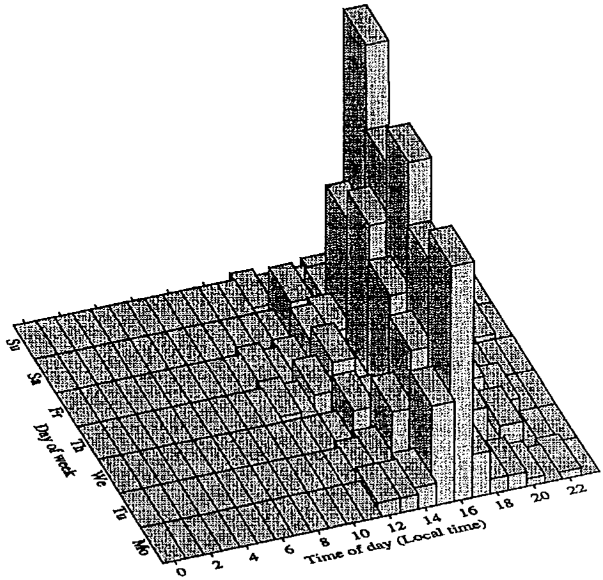

Fig. 9. Diurnal and weekly distribution of seismic events in the Russian Karelia and adjacent areas. They are evidently mining and other industrial explosions with shooting during prime working hours and afternoons. The activity is slightly higher on Fridays.

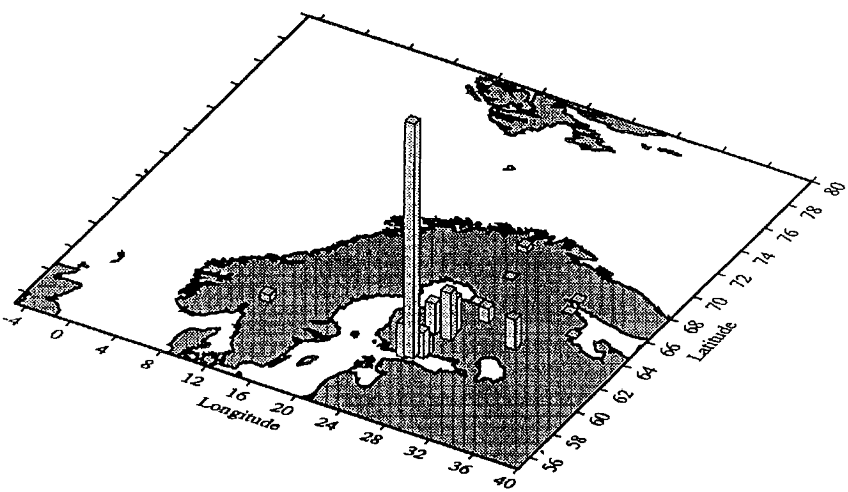

Fig. 10. Event reporting frequencies for agencies/stations of explosions in Russian Karelia. The Finnish stations, most of which are within 300 km exhibited the best monitoring capabilities. The column height at the Helsinki Data Center represents 416 events, which is close to 86 % of all the events in the area in 1991.

2.3. Kola peninsula and adjacent areas (Figures 11-13)

The seismic event locations reflect the diverse and extensive mining activities taking place in this area (Fig. 11). Again, there is a good diurnal clustering of events in the afternoon and there is an increased amount of explosions in weekends (Fig. 12).

Recordings of the Kola events stem mainly from the Finnish stations and the Helsinki Data Center (Fig. 13). More extensive studies of the Kola Peninsula seismicity are presented by *Kremenetskaya* (1991), *Kremenetskaya* and *Trjapitsin* (1992), and lately by *Mykkeltveit* (1993).

