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# Observed Characteristics of Regional Seismic Phases and Implications for *P*/*S* Discrimination in the European Arctic

FRODE RINGDAL,[1] ELENA KREMENETSKAYA[2]
and VLADIMIR ASMING[2]

*Abstract*—In this paper, we use data from seismic stations operated by NORSAR, the Kola Regional Seismological Centre (KRSC) and IRIS to study the characteristics of regional phases in the European Arctic, with emphasis on the *P*/*S* ratio discriminant. While the detection and location capability of the regional station network is outstanding, source classification of small seismic events has proved very difficult. For example, the $m_b = 3.5$ seismic event near Novaya Zemlya on 16 August, 1997 has been the subject of extensive analysis in order to locate it reliably and to classify the source type. We consider the application of the *P*/*S* discriminant in the context of this event and other events observed at regional distances in the European Arctic. We show that the *P*/*S* ratios of Novaya Zemlya nuclear explosions measured in the 1–3 Hz filter band scale with magnitude, indicating a need for caution and further research when applying *P*/*S* discriminants. Using mainly data from the large NORSAR array, we note that observed *P*/*S* amplitude ratios in the European Arctic show large variability for the same source type and similar propagation paths, even when considering closely spaced observation points. This effect is most pronounced at far regional distances and relatively low frequencies (typically 1–3 Hz), but it is also significant on closer recordings (around 10 degrees) and at higher frequencies (up to about 8 Hz). Our conclusion from this study is that the *P*/*S* ratio at high frequencies (e.g., 6–8 Hz) shows promise as a discriminant between low-magnitude earthquakes and explosions in the European Arctic, but its application will require further research, including extensive regional calibration and detailed station-source corrections. Such research should also focus on combining the *P*/*S* ratio with other short-period discriminants, such as complexity and spectral ratios.

**Key words:** Seismic sources, discrimination, wave propagation regional phases.

## *Introduction*

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 northwest Russia and adjacent sea areas. The overall objective is to characterize the seismicity of this region, to investigate the detection and location

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[1] NORSAR, Kjeller, Norway. E-mail: frode@norsar.no
[2] Kola Regional Seismological Centre (KRSC), Apatity, Russia.

capability of regional seismic networks and to study various methods for screening and identifying seismic events in order to improve monitoring of the Comprehensive Test-Ban Treaty (CTBT). 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 Fig. 1), provides a detection capability for the Barents/Kara Sea region that is close to $m_b = 2.5$ (RINGDAL, 1997).

The Kara Sea seismic event on 16 August, 1997 that was reported by the prototype International Data Center has caused 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 event in the Kara Sea close to the Novaya Zemlya coast on 1 August 1986. This event was classified as an earthquake, based upon the focal solution and depth estimate (19 km) of MARSHALL *et al.* (1989). The event on 16 August 1997 ($m_b = 3.5$) was studied by several investigators (RICHARDS and KIM,

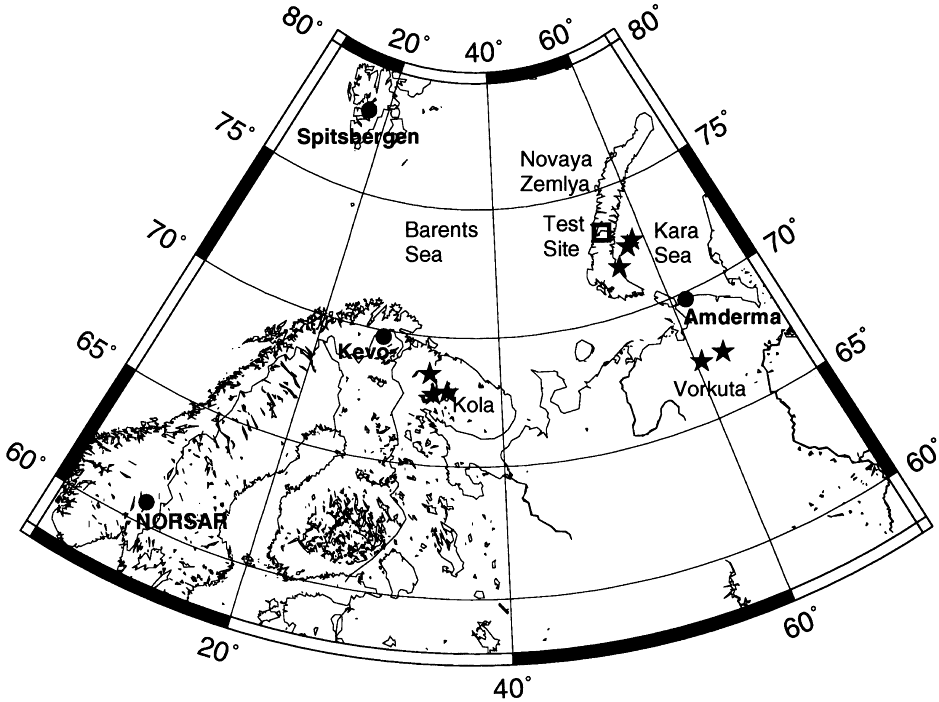


Figure 1
Regional network of seismic stations and seismic events analyzed in this study. The location of the Novaya Zemlya nuclear test site is indicated.

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 (e.g., WALTER *et al.*, 1995; TAYLOR, 1996; HARTSE *et al.*, 1997), 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 been discussed by RINGDAL (1997). Nuclear and chemical explosions were conducted at Novaya Zemlya until 1990, however 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 low-magnitude 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 are no available digital recordings at near-regional distances (less than 12 degrees) for any of the above-mentioned smaller events. Although there have 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 good selection of reference earthquakes and mining explosions. For example, there are 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).

