NORSAR

NORSAR Scientific Report No. 2-98/99

Semiannual Technical Summary

1 October 1998 - 31 March 1999

Kjeller, May 1999

6.5 Observed Characteristics of Regional Seismic Phases and Implications for P/S Discrimination in the Barents/Kara Sea Region

Abstract

In this paper, we 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. While the detection and location capability of the regional network is outstanding, source classification of small seismic events has proved very difficult. In particular, the seismic event near Novaya Zemlya on 16 August 1997 at 02:11 GMT has been the subject of extensive analysis in order to locate it reliably and to classify the source type. It has been argued that this event could be confidently classified as an earthquake, especially based on observed P/S ratios. We consider some of this evidence in light of other observations of earthquakes and explosions in the region, including NORSAR recordings of past underground nuclear explosions. We show that there is an apparent source scaling of the P/S ratio of Novaya Zemlya explosions recorded at NORSAR 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. Furthermore, this amplitude ratio shows 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. Our conclusion from this study is that the P/S ratio even at high frequencies is, with present knowledge, not sufficiently stable to be used as a reliable discriminant between earthquakes and explosions. Future application of this discriminant will require extensive regional calibration and detailed station-source corrections.

Key Words: Seismic sources, Discrimination, Wave propagation

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 North-West Russia and adjacent sea areas. 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 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. 6.5.1) provides a detection capability for the Barents/Kara Sea region that is close to $m_b = 2.5$ (Ringdal, 1997).

The 16 August 1997 seismic event in the Kara Sea 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 (mb=4.3) in the Kara Sea close to the NZ coast on 1 August 1986 (Marshall et al, 1989). The 16 August event (mb=3.5) has been classified as an earthquake by several investigators (Richards and Kim, 1997; Hartse, 1998), mostly based on 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 discriminant has been extensively studied in many areas of the world, but at present there is no consensus on the applicability of this discriminant on a global basis.

Data

The seismicity of the Barents/Kara sea region is quite low as 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 regional arrays were established after this time. In addition, these explosions were generally large, except for two smaller nuclear explosion in 1977 and 1984, and two chemical explosions in 1978 and 1987 (Ringdal, 1997, Khristoforov, 1996). A small presumed earthquake 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 these 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 usually no confirmed evidence 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 6.5.1 and shown in Fig. 6.5.1 together with the station network. Some of the smaller events have been located by Kremenetskaya et al (1999).

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. We will in the following compare the P/S ratios as recorded by individual sensors in the array. Fig. 6.5.2 shows, as an example, recordings at the center seismometer of the 7 NORSAR subarrays for the nuclear explosion of 9 Oct 1977. The magnitude is 4.5 and the epicentral distance is about 20 degrees. The data have been filtered in the band 1.0-3.0 Hz. The following observations can be made:

- 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 (see also Ringdal, 1990)

It may be concluded from the variability shown in this figure that P/S in the 1-3 Hz frequency band is not a very promising discriminant when using data recorded at a single station. Recent studies for Central Asia (Hartse et al, 1997), has 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.

We have studied the P/S ratio as a function of magnitude (world-wide as well as NORSAR) for 16 Novaya Zemlya nuclear explosions for which attenuated channel data were available. As discussed by Ringdal (1997b), a magnitude-dependent trend is clearly seen, and is similar regardless of the reference magnitude used. This indicates that P-wave focusing effects 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 state that comparing the P/S ratios of large and small events could easily give misleading conclusions.

An illustration for two of these explosions is shown in Fig. 6.5.3. The difference in P/S ratios between these two explosions is in fact at least as large as the differences seen for Kevo recordings comparing the 16 August 1997 event and a nuclear explosion at Novaya Zemlya (Fig. 6.5.4). We note that these Kevo recordings, which compare two events with a magnitude difference of two full units, have been used as an indication of a different source type for these two events. Admittedly, the Kevo recordings are in a higher frequency band (3-5 Hz), but it would seem reasonable that a source scaling as described above might in fact be present also at these higher frequencies.