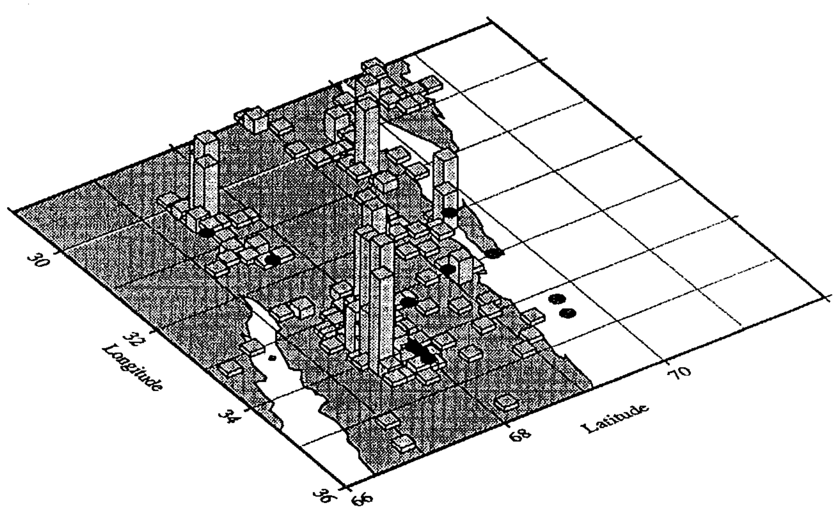

Fig. 11. Events on Kola Peninsula and adjacent areas, see Fig. 3 for symbols. The highest concentration occurred near known mining sites, (black dots). The total number of events in the area was 780 for 1991. The highest bin represents 38 events. The few occurring earthquakes are marked by black diamonds.

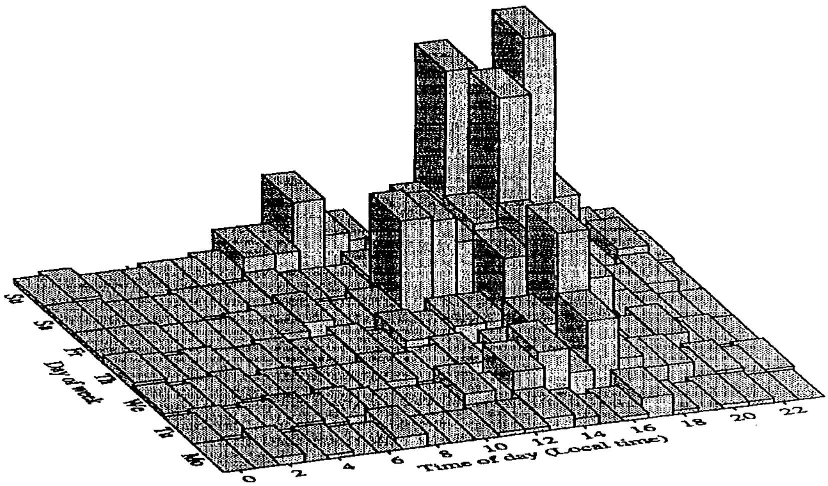

Fig. 12. Diurnal and weekly distribution of seismic events in Kola and adjacent areas for 1991. The majority of events for 1991 occurred during working hours (afternoon) with strongly increased activity during

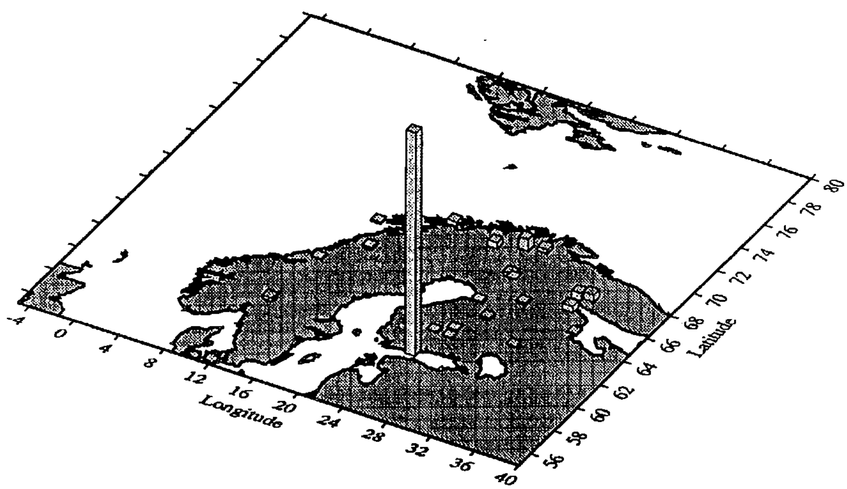

Fig. 13. Event reporting frequencies for agencies and stations of explosions on Kola Peninsula. The column height at Helsinki represents 470 events.

2.4. Western Norway explosions (Figures 14-16)

There is no mining operation in the area shown in Figure 14, but road and construction related explosions are numerous. 192 events occurred around Bergen out of which 46 were listed as earthquakes. This explains partly the dispersion of epicenters, but also, because there is no analyzed template system in use at the Bergen Observatory. The diurnal and weekly distribution of origin times is also relatively dispersed (Fig. 15), eventhough clear concentration at 15 hours on working days is clear. Most of the nocturnal events are earthquakes. The main part of detecting stations is located in western Norway (Fig. 16).