## *Regional Phases*

Wave propagation characteristics of short-period seismic phases in the European Arctic have been studied by many authors (e.g., SERENO *et al.*, 1988; BAUMGARDT, 1990). This region is characterized by very efficient *P*- and *S*-phase propagation at

Table 1

*List of seismic events used in this study*

| Date/time | Location | $m_b$ | Comment |
|---|---|---|---|
| 04.09.72/07.00.00 | 67.75 N, 33.10 E | 4.3 | Nuclear explosion, Kola Peninsula |
| 20.10.76/08.00.00 | 73.40 N, 54.85 E | 4.9 | Nuclear explosion, Novaya Zemlya |
| 09.10.77/11.00.00 | 73.414 N, 54.935 E | 4.5 | Nuclear explosion, Novaya Zemlya |
| 11.10.82/07.15.00 | 73.33 N, 54.60 E | 5.5 | Nuclear explosion, Novaya Zemlya |
| 10.08.78/08.00.00 | 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) |
| 16.04.89/ 06.34.42 | 67.61 N, 33.81 E | 3.5 | Earthquake in Khibiny mine (KREMENETSKAYA and ASMING, 1995) |
| 16.06.90/ 12.43.28 | 68.52 N, 33.09 E | 4.0 | Earthquake, felt in Murmansk, Kola Peninsula |
| 24.10.90/14.58.00 | 73.360 N 54.670E | 5.6 | Nuclear explosion, Novaya Zemlya |
| 23.02.95/ 21.50.00 | 71.856 N, 55.685 E | 2.5 | Located by KREMENETSKAYA *et al.* (1999) |
| 26.06.96/21.32.15 | 67.73 N, 32.92 E | 3.0 | Earthquake Imandra, near Khibiny mines |
| 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 colocated with preceding event |
| 14.02.98/ 00.49.37 | 67.34 N, 62.9 E | 2.4 | Mining explosion – Vorkuta region |
| 17.08.99/04.44.36 | 67.865 N, 34.454 E | 4.3 | Earthquake/mine collapse, felt in Revda, Kola Peninsula |

high frequencies, whereas the Lg phase, which is often the largest observed phase at low frequencies, is usually strongly attenuated at high frequencies (Fig. 2a). Furthermore, the Lg phase is subject to blockage on certain paths (BAUMGARDT, 1990). For example, Lg is not observed in Fennoscandia for nuclear explosions at Novaya Zemlya, for which the travel path crosses the thick sedimentary layers of the central Barents Sea. This has been shown for the ARCESS array (distance 10 degrees) by BAUMGARDT (1990), and is likewise apparent on the more distant NORSAR array recordings as illustrated in Figure 2b. For these reasons, we focus in this paper on the $P$ and $S$ phases, in particular by considering the $P/S$ ratio at high frequencies.

The NORSAR large array (BUNGUM *et al.*, 1971) is a particularly valuable data source for regional discrimination studies in the European Arctic. This array has an extensive database of digital recordings dating from about 1970, including a number of earthquakes and nuclear explosions in this region. The large aperture of NORSAR, combined with the large number of short-period seismometers (initially 132, now 42) 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.

Since we want to use the NORSAR data at high frequencies, we need to discuss the response and digitizing procedure employed at the NORSAR array. As described by BUNGUM *et al.* (1971), the *SP* channels are sampled at 20 Hz, which in principle

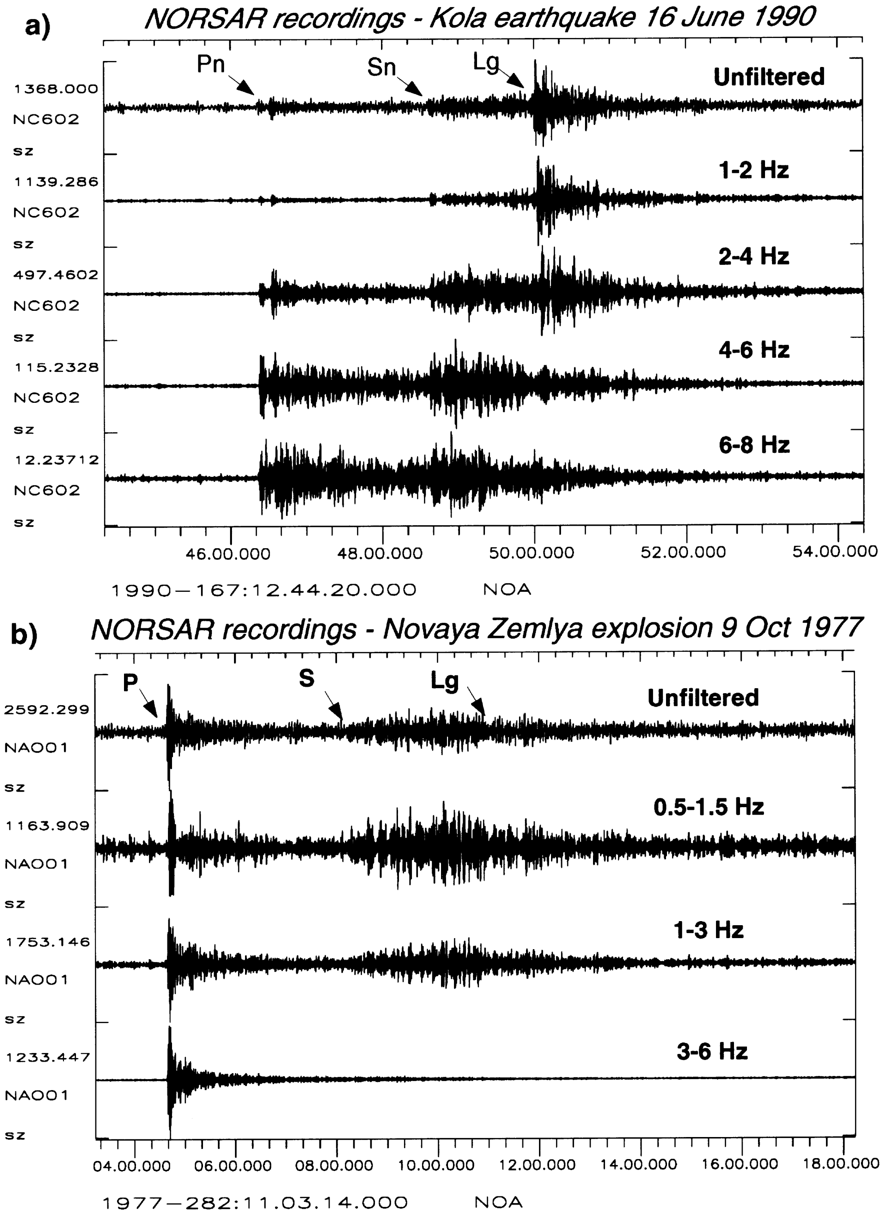


Figure 2

Illustration of regional phase propagation as seen using NORSAR data. Part a) shows recordings by the NORSAR SP seismometer 06C02 unfiltered and filtered in four frequency bands for the Kola earthquake of 16 June 1990 (distance 11 degrees). Note the differences in frequency contents of the various seismic phases and that the Lg phase is not visible above 4 Hz. Part b) shows the NORSAR center seismometer data for a nuclear explosion at Novaya Zemlya (distance 20 degrees). In this case, the Lg phase is essentially absent, and there is no visible *S*-wave energy above 3 Hz.