NORSAR 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 have investigated the pattern of P/S ratio across the full NORSAR array (22 subarrays, center sensors) for the nuclear explosion in the Kola Peninsula on 4 September 1972 (see Fig. 6.5.5). This explosion had an epicentral distance of only about 11 degrees, and consequently has a fair amount of high-frequency energy both for the P and the S phase. The P/S ratio varies considerably across NORSAR even in the frequency range 3-5 Hz, but the variation is considerably less than for the 1-3 Hz recording of the Novaya Zemlya nuclear explosion shown earlier. This indicates that the P/S ratio may be more promising as a discriminant in this higher frequency band.

In order to assess this further, we show in Fig. 6.5.6 selected NORSAR traces for an earthquake in the Kola Peninsula in 1990 (felt in the Murmansk district) and the Kola nuclear explosion in 1984 (colocated with the 1972 explosion). 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. Thus, the performance of the P/S ratio discriminant is questionable even in the 3-5 Hz frequency band.

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 (Fig. 6.5.7).

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.

Use of Amderma data for studying P/S ratios

Fig. 6.5.8 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

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 be relied upon for regional event discrimination..

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.

We do not believe that the 16 August 1997 events can 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.

It is clear from this study that more research is needed on regional travel-time calibration, regional signal characteristics and application of M_s:m_b and other discriminants 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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Table 6.5.3. Seismic events referenced 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
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)
25.08.87 / 14.00.00	73.380 N, 54.780 E	3.2	Chemical explosion-974 ton (Khristo-forov, 1996)
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

