RESEARCH IN REGIONAL SEISMIC MONITORING

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ABSTRACT

During the last decade, a network of sensitive regional arrays has been installed in northern Europe in preparation for the global seismic monitoring network under the Comprehensive Nuclear-Test-Ban treaty (CTBT). This regional network, which comprises stations in Fennoscandia, Spitsbergen and northwestern Russia provides a detection capability for the European Arctic that is close to m_b = 2.5, using the Generalized Beamforming (GBF) method for automatic phase association and initial location estimates.

We have implemented some new improvements to the regional GBF processing system currently used at NORSAR. Among the improvements are inclusion of the SPITS array in the GBF procedure, expansion of the beam grid coverage, increased density of the beampacking grid to allow more accurate epicenter determinations and improved detector and f-k recipes for six of the arrays used in GBF. As a result, the processing coverage of the European Arctic is significantly improved, with a much larger number of valid detected events and correspondingly better locations. Primarily, this improvement is due to the inclusion of the very sensitive SPITS array. Using various criteria to reduce the occurrence of spurious phase associations, we conclude that there are significant improvements in the detection and location performance in all regions covered by the regional network. We note that the NORSAR GBF system is capable of detecting and locating seismic events up to one order of magnitude smaller than the automatic association process currently used by the prototype International Data Center, This is due to a combination of better regional array coverage and less strict event definition criteria.

We have continued our studies to use data from the regional networks operated by the Kola Regional Seismological Centre (KRSC) and NORSAR to study the seismicity and characteristics of regional phases of the Barents/Kara Sea region. These studies have encompassed the traditional M_S:m_b discriminant, using surface waves recorded at regional distances, as well as short-period regional discriminants such as the P/S ratio. We have applied these discriminants to events with known source type as well as "unknown" events. The regional M_S: m_b results are encouraging, whereas the short-period discriminants will need further research, and will probably only be effective after extensive regional calibration and in combination with detailed station-source corrections.

A workshop was held in Oslo, Norway during 12-14 January 1999 in support of the global seismic event location calibration effort currently being undertaken by the Preparatory Commission's Working Group B in Vienna. Among the contributions were recent results provided by NORSAR and KRSC of our joint regional calibration effort in the European Arctic, which has resulted in much improved travel-time models for this region. We show by examples that significant improvements in event location precision can be achieved compared to using the IASPEI model, and we use the regional model to calculate locations of some recent small seismic events in the Novaya Zemlya region of interest in a CTBT monitoring context.

Key Words: detection, location, discrimination, seismic data analysis

OBJECTIVE

This work represents a continued effort to study earthquakes and explosions in the Barents/Kara Sea region, which includes the Russian nuclear test site at Novaya Zemlya. The overall objective is to characterize the seismicity of this region, to investigate the detection and location capability of regional seismic networks and to study various methods for screening and identifying seismic events in order to improve monitoring of the Comprehensive Nuclear-Test-Ban Treaty.

RESEARCH ACCOMPLISHED

NORSAR and Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences have for many years cooperated in the continuous monitoring of seismic events in North-West Russia and adjacent sea areas. The research has been based on data from a network of sensitive regional arrays which has been installed in northern Europe during the last decade in preparation for the CTBT monitoring network. This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia (see Figure 1) provides a detection capability for the Barents/Kara Sea region that is close to m_b = 2.5 (Ringdal, 1997).

The research carried out during this effort is documented in detail in several contributions contained in the NORSAR Semiannual Technical Summaries. In the present paper we will limit the discussions to some recent results of interest in the context of applying the P/S discriminant to seismic events in the Barents/Kara Sea region.

The Kara Sea seismic event on 16 August 1997 that was reported by the prototype International Data Center has caused a considerable and renewed interest in the seismicity of the region surrounding the Novaya Zemlya islands. Historically, registered earthquake activity in this region has been virtually nonexistent, with the exception of one presumed earthquake in the Kara Sea close to the Novaya Zemlya coast on 1 August 1986 (Marshall et al, 1989). The event on 16 August 1997 (m_b =3.5) has been studied by several investigators (Richards and Kim, 1997; Hartse, 1998), with particular attention to the P/S ratio observed at high frequencies.