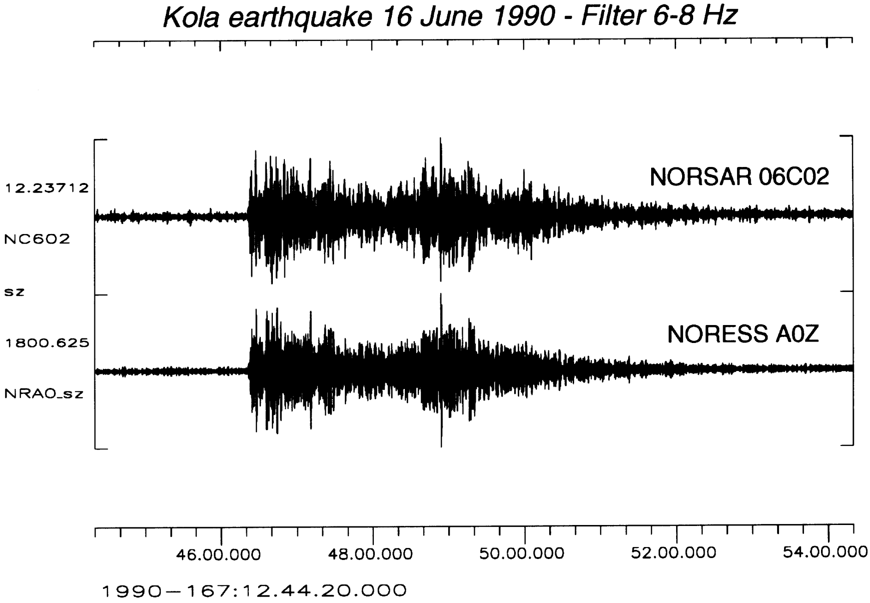


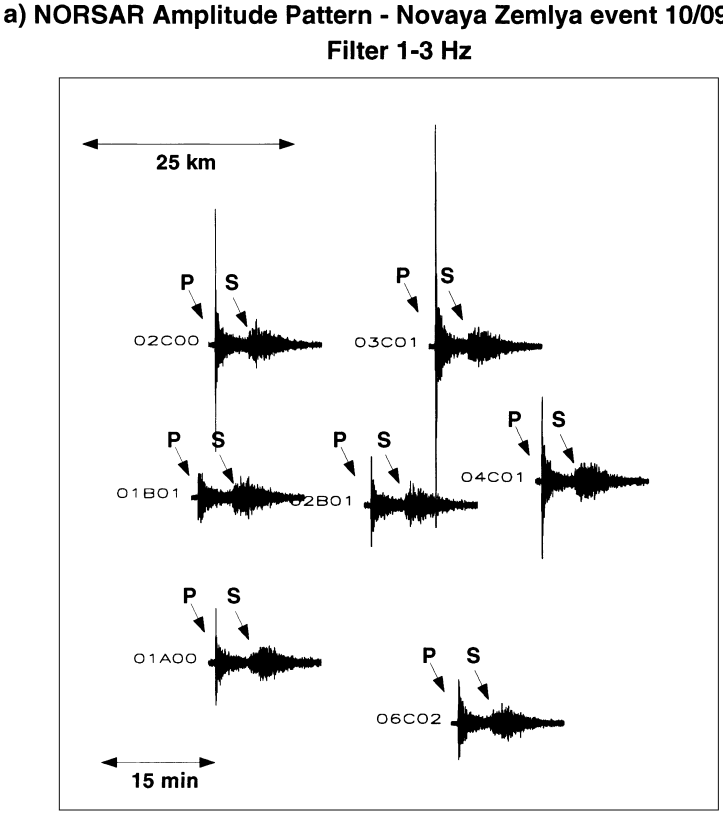
Figure 3
Comparison of narrow-band waveforms (6–8 Hz) for the NORSAR seismometer 06C02 (sampled at 20 Hz, with attenuated response above 5 Hz) and the colocated NORESS A0 seismometer (sampled at 40 Hz). There is a high consistency between the two traces.

should provide useful data up to the Nyquist frequency of 10 Hz. However, above 5 Hz, a presampling (analog) filter with a slope of 24 db/octave is applied, and this reduces the sensitivity and resolution at the highest frequencies. We have investigated the effect of this problem by comparing NORSAR 06C02 sensor data to the colocated NORESS center seismometer (A0) in various filter bands and at various signal-to-noise ratios. Since NORESS data (available since 1985) are sampled at 40 Hz, this array has useful data up to at least 16 Hz frequency. The comparison has shown a high degree of consistency, and thus indicates that the NORSAR data can indeed be used up to about 8 Hz (see Fig. 3 for an example).

## *Data Analysis*

### *Novaya Zemlya Events*

The NORSAR array has numerous 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. We will in the following compare the $P/S$ ratios (based on maximum amplitudes) as recorded by individual sensors in the array. Figures 4a and b show, as examples, recordings at one



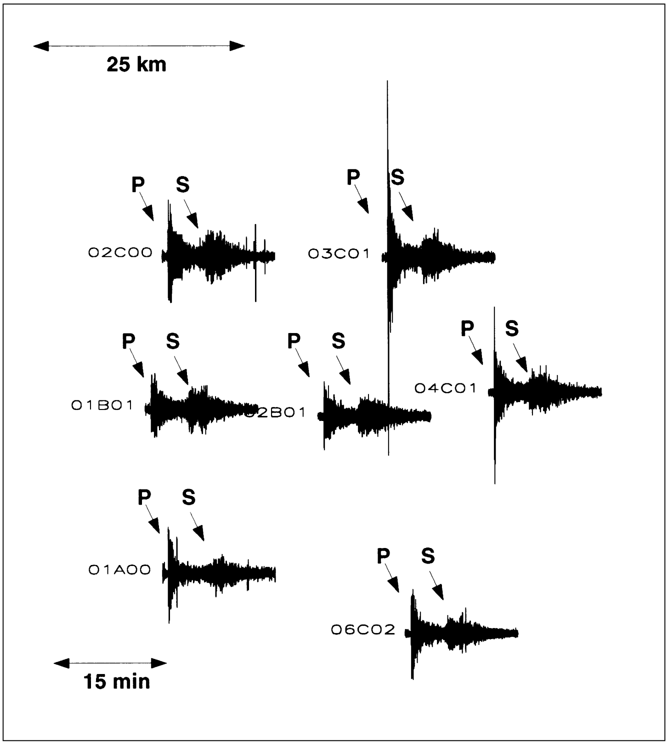
a) NORSAR Amplitude Pattern - Novaya Zemlya event 10/09/77
Filter 1-3 Hz

