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7.1 Seismic monitoring of the Barents/Kara sea region

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Introduction

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 a comprehensive nuclear test ban treaty (CTBT). This regional network, which comprises stations in Fennoscandia, Spitsbergen and NW Russia, provides a detection capability for the Barents/Kara Sea region that is close to $m_b = 2.5$, using the generalized beamforming method for phase association and initial location estimates. Several low-magnitude seismic events have been detected and located during this period, including 31 December 1992 ($m_b = 2.7$), 13 June 1995 ($m_b = 3.5$), 13 January 1996 ($m_b = 2.4$) and 16 August 1997 (m_b=3.5 and 2.6). While this demonstrates that the detection and location capability of the regional network is outstanding, source classification of these events has proved very difficult. Thus, even for the $m_b = 3.5$ events in 1995 and 1997, we have been unable to provide a confident classification of the source as either an earthquake or an explosion using available discriminants. 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. Some scientists have forwarded arguments that this event could be confidently classified as an earthquake, especially based on observed P/S ratios. In this paper 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. 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.

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 Test Ban Treaty. In particular, the task includes investigating the possibilities and limitations of utilizing the P/S ratio to characterize seismic events at low magnitudes in this region.

Research accomplished

Detection and location capability of the regional network

Seismicity studies

NORSAR has for many years been cooperating with the Kola Regional Seismological Centre (KRSC) of the Russian Academy of Sciences in the continuous monitoring of seismic events in North-West Russia and adjacent sea areas.