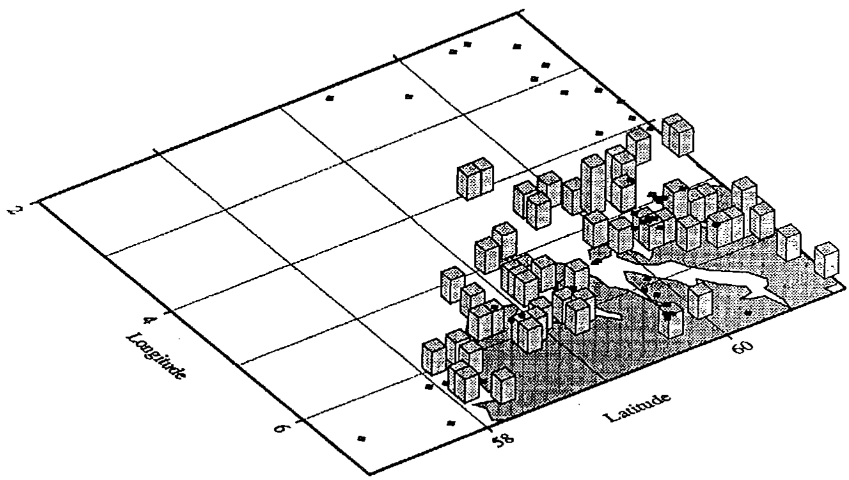

Fig. 14. Western Norway events in 1991, see Fig. 3 for symbols. The most active zone was around Bergen, (the highest bin represents only 7 events), where different construction works took place. The area contributed 192 events in 1991, out of which 46 were listed as earthquakes.

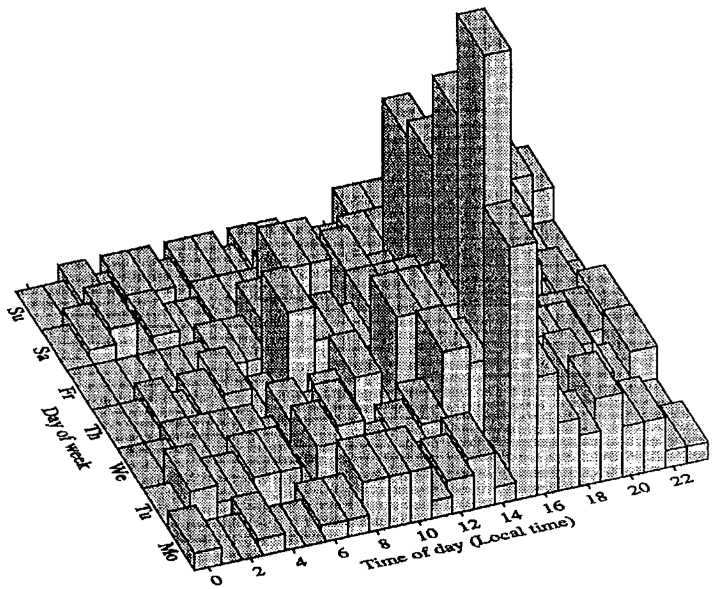

Fig. 15. Diurnal and weekly distributions of seismic events in western Norway. The highest activity is during working hours. Typically there is less activity during weekends. The relatively large number of earthquakes (46 out of 192 events) explains the dispersion in the diurnal distribution.

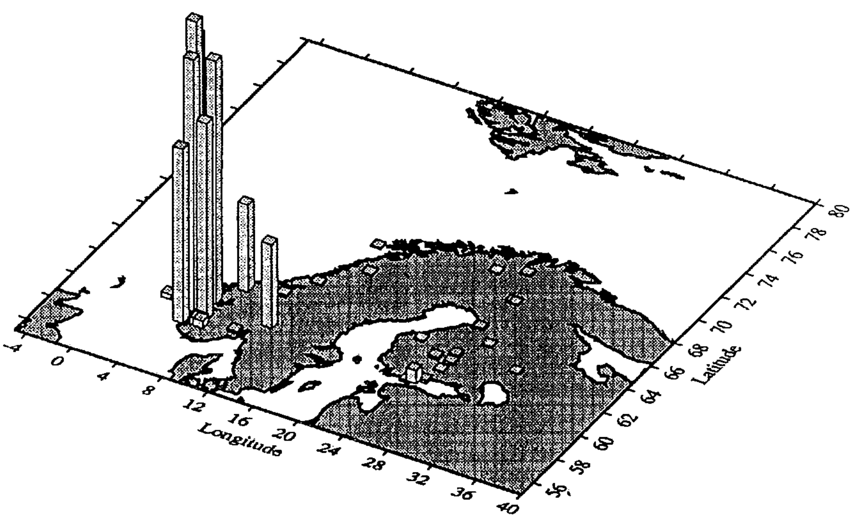

Fig. 16. Event reporting frequencies for agencies and stations of explosions and earthquakes in western Norway. The western Norwegian network reported mainly Norwegian coastal events, with the highest column for the station ASK accounting for 241 events. Some events, reported also in Finland and western Russia, were evidently earthquakes.