Figure 4
Recordings at the center seismometer of the 7 current NORSAR subarrays a) for the Novaya Zemlya nuclear explosion of 9 October 1977 and b) for the 1 August 1986 event. The magnitudes are 4.5 and 4.3 and the epicentral distance is about 20 degrees in both cases. The data have been filtered in the band 1.0–3.0 Hz. Note the large variation in $P/S$ ratios.

seismometer of each of the 7 NORSAR subarrays for the nuclear explosion of 9 Oct. 1977 and the 1 August 1986 presumed earthquake. The magnitudes are 4.5 and 4.3 respectively, and the epicentral distance is about 20 degrees in both cases. The data have been filtered in the band 1.0–3.0 Hz. The following observations can be made:

- The $P/S$ ratios display considerable variability (about an order of magnitude) across the array.
- This variability is dominated by strong $P$-wave focusing effects across NORSAR (see also RINGDAL, 1990).
- The amplitude patterns for the two events are rather similar, although not identical.

It may be concluded from the variability shown in this figure that the $P/S$ ratio in the 1–3 Hz frequency band is not a very promising discriminant when using data



**b) NORSAR Amplitude Pattern - Novaya Zemlya event 08/01/86**
**Filter 1-3 Hz**

Figure 4b

recorded at a single station. Recent studies for Central Asia (HARTSE *et al.*, 1997), have shown that the *P*/*S* discriminant for that region appears effective at frequencies above 4 Hz, but performs poorly for frequencies below 4 Hz. At NORSAR, there is almost no significant *S*- wave energy above 3 Hz for nuclear explosions at Novaya Zemlya, thus 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 30 dB). The attenuated channel has been available since 1976, and therefore provides a good database of unclipped short-period recordings of Novaya Zemlya explosions.

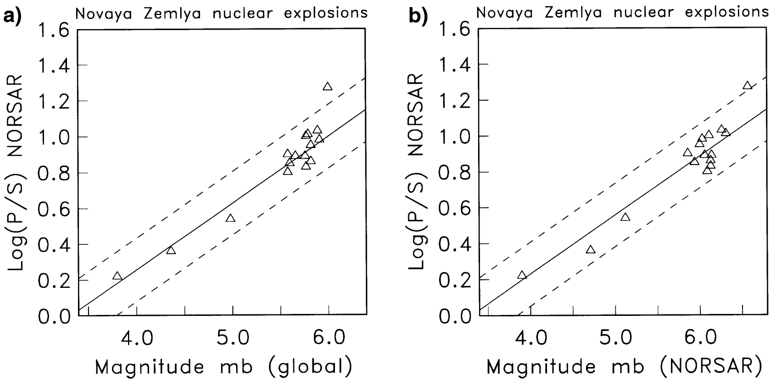


Figure 5
NORSAR $P/S$ ratios (seismometer 01A01) in the 1.5–2.5 Hz filter band for a suite of 16 Novaya Zemlya nuclear explosions. Parts a) and b) show $\log(P/S)$ as a function of worldwide $m_b$ and NORSAR $m_b$, respectively. Note the similar trend for the two cases.

Figures 5a-b show the $P/S$ ratio (ratios of maximum amplitudes) as a function of magnitude $m_b$ (worldwide $m_b$ as well as NORSAR $m_b$) 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 a NORSAR $m_b$ bias relative to worldwide $m_b$. The similarity of the two plots indicates that source-to-station specific $P$-wave focusing effects at NORSAR are not a dominant cause of the observed trend. There could be other possible explanations, such as systematic differences in depth of burial or source corner frequency effects, nonetheless we do not intend to extensively examine this topic. We note, however, that a somewhat similar observation was made by TAYLOR (1996) for Nevada Test Site explosions. He found that the Pg/Lg ratio increases with magnitude for all frequency bands considered, consequently earthquake explosion separation is better at high magnitudes (see also WALTER *et al.*, 1995). In our case, we have no data to investigate the $P/S$ ratio as a function of magnitude for frequencies above 3 Hz, and we have made no attempt to examine whether a similar magnitude dependency exists for earthquakes. For our purposes, it is sufficient to note that comparing the $P/S$ ratios of large and small events in a discrimination context could easily give misleading conclusions. An illustration, in an expanded scale, for four of the explosions in our data set is shown in Figure 6.

### *Kola Peninsula Events*

In order to illustrate the behavior of the $P/S$ discriminant at higher frequencies, we show in Figure 7 the pattern of recorded signals ($P$ and $S$ phase) across the full

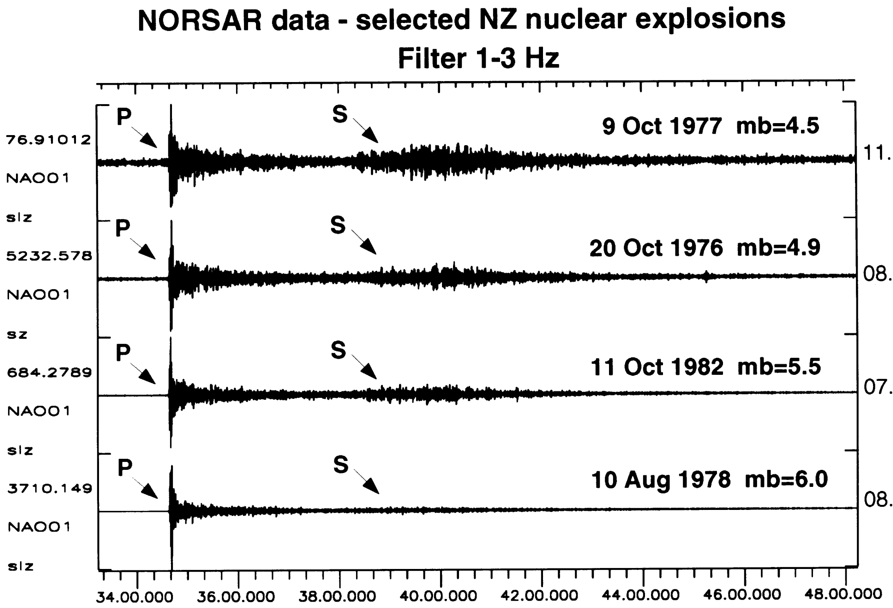


Figure 6
NORSAR recordings (seismometer 01A01) of four Novaya Zemlya nuclear explosions, filtered in the 1–3 Hz band. The traces show a selection of magnitudes, with the smallest explosion ($m_b$ = 4.5) at the top, and the largest ($m_b$ = 6.0) at the bottom. Note the systematic increase in $P/S$ ratios with magnitude.