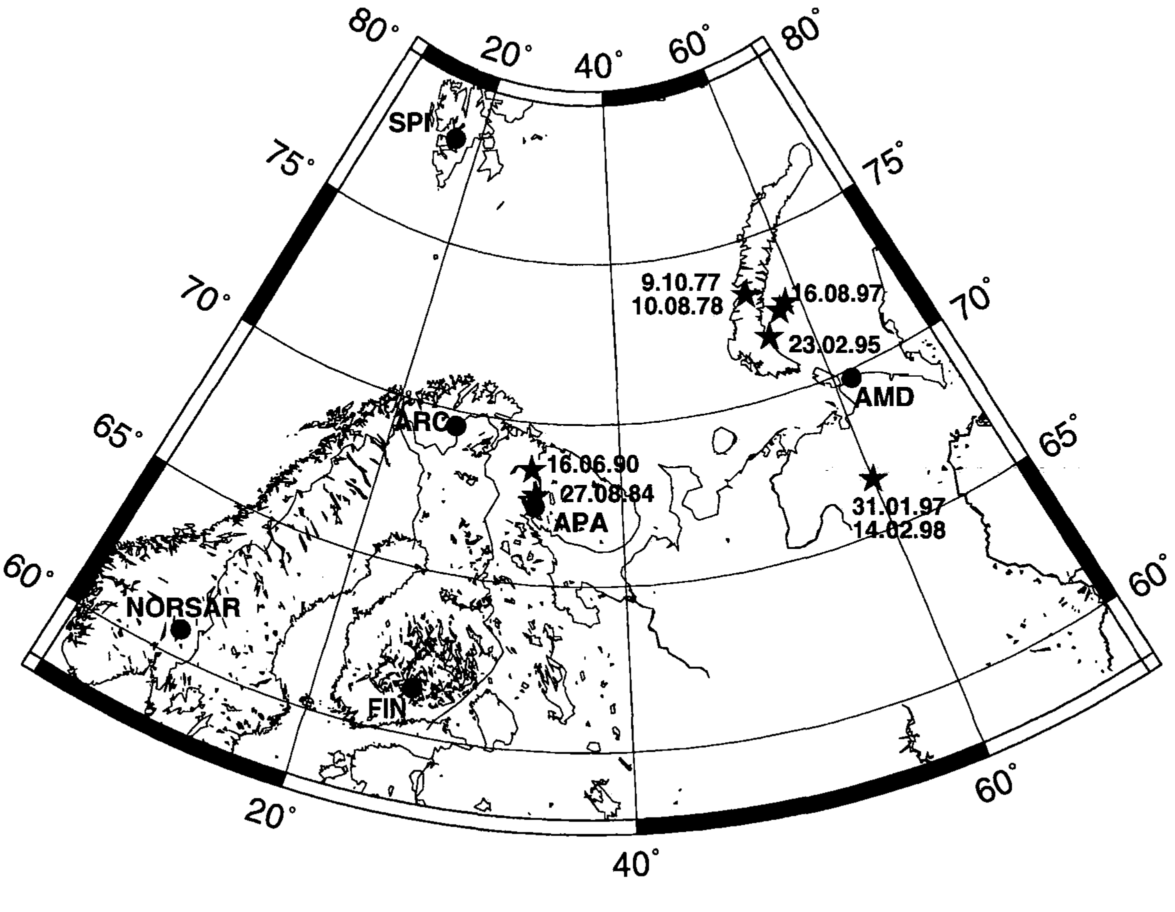


Fig. 6.5.1. The network of regional arrays in Fennoscandia and adjacent areas. The locations of the seismic events used in this study are indicated.