3. *Discussion*

The seismicity in Fennoscandia is very moderate with two or three earthquakes a week, equivalent to a few percents of our explosion data base for 1991. Even if teleseismic events are taken into account, the dominance of local explosions prevails, contributing 80-95 % of the total event recording population at every station in this region. If all event records were subject to the same careful screening, about 90 per cent of the analyst workload would be tied to local explosion recordings of little or no scientific value. In practice such work allocations are not feasible over extended periods of times at most seismological observatories. However, as most of the explosion epicenters are located in northern and eastern Fennoscandia, the excellent bulletin work performed at the Helsinki Data Center has in practice proved to be most beneficial for similar work at the other Nordic seismological centers. All event records from the stations in the coastal areas of Norway (Bergen Observatory) are carefully analyzed, but the number of recorded events is low due to a combination of high noise levels and also, relatively high signal attenuation for travel paths beneath the Caledonian mountain range. NORESS and ARCESS produced automatic bulletins in 1991, but their event listings were, as mentioned, only occasionally included in the Nordic bulletins.

The major outcome of our study of the Fennoscandian seismicity for 1991 is that the event population is completely dominated by numerous mining, quarry and other explosions. Such industrial operations are often stationary in space, and as demonstrated exhibit well defined temporal patterns. The former feature is not always obvious from the bulletin data as illustrated in Fig. 5 for the Kiruna-Malmberget mining district. Note, that most of these event locations, do not stem from the national Finnish bulletins, but from readings of stations in northern Norway. Anyway, the issues of incorporating well-established seismicity information and stationary signal attributes are of particular importance for automatic seismic network operations. The observational data at hand are often less voluminous and less reliable than those extracted through analyst inspections of station records (*Ruud* and *Husebye* 1992, *Ruud et al.* 1993). As mentioned above, formal epicenter solutions could be unreliable when based on P-arrival times only due to odd network configurations. The kind of seismicity information to be incorporated will naturally be spatial and temporal characteristics of mining operations. For example, being confident that given event recordings stem from a specific mine, the coordinates of that mine should replace the formal, seismic epicenter solution.

Another seismicity parameter of interest is station detectability, that is which stations are most likely to record explosions from a specific mine. Unfortunately, the bulletin listings are as mentioned incomplete on this account, so we only plotted the event reporting frequency for those stations and agencies, for which data were available (Figs. 6, 10, 13 and 16). Notice that the dominance of reportings from Helsinki, reflects the extensive usage of the template system in Finland and does not refer to a particular station.

This kind of information would be useful for detecting phase association errors; for example western Norway stations are unlikely to detect mining explosions in the Kola and Karelian areas. Moreover, most of the Fennoscandian mining explosions are small magnitude (M_L<2) events and seldom recorded beyond distances of a 4-500 km (Figs. 6, 10, 13 and 16; *Ruud* and *Husebye* 1992).

To use signal attributes in automatic seismic network operations require wave form stationarity for a given station for a specific mine. This appears often to be the case in Fennoscandia, so the challenge here is to mimic analyst template operation numerically. The mentioned elaborated IMS-system (*Bache et al.* 1990, *Bratt et al.* 1990) has provisions for implementing such features and also learning abilities useful solutions to the above kind of "artificial intelligence" (AI) problems have proved difficult in practice. Anyway, basic requirements here are compilation of reference events for every station in the network, and that the initial of epicenter location is accurate (*Rivière-Barbier* and *Grant* 1993). A remark her is that no network can be operated fully automatic in terms of producing high-quality bulletins, simply because signal attributes for weak events would be unreliable due to noise contamination.

4. *Summary remarks*

We have in this study examined the seismic aspect of the mining activities and other in Fennoscandia, which are characterized by clear temporal and spatial patterns. Analysts in Helsinki have taken full advantage of such knowledge so as to significantly ease the daily work load.