NORSAR array (22 subarrays, center sensors) for the nuclear explosion in the Kola Peninsula on 4 September 1972. The filter band is 4–6 Hz. This explosion had an epicentral distance of only about 11 degrees, and consequently has a considerable amount of high-frequency energy both for the *P* and the *S* phase. The *P*-wave amplitudes (and consequently the *P*/*S* ratio) vary considerably across NORSAR, even in this frequency range, however the variation is considerably less than for the 1–3 Hz recordings of the Novaya Zemlya events shown earlier. This indicates that the P/S ratio may be more stable in higher frequency bands such as the band shown.

In order to assess further the discrimination potential of the *P*/*S* ratio, we show in Figure 8 selected NORSAR traces, filtered in the 6–8 Hz band, for three Kola Peninsula events of similar magnitude: a nuclear explosion in 1984, colocated with the 1972 explosion, an earthquake near Murmansk in 1990 and an earthquake in 1999 in Revda. All are at an epicentral distance of between 11 and 12 degrees and similar azimuths. In general, the *P*/*S* ratios are higher for the explosion, although there are cases where the difference is slight.

We have also plotted the same three events as recorded by the much closer Kevo station, together with two additional, smaller earthquakes in the Kola Peninsula (Fig. 9). In this case we show three filter band, and we note that the nuclear explosion

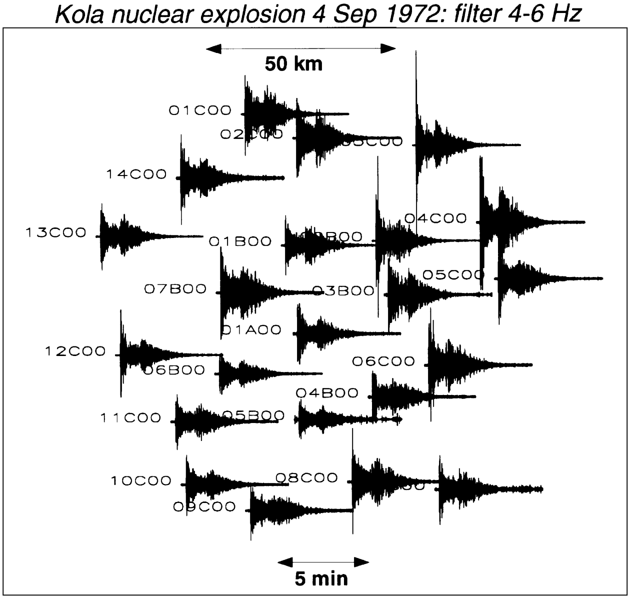


Figure 7
Amplitude pattern across the 100 km aperture original NORSAR array for the *P* and *S* phase of the Kola nuclear explosion on 4 September 1972 (distance 11–12 degrees). The data have been filtered in the 4–6 Hz band. Note that there is a strong variation in *P*/*S* ratios, although less than what was shown in Figure 4 for the 1–3 Hz band.

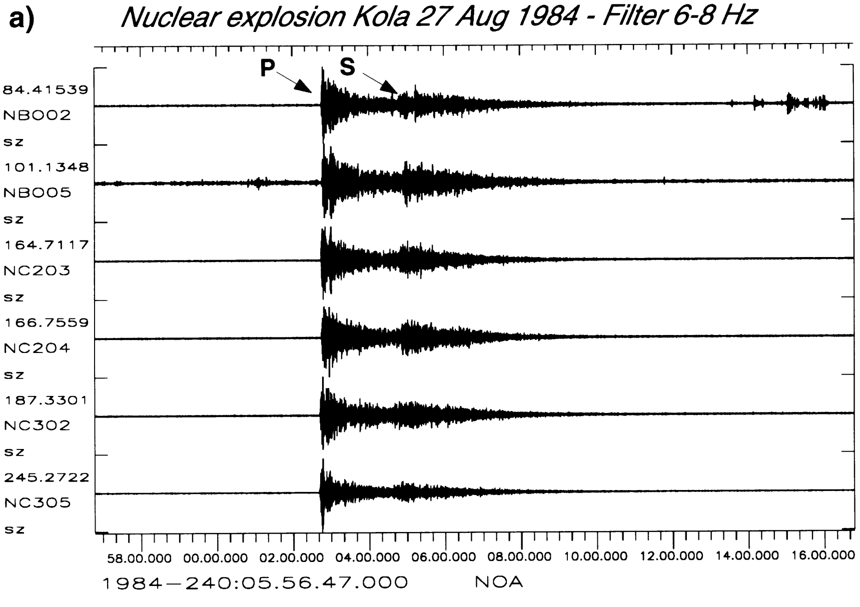


Figure 8
Selected NORSAR traces for a) the Kola nuclear explosion in 1984 (colocated with the 1972 explosion), b) the earthquake in the Kola Peninsula in 1990 (felt in the Murmansk district) and c) the Revda earthquake in 1999. All are at an epicentral distance of between 11 and 12 degrees. The data have been filtered in the 6–8 Hz band.