This paper addresses the possibilities and limitations of utilizing the P/S ratio to characterize seismic events at low magnitudes in this region. We note that the P/S and other similar discriminants (e.g. Pn/Lg) have been extensively studied in many areas of the world, but at present there is no consensus on the applicability of such discriminants on a global basis.

Data

The seismicity of the Barents/Kara Sea region has previously been discussed by Ringdal (1997). Nuclear and chemical explosions were conducted at Novaya Zemlya until 1990, but the availability of regional data for these events is quite limited because most of the high-quality regional arrays in Fennoscandia and adjacent areas were established after this time. In addition, the Novaya Zemlya explosions were generally large, except for two smaller nuclear explosion in 1977 and 1984, and two chemical explosions in 1978 and 1987. A small presumed earthquake (Marshall et al, 1989) occurred on Novaya Zemlya near the nuclear test site in 1986. To our knowledge, there is no available digital recordings at near-regional distances (less than 12 degrees) for any of the abovementioned smaller events. Although there has been several low-magnitude seismic events detected near Novaya Zemlya in recent years, they are difficult to use for establishing or testing regional discriminants, since there is no confirmed evidence available as to their source type.

In other parts of the European Arctic, there is a quite good selection of reference earthquakes and mining explosions. For example, there are some well-known mining areas in the Kola Peninsula and Vorkuta south of Novaya Zemlya. The seismic event occurrence is also very high in the Spitsbergen area and offshore Norway (to the north and west). These events are presumably mostly earthquakes.

We have made a selection of known nuclear explosions, known earthquakes and some unknown events as a basis for this study. The events are listed in Table 1 and shown in Figure 1 together with the station network. Some of the smaller events have been located by Kremenetskaya et. al. (1999).

Date/time	Location	m_b	Comment
04.09.72/ 07.00.00	67.75 N, 33.10 E	4.3	Nuclear explosion, Kola Peninsula
09.10.77/ 10.59.58	73.414 N, 54.935 E	4.5	Nuclear explosion, Novaya Zemlya
10.08.78/ 07.59.58	73.293 N, 54.885 E	6.0	Nuclear explosion, Novaya Zemlya
27.08.84/ 06.00.00	67.75 N, 33.00 E	4.3	Nuclear explosion, Kola Peninsula
01.08.86/ 13.56.38	72.945 N, 56.549 E	4.3	Located by Marshall et.al. (1989) (presumed to be an earthquake)
16.06.90/ 12.43.28	68.52 N, 33.09 E	4.0	Earthquake, felt in the Murmansk region
24.10.90/ 14.57.58	73.360 N, 54.670E	5.6	Nuclear explosion, Novaya Zemlya
23.02.95/ 21.50.00	71.856 N, 55.685 E	3.5	Located by Kremenetskaya et. al. (1999)
31.01.97/ 04.23.53	67.3 N, 60.6 E	2.5	Mining explosion — Vorkuta region
16.08.97 02.11.00	72.510 N, 57.550 E	3.5	Located by Ringdal et al (1997)
16.08.97 06.19.10	72.5 N, 58 E	2.6	Probably co-located with preceding event
14.02.98/ 00.49.37	67.34 N, 62.9 E	2.4	Mining explosion — Vorkuta region

Table 1: List of seismic events used in this study.