With digital seismograph networks being deployed in various parts of the region the challenge is to teach our computers to locate reliably, and identify the many thousands of explosions being recorded annually. This would require much painstaking work, since surprisingly little detailed information is available on many mining operations in particular in north-western Russia, but also elsewhere (short term construction works). However, we feel confident that this kind of problem can be solved using robust "grid search" techniques for incorporating á priori seismicity knowledge of the kinds dealt with here. The difficult problem is to mimic numerically the analyst's ability to quickly recognize mine specific waveforms. This implies that signal attributes are spatially stationary, which is often the case (*Rivière-Barbier* and *Grant*, 1993).

Observationally seismology has progressed tremendously over the last decade in terms of station design and deployment, digital recording, satellite communication and advanced data center facilities in various countries. A paradox in this context is the scant attention paid to the pressing problem of automatic signal analysis and bulletin production. With a few exceptions too small efforts are invested in this most essential aspect of network operation and earthquake monitoring.

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References

Bache, T., Bratt, S.T., Wang, J., Fung, R.M., Kobryn C. and Given, J.W., 1990: The intelligent monitoring system. *Bull. Seism. Soc. Am.* **80**, 1833-1851.

Bratt, S., Swanger, H. J., Stead, R. J., Ryall F. and Bache, T. C., 1990: Initial results from the intelligent monitoring system. *Bull. Seism. Soc. Am.* **80**, 1852-1873.

Dowla, F., Taylor S. and Anderson, R., 1990: Seismic discrimination with artificial neural networks preliminary results with regional spectral data. *Bull. Seism. Soc. Am.* **80**, 1346-1373.

Joswig, M. and Schulte-Theis, M., 1993: Master-event correlations of weak local earthquakes by dynamic waveform matching. *Geophys. J. Int.* **113**, 562-574.

Kremenetskaya, E.O., 1991: Contemporary seismicity of the NW part of the USSR, Semiann. Tech. Summ., 1 April -30 September 1991, NORSAR Sci. Rep. 1-91/92, Kjeller, Norway

Kremenetskaya, E.O. and Trjapitsin, V.M., 1992: Induced seismicity in the Khibiny Massif (Kola Peninsula), Semiann. Tech. Summ., 1 April - 30 September 1991, NORSAR Sci. Rep. 1-91/92, Kjeller, Norway

Mykkeltveit, S., 1993: Mining explosions in the Khibiny Massif (Kola Peninsula of Russia) recorded at the Apatity three-component station, RNF/NORSAR Tech. Rep., Kjeller, Norway; pp. 27.

Rivière-Barbier, F. and Grant, L.T., 1991: Cluster analysis of closely spaced mining blasts as a method of event location. Presented at the AGU 1991 fall meeting, San Fransisco, California, USA, 9-13 December 1991.

Rivière-Barbier, F., 1993a: Constructing a reference event list for ARCESS; Sci. Rep. No. C93-03, Center for Seismic Studies, Arlington, Va., USA; 196 pp.

Rivière-Barbier, F., 1993b: Constructing a reference event list for NORESS; Sci. Rep. No. C93-06, Center for Seismic Studies, Arlington, Va., USA; 88 pp.

Rivière-Barbier, F. and Grant, L.T., 1993: Identification and location of closely spaced mining events. *Bull. Seism. Soc. Am.* **83**, 1527-1546.

Ruud, B.O. and Husebye, E.S., 1992: A new three-component station detector and automatic single station bulletin production. *Bull. Seism. Soc. Am.* **82**, 221-237.

Ruud, B.O., Lindholm, C.D. and Husebye, E.S., 1993: An exercise in automating seismic record analysis and network bulletin production. *Bull. Seism.Soc.Am.* **83**, 660-679.

Tarvainen, M., 1992: Monitoring and analyzing regional seismic events using a network of three-component stations. *Geophysica* **27**(1-2), 63-78.

Tsvang, S.L, Pinsky, V.I. and Husebye, E.S., 1993: Enchanced seismic source discrimination using NORESS recordings from Eurasian events. *Geophys. J. Int.* **112**, 1-14.

United States Delegation, 1992: Location calibration of mining explosions preliminary results, GSE/US/73, Geneva, March 1992.

Uski, M., Pelkonen, E., Franssila, M. and Raime, M., 1992: Seismic events in northern Europe (Helsinki Bulletin). Institute of Seismology, University of Helsinki, Report series **R**, Yliopistopaino (University of Helsinki Press).

Vesanen, E., 1944: Über die typenanalytische Auswertung der Seismogramme, Ph. D. Thesis, Annales Academiæ Scientiarum Fennicæ, Helsinki; 244 pp.