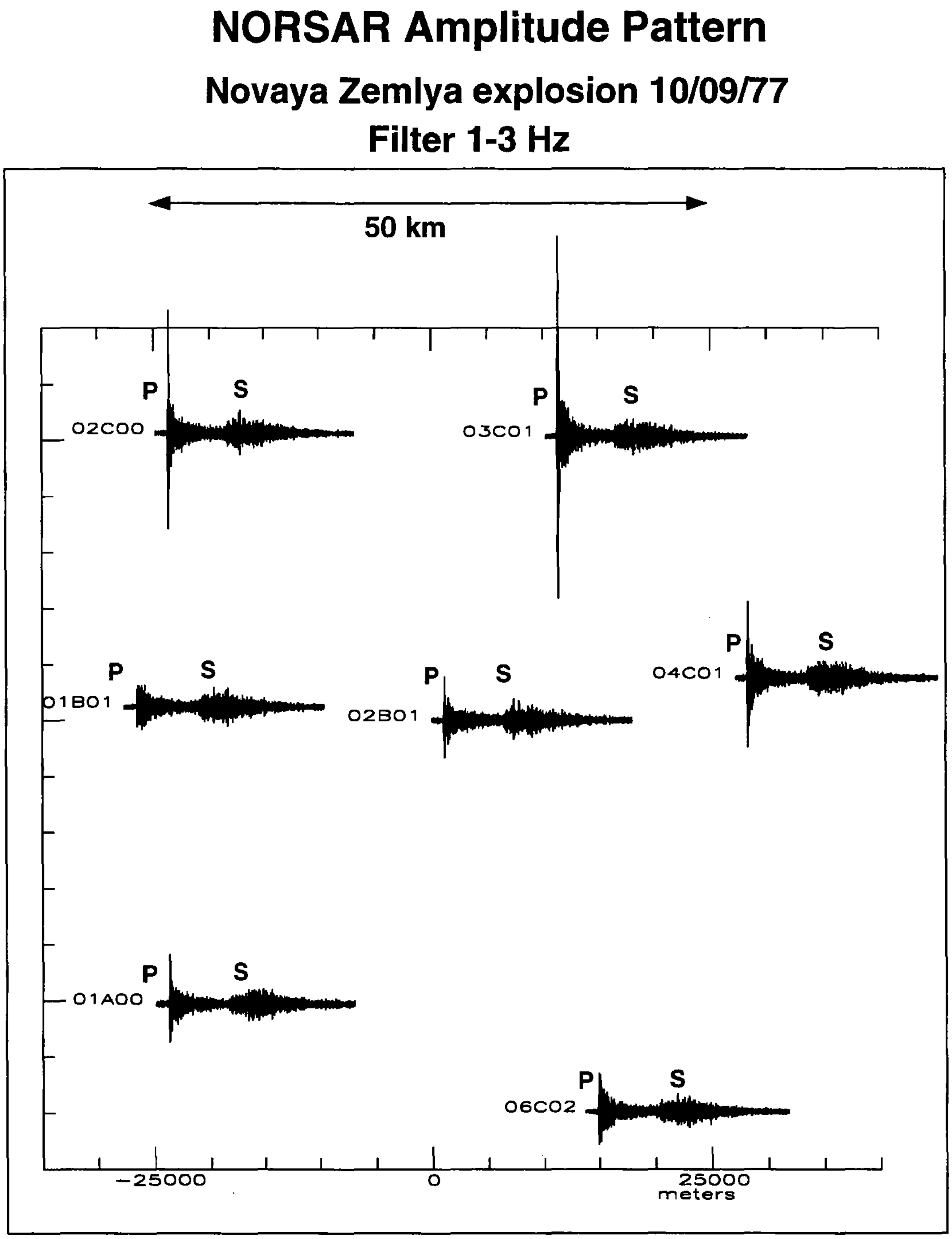


Fig. 6.5.2. Recordings at the center seismometer of the 7 NORSAR subarrays for the Novaya Zemlya nuclear explosion of 9 Oct 1977. The magnitude is 4.5 and the epicentral distance is about 20 degrees. The data have been filtered in the band 1.0-3.0 Hz. Note the large variation in P/S ratios.

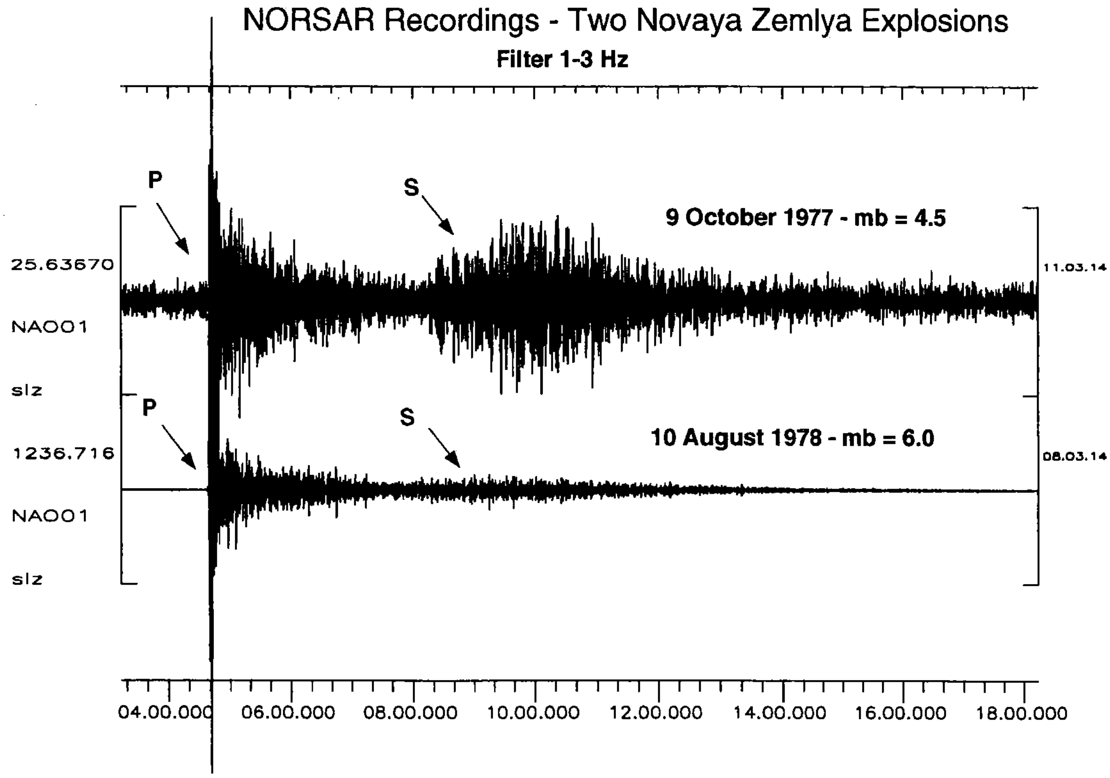


Fig. 6.5.3. NORSAR recordings (seismometer 01A01) of two Novaya Zemlya nuclear explosions, filtered in the 1-3 Hz band. The top trace shows a small explosion (m_b=4.5), whereas the bottom trace shows a large explosion (m_b=6.0). The vertical scale has been amplified to highlight the difference in P/S ratio between the two events.