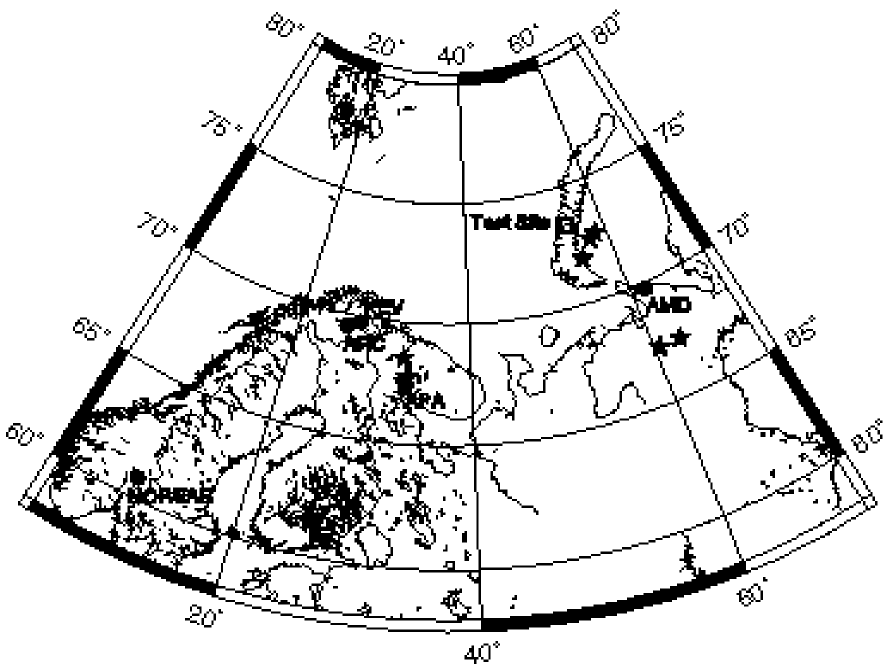

Fig. 1. Regional network of seismic stations and seismic events analyzed in this study. The location of the Novaya Zemlya nuclear test site is indicated.

P/S Ratios Observed at NORSAR

Novaya Zemlya events

The NORSAR large array (Bungum et. al., 1971) has an extensive database of recordings from events near Novaya Zemlya, including some nuclear explosions of magnitudes similar to those of the 16 August event and the nearby presumed earthquake of 1 August 1986. The large aperture of NORSAR makes it possible to study the spatial variability of signal characteristics for the same seismic event over an area extending up to 100 km across. Ringdal et. al. (1998) made the following observations for the 1-3 Hz filter band:

- ♦ The P/S ratios show very large variability (about an order of magnitude) across the array.
- ♦ This variability is dominated by strong P-wave focusing effects across NORSAR

They concluded that the P/S ratio in the 1-3 Hz frequency band is not a very promising discriminant when using data recorded at a single station. They noted, however, recent studies for Central Asia (Hartse et al, 1997), which have shown that the P/S discriminant for that region appears effective at frequencies above 4 Hz, but has a poor performance for frequencies below 4 Hz. At NORSAR, there is almost no significant S-wave energy above 4 Hz, so we are confined to consider the lower frequencies for Novaya Zemlya events.

Source scaling of the P/S ratio

The NORSAR array data base includes digital recordings of both large and small nuclear explosions from Novaya Zemlya. It is instructive to study the P/S pattern of these explosions as a function of the event size. In order to accomplish this, we have used the one NORSAR sensor (01A01) that has dual gain recording (the usual high-gain channel and a channel that is attenuated by 30dB). The attenuated channel has been available since 1976, and therefore provides a good data base of unclipped short period recordings of Novaya Zemlya explosions.

Figure 2 a-b shows the P/S ratio as a function of magnitude m_b (world-wide as well as NORSAR) for 16 Novaya Zemlya nuclear explosions for which attenuated channel data were available. A magnitude-dependent trend can be clearly seen, and can be approximated by:

$$\log(P/S) = 1.35 m_b + c$$

The slope is similar in the two plots, whereas the value of the constant c is slightly different due to the NORSAR bias relative to world-wide m_b. This indicates that source-to station specific P-wave focusing effects at NORSAR are not a dominant cause of the trend. There could be other possible explanations, such as systematic differences in depth of burial or source corner frequency effects, but for our purposes, it is sufficient to note that comparing the P/S ratios of large and small events could easily give misleading conclusions.