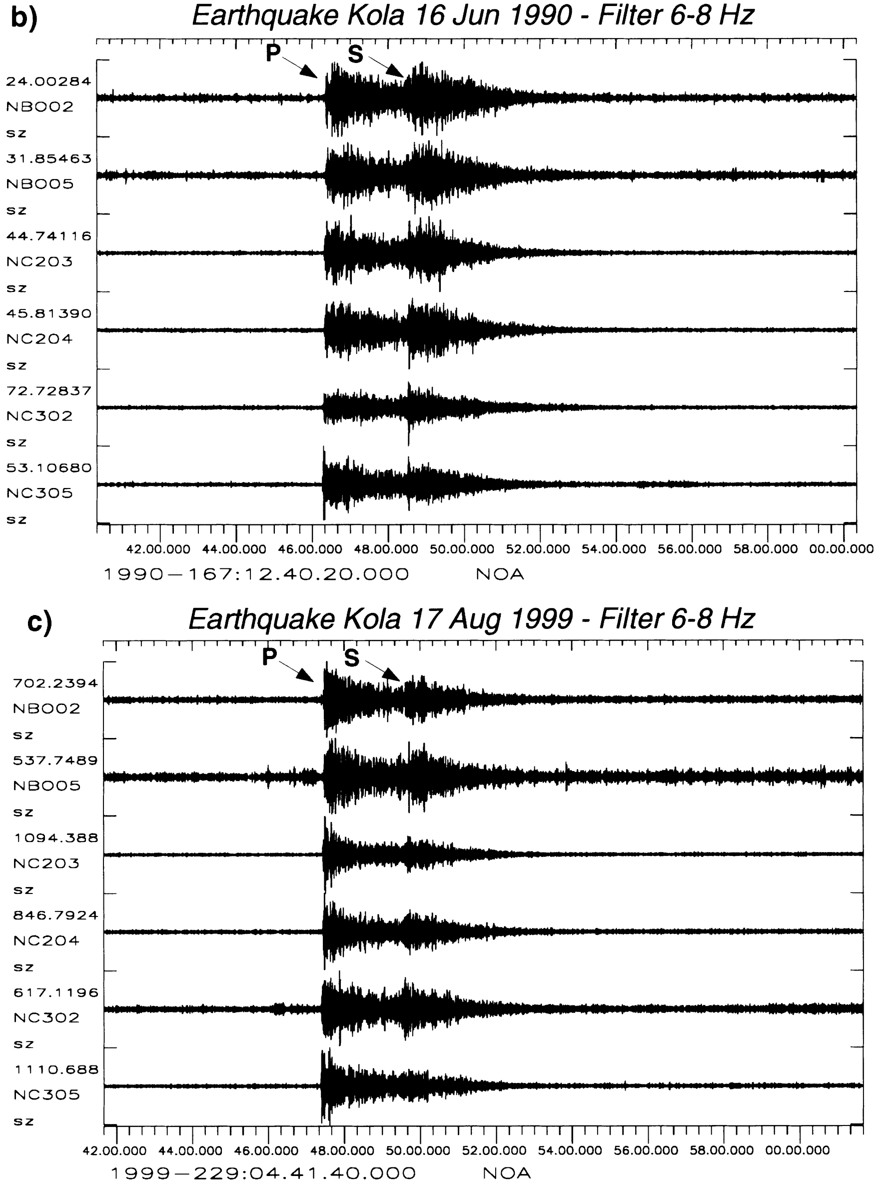


Figure 8b,c

has a considerably higher *P*/*S* ratio than the earthquakes in the 5–7 Hz band. On the other hand, there appears to be no clear separation in *P*/*S* ratios between the earthquakes and the explosion in neither the 3–5 Hz band nor the 7–9 Hz band. The data indicates that the *P*/*S* ratio discriminant has promise, but that considerable

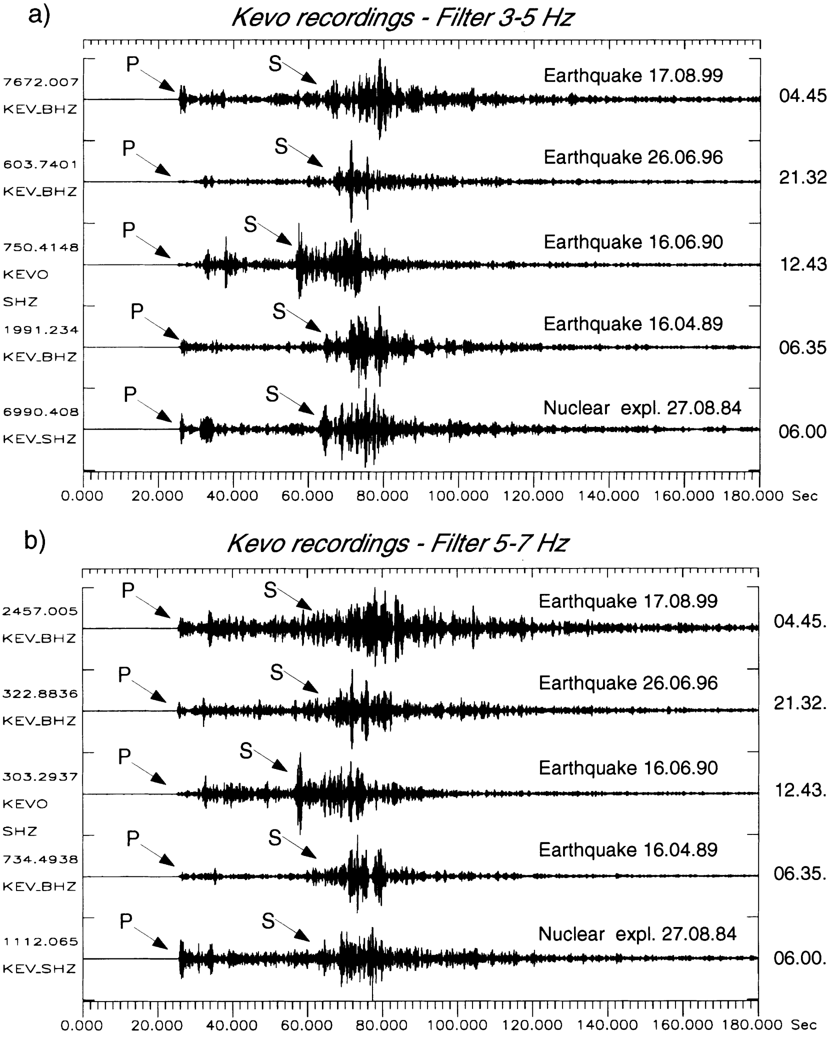


Figure 9

Recordings by the Kevo station in Finland (vertical component) for four Kola earthquakes and the 1984 Kola nuclear explosion. The epicentral distance is 2–3 degrees, and the data have been filtered in three different passbands.

caution must be exercised when applying it in narrow filter bands on the basis of one or a few stations.