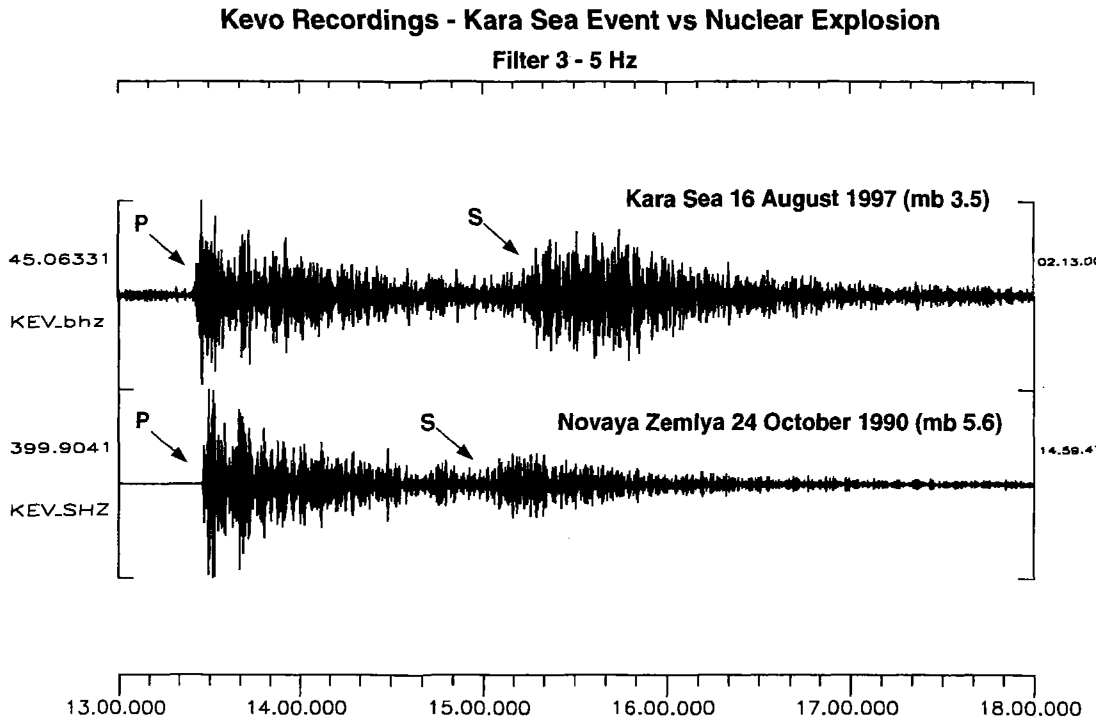
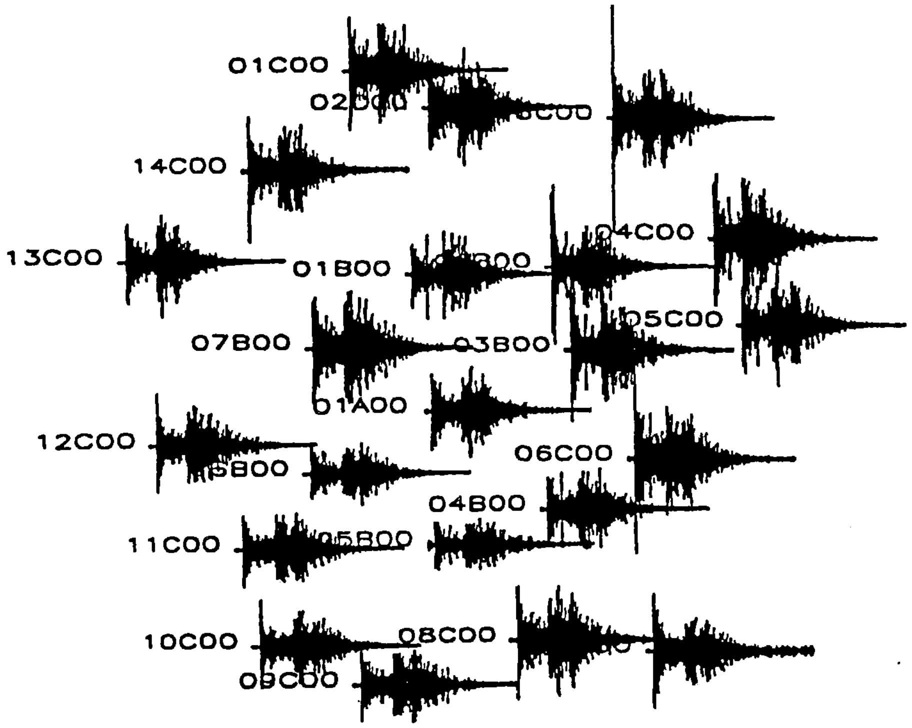