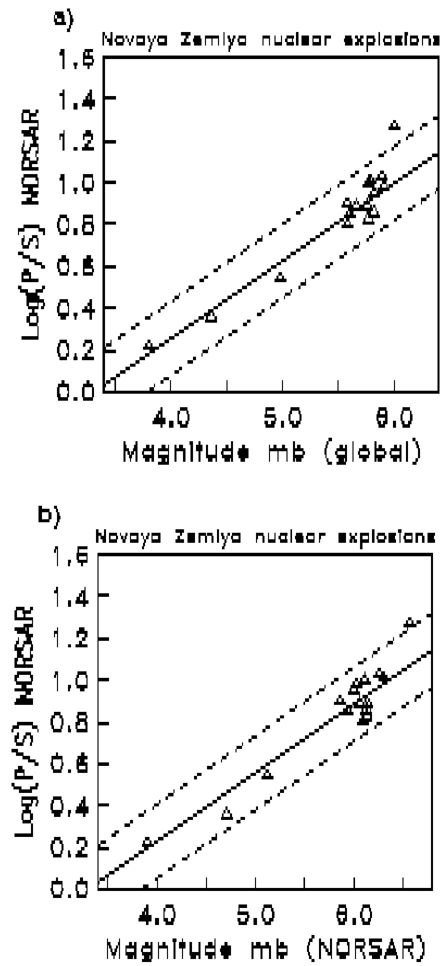

Fig. 2. NORSAR P/S ratios (seismometer 01A01) in the 1.5-2.5 Hz filter band for a suite of 16 Novaya Zemlya nuclear explosions. Parts a) and b) show log(P/S) as a function of world-wide m_b and NORSAR m_b, respectively. Note the similar trend for the two cases.

Recordings of Kola nuclear explosion and earthquake

In order to illustrate the behavior of the P/S discriminant at higher frequencies (3-5 Hz), we show in Figure 3 selected NORSAR traces for an earthquake in the Kola Peninsula in 1990 (felt in the Murmansk district) and a Kola nuclear explosion in 1984 (colocated with the 1972 explosion discussed by Ringdal et. al. (1998)). Both are at an epicentral distance of between 11 and 12 degrees. It appears that the P/S ratio is slightly higher for the explosion, but the difference is not very significant in view of the relative variation in P/S ratios for each event. On the other hand, a similar figure for recordings at the Kevo station (Figure 4) shows a clear difference in the P/S ratio between the two events. Thus, it is indicated that the P/S ratio discriminant could be effective at high frequencies if a good azimuthal distribution of recordings is available, but more data will be required for further assessment of its discrimination potential.

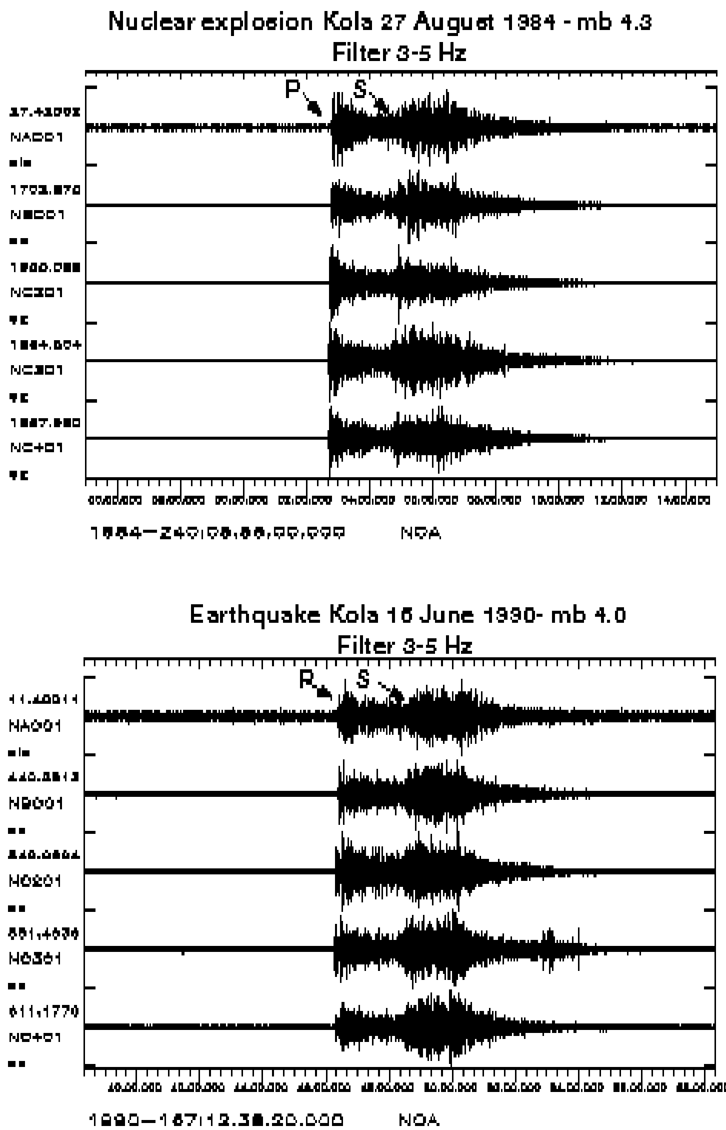

Fig. 3.Selected NORSAR traces for an earthquake in the Kola Peninsula in 1990 (felt in the Murmansk district) and the Kola nuclear explosion in 1984. Both are at an epicentral distance of between 11 and 12 degrees. The data have been filtered in the 3-5 Hz band.