We further comment on the events used in the comparisons in this section. The two nuclear explosions (1972 and 1984) were carried out inside an abandoned mine in the Khibiny Massif, for the purpose of testing ore crushing technology (Mikhailov *et al.*, 1996). The largest earthquake (Revda, 1999) is currently being actively

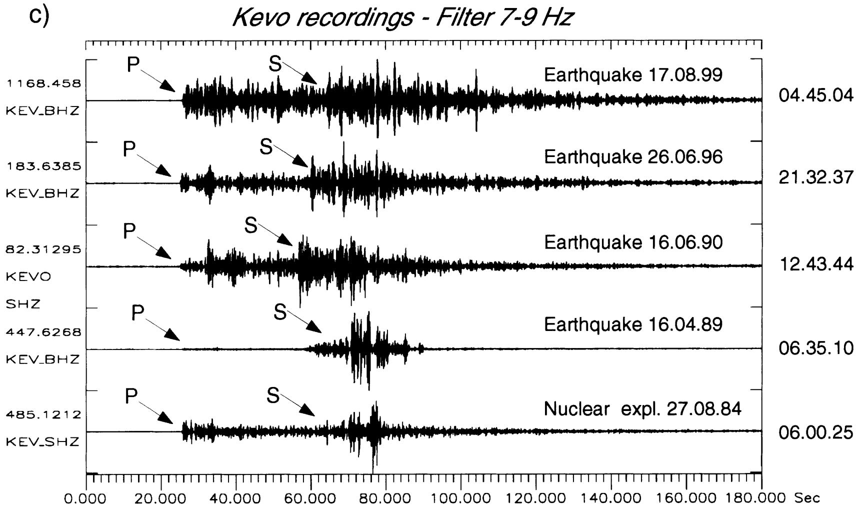


Figure 9c

studied. This earthquake, which was associated with a large mine collapse in the Lovozero Massif, was preceded by numerous foreshocks several months in advance, and was followed by several aftershocks. The 1989 Khibiny earthquake caused a surface rupture with a maximum measured displacement of 15–20 cm inside a mine, and was apparently triggered by a mining explosion (KREMENETSKAYA and ASMING, 1995). The Imandra earthquake of 1996 occurred about 30 km from the closest Khibiny mine, with an estimated depth of 15 km. The 1990 earthquake near Murmansk was not in a known mining area.

### *Kara Sea / Northern Urals Events*

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 collaborated on locating this event, each carrying out independent analysis (RINGDAL *et al.*, 1997). 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.

Figure 10 depicts Kevo recordings comparing the 16 August 1997 event and a nuclear explosion at Novaya Zemlya . The difference in $P/S$ ratios is striking, however we note that there is a difference in magnitude of two full units between the events.

The Kevo recordings have been filtered in a considerably higher frequency band than the explosions shown in Figure 6, and we have no data to determine whether a source scaling as observed in the 1–3 Hz band might in fact also be present at these higher frequencies. We note that we have seen no examples of Novaya Zemlya nuclear explosions with observed with *P* and *S* waves of nearly the same amplitude at frequencies above 5 Hz. Unfortunately, digital recordings at regional distances are not available for any of the smaller nuclear explosions at Novaya Zemlya.

Perhaps the best indication of an earthquake source would be the presence of possible aftershocks. 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 occurring about 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 (Fig. 11).

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 been unable to identify additional aftershocks during the two weeks following the main event.

## *Amderma Recordings*

Figure 12 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 4–8 Hz and 8–16 Hz bands. 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 in the 4–8 Hz band. In the 8–16 Hz band the picture is somewhat different, with the two events of 16 August 1997, registering the lowest $P/S$ ratios. Unfortunately, we have no confirmed earthquake recordings at Amderma at a similar epicentral distance.

We also note the high signal-to-noise ratio for these small events as recorded at Amderma. By a straightforward scaling procedure, we have estimated a detection threshold of about $m_b = 1.8$ for the Amderma station at this epicentral distance (300 km). For comparison, the estimated detection threshold at the Spitsbergen

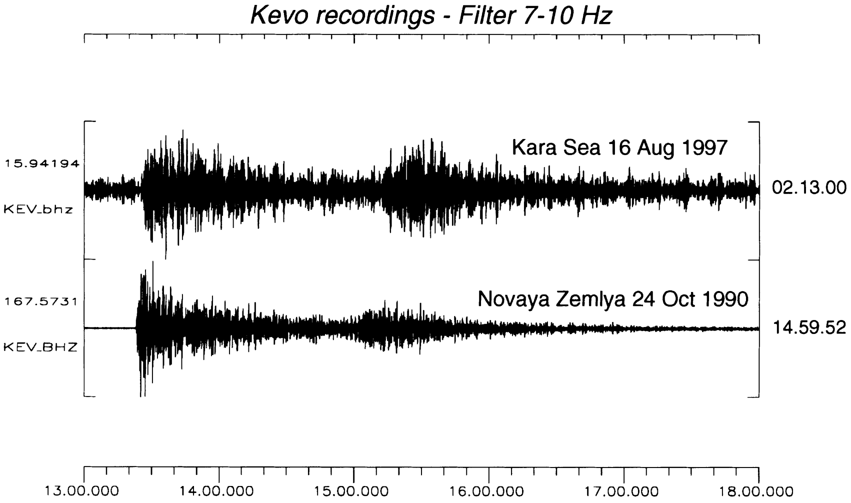


Figure 10
Kevo vertical component recordings filtered in the 7–10 Hz band. The top trace shows the 16 August 1997 seismic event ($m_b = 3.5$), whereas the bottom trace shows the 24 October 1990 Novaya Zemlya nuclear explosion ($m_b = 5.6$).