Fig. 6.5.4. KEVO recordings filtered in the 3-5 Hz band. The top trace shows the 16 August 1997 seismic event (m_b=3.5), whereas the bottom trace shows the 24 October 1990 Novaya Zemlya nuclear explosion (m_b=5.6).

NORSAR amplitude pattern

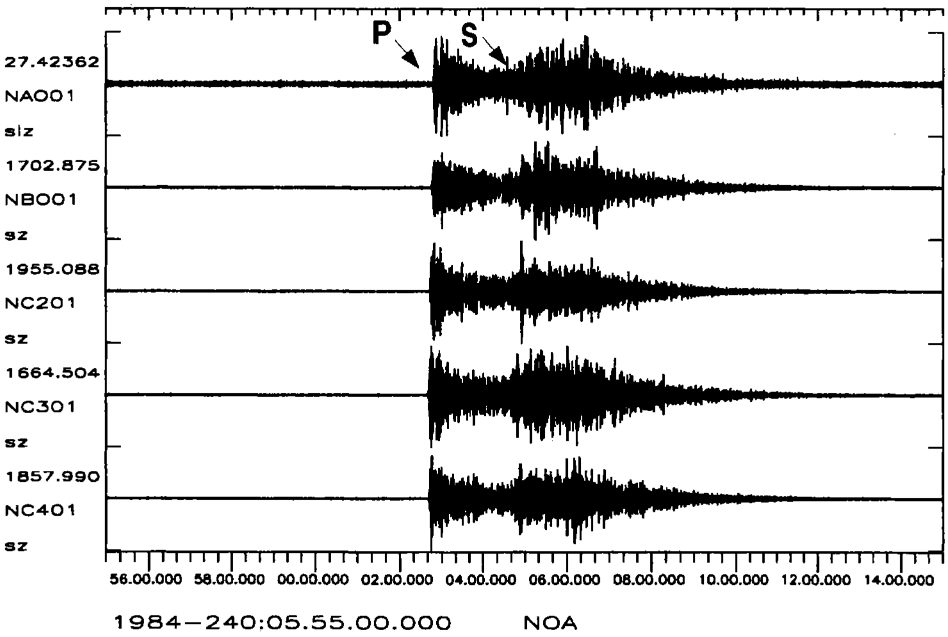


P and S waves (3.0-5.0 Hz)

Nuclear explosion in Kola (mb=4.5) 4 Sep 1972

Fig. 6.5.5. Amplitude pattern across NORSAR for the P and S phase of the Kola nuclear explosion on 4 September 1972 (distance 11 degrees). The data have been filtered in the 3-5 Hz band. Note that there is a strong variation in P/S ratios, although less than what was shown in Fig. 6.5.2 for the 1-3 Hz band.