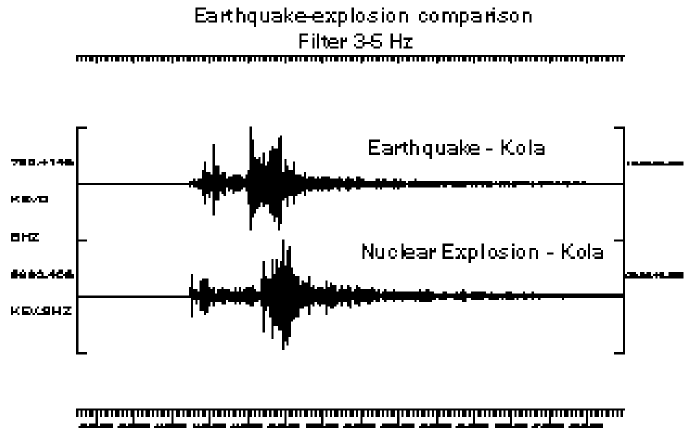

Fig. 4. Recordings by the Kevo station in Finland for the same earthquake and explosion shown in Fig. 3. The epicentral distance is 2-3 degrees, and the data have been filtered in the 3-5 Hz band. Note the significantly greater P/S ratio for the explosion.

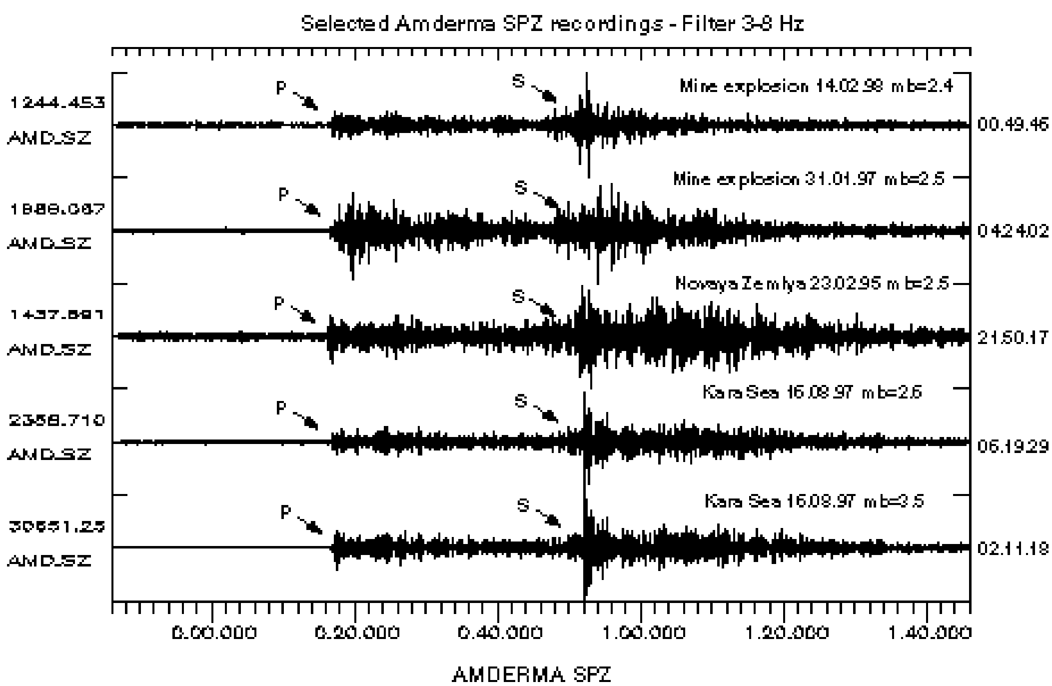

Fig 5. Amderma vertical component recordings of five seismic events at a similar epicentral distance from the station (about 300 km). The data have been filtered in the 3-8 Hz band. The five events are the two Kara Sea events on 16 August 1997, two mining explosions in Vorkuta south of the station, and a small event at the coast of Novaya Zemlya in 1995. The scaling factor in front of each trace is indicative of the relative size of the events.