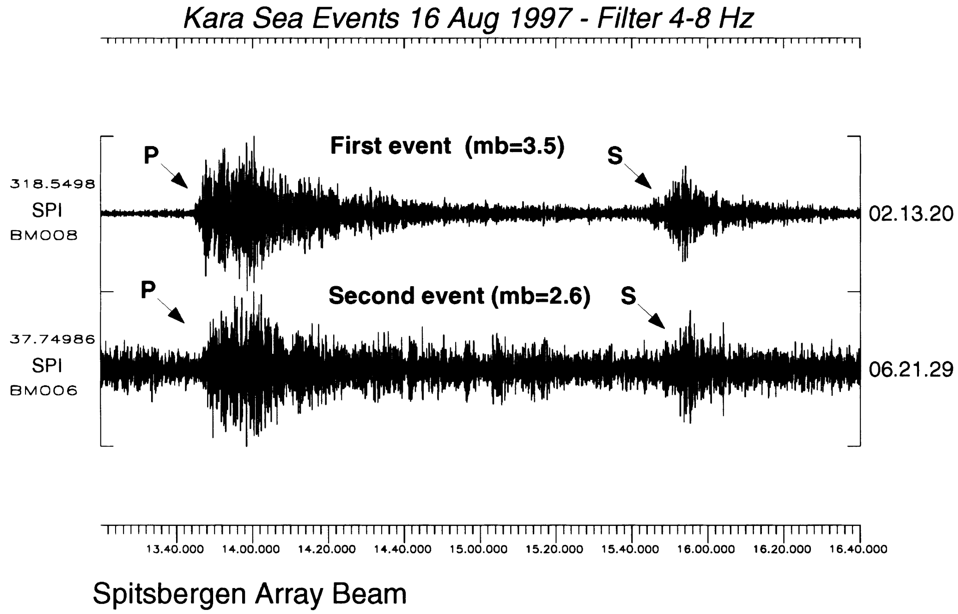
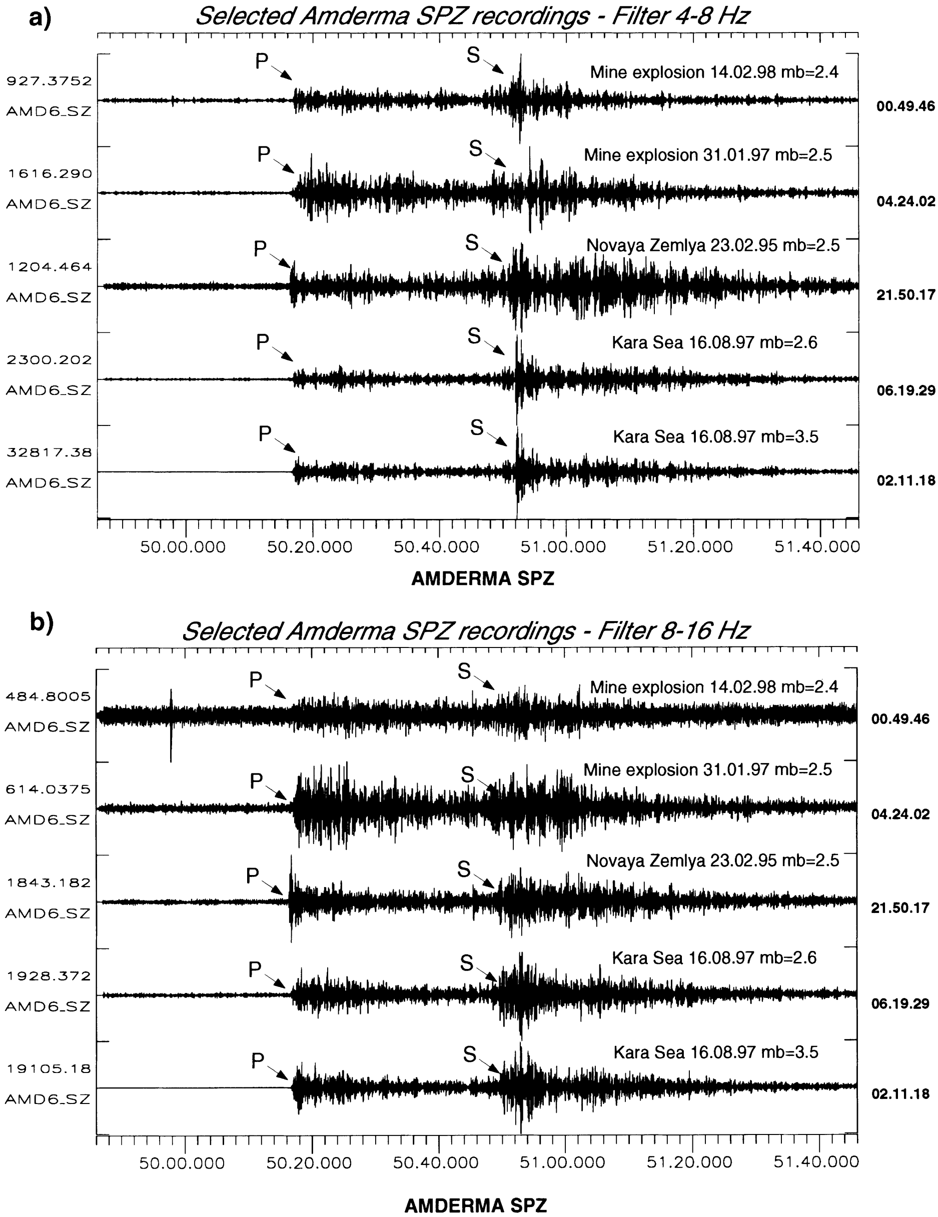


Figure 11
Recordings by the Spitsbergen array of the two events on 16 August 1997. The traces are array beams steered towards the epicenter, and with an $S$-type apparent velocity in order to enhance the $S$ phase. The traces are filtered in the 4–8 Hz band. Note that the traces are very similar, although not identical. The scaling factor in front of each trace is indicative of the relative size of the two events.



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array is about 2.5 for seismic events near the Kara Sea site, and somewhat higher (about 3.0) for events in the Vorkuta region.

## *Conclusions*

Case studies for the Barents/Kara Sea region, some of which are discussed briefly in this paper, have demonstrated that the $P/S$ ratio discriminant is ineffective at low frequencies (1–3 Hz), however it shows promise at higher frequencies (e.g., 6–8 Hz) in this region. The discriminant should be applied with considerable caution when attempting to identify the source type of seismic events in the European Arctic. Future application of the $P/S$ discriminant in this region will require extensive regional calibration and detailed station-source corrections. Future research should also focus on combining the $P/S$ ratio with other short-period discriminants, such as complexity and spectral ratios.

We show that in the 1–3 Hz filter band the $P/S$ ratio of Novaya Zemlya explosions recorded at the NORSAR array scale with magnitude in such a way that the larger explosions have a relatively high $P/S$ ratio. Such an effect would make a reliable comparison difficult between $P/S$ ratios of small and large events, and indicate a need for caution and further research when applying the $P/S$ discriminant. We note that the $S$-wave signal-to-noise ratios for this set of events are not sufficient to determine if there is such a scaling relationship above 3 Hz.

The Kara Sea event on 16 August 1997 provides 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.

It is clear from this study that more research is needed on regional signal characteristics in the European Arctic and the application of discriminants such as the $P/S$ ratio at regional distances. An interesting approach, which is beyond the scope of this paper, is to carry out a systematic study of the variability of the $P/S$ ratio in different frequency bands and at different epicentral distances, using the comprehensive NORSAR large array database of regional explosions and earthquakes, supplemented with other available digital data. 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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