Nuclear explosion Kola 27 August 1984 - mb 4.3
Filter 3-5 Hz



Earthquake Kola 16 June 1990- mb 4.0
Filter 3-5 Hz

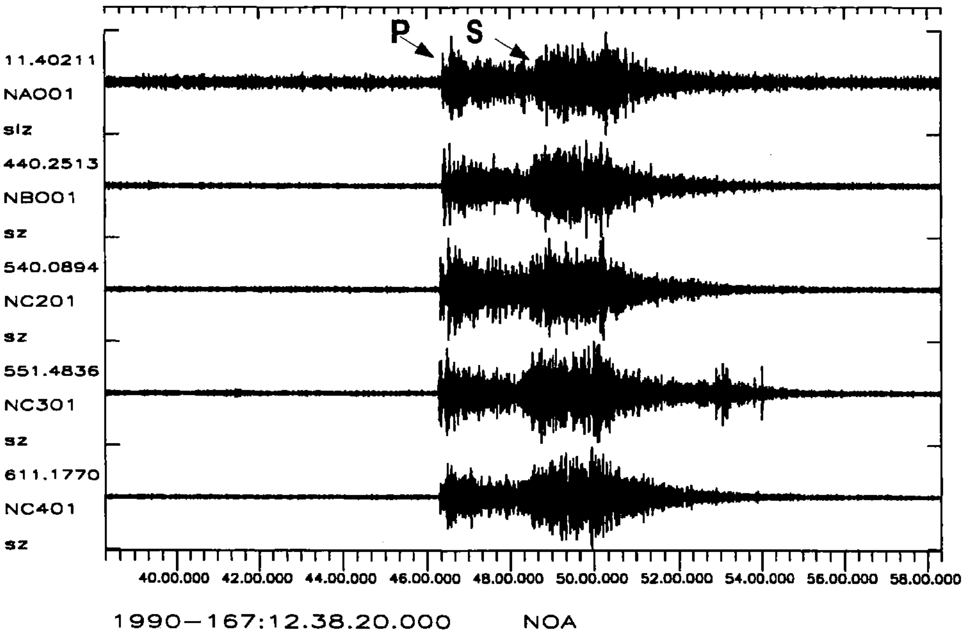


Fig. 6.5.6. Selected NORSAR traces for an earthquake in the Kola Peninsula in 1990 (felt in the Murmansk district) and the Kola nuclear explosion in 1984 (colocated with the 1972 explosion). Both are at an epicentral distance of between 11 and 12 degrees. The data have been filtered in the 3-5 Hz band.

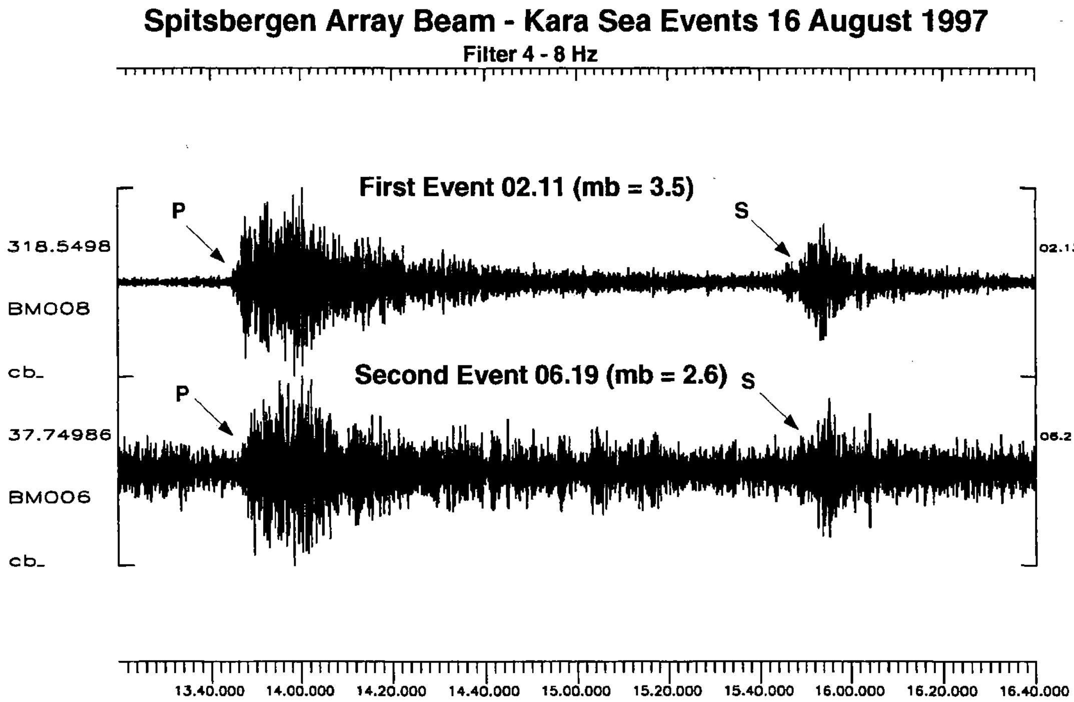


Fig. 6.5.7. Recordings by the Spitsbergen array of the two events on 16 August 1997. The traces are array beams steered towards the epicenter, and with an S-type apparent velocity in order to enhance the S-phase. The traces are filtered in the 4-8 Hz band. Note that the traces are very similar, although not identical. The scaling factor in front of each trace is indicative of the relative size of the two events.

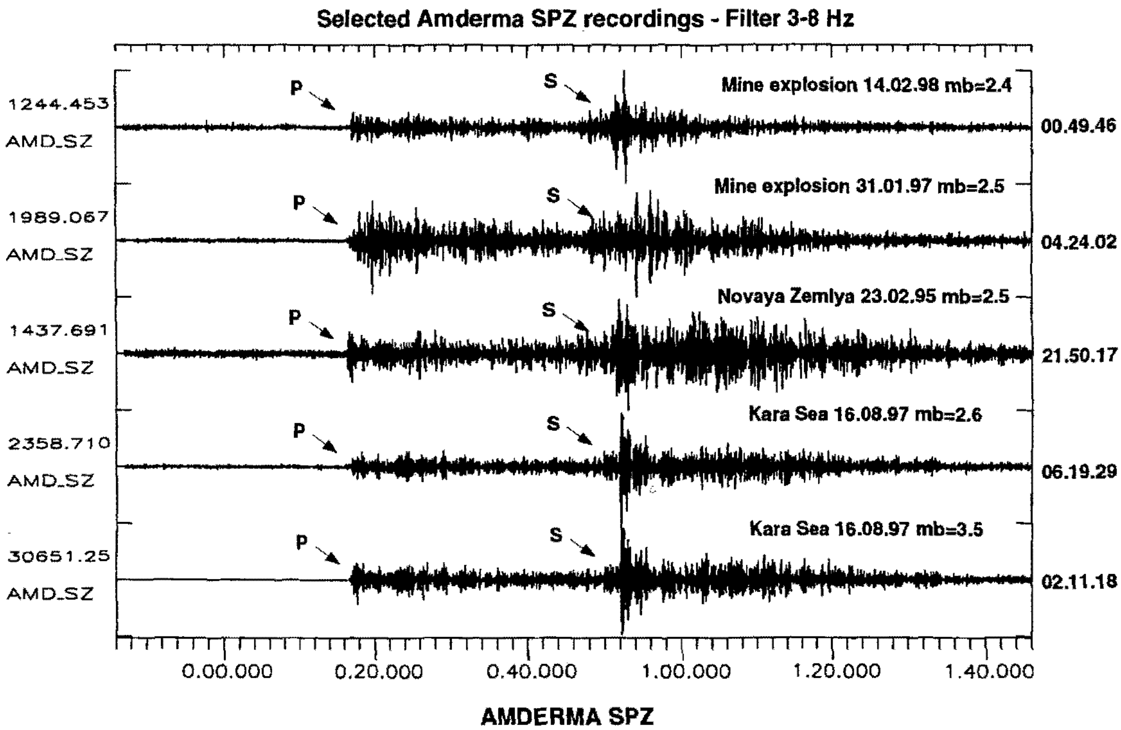


Fig. 6.5.8. Amderma vertical component recordings of five seismic events at a similar epicentral distance from the station (about 300 km). The data have been filtered in the 3-8 Hz band. The five events are the two Kara Sea events on 16 August 1997, two mining explosions in Vorkuta south of the station, 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.