The 16 August 1997 Event

On 16 August 1997, the CTBT prototype International Data Center in Arlington, Va. reported a small seismic disturbance located in the Kara Sea, near the Russian nuclear test site on Novaya Zemlya. The event caused considerable interest, since initial analysis indicated that the seismic signals had characteristics similar to those of an explosion.

NORSAR and KRSC worked together on locating this event, each carrying out independent analysis. Since some phase onsets were very difficult to read, this was quite useful, and the results were very consistent. We were very quickly able to confirm beyond doubt that the 16 August 1997 event was located in the Kara Sea, at least 100 km from the Novaya Zemlya nuclear test site.

Perhaps the best indication of an earthquake source would be the presence of several aftershocks, if such could be found. We have carried out a detailed search for aftershocks of the 16 August 1997 event, using both Spitsbergen array data and data that later have become available at KRSC from the Amderma station south of Novaya Zemlya.

Our search of Spitsbergen data, which was conducted by detailed visual inspection of the array beam, enabled us to find a second (smaller) event from the same site a little more than 4 hours after the main event. This second event had Richter magnitude 2.6, and could be quite clearly seen to originate from the same source area (Ringdal et. al., 1998).

This conclusion was supported when Amderma data became available at KRSC some weeks later. In spite of very careful analysis of both Spitsbergen and Amderma data, we have not been able to identify additional aftershocks during the two weeks following the main event.

P/S ratios of regional events recorded at Amderma

Figure 5 shows Amderma vertical component recordings of five seismic events at a similar epicentral distance from the station (about 300 km). The data have been filtered in the 3-8 Hz band. The five events are the two Kara Sea events on 16 August 1997, two mining explosions in Vorkuta south of the station, and a small event at the coast of Novaya Zemlya in 1995 (Kremenetskaya et. al.,1999).

The recordings are quite instructive. As can be seen by the scaling factor in front of the traces, the events vary in size by about an order of magnitude. It is noteworthy that the two Vorkuta explosions have very different P/S ratios, and encompass the range of P/S ratios for the other three events. This should however, not be taken as an indication of explosive sources for the other events, since we have demonstrated that the P/S ratio does not have sufficient stability to provide confident source identification. Unfortunately, we do not have any confirmed earthquake recordings at Amderma at a similar epicentral distance.

It is of interest to note that for both the event in 1995 and the first event in 1997, the estimated origin times (assuming zero depth) are almost exactly on the minute. These origin times have been calculated by using the Barents travel time model (Kremenetskaya et. al., 1999) , and are estimated to be accurate to within less than 1.0 seconds. This could be taken as indicators that one or both of these two events were man-made. However, it should be noted that the second event on 16 August 1997 did not occur on the entire minute. In any case, our waveform analysis does not support any assertion about the nature of the 16 August event either as an earthquake or as an explosion.

CONCLUSIONS AND RECOMMENDATIONS

We conclude from this study that the P/S ratio is currently unproven as a seismic discriminant, and should be applied with great caution when attempting to identify the source type of seismic events. Case studies for the Barents/Kara Sea region, some of which are discussed briefly in this paper, have demonstrated that the P/S ratio, even at high frequencies, is rather unstable and should not at present be relied upon for regional event discrimination.

The Kara Sea events on 16 August 1997 provide an interesting case study for the Novaya Zemlya region. It highlights the fact that even for this well-calibrated region, where numerous well-recorded underground nuclear explosions have been conducted, it is a difficult process to reliably locate and classify a seismic event of approximate m_b 3.5.

Our conclusion from this study is that the 16 August 1997 events cannot be positively identified as earthquakes on the basis of seismological evidence. On the other hand, neither is there any evidence based on the observed waveforms to confidently classify these events as explosions. Therefore, the source type of these two events remains unresolved on the basis of available seismological evidence.

It is clear from this study that more research is needed on regional signal characteristics in the European Arctic and the application of additional discriminants, such as M_S:m_b at regional distances. It would be a particularly useful exercise to carry out a small chemical calibration explosion, in order to improve the seismic calibration of Barents/Kara Sea region. Such an explosion, even if not recorded teleseismically, would provide valuable additional information for future studies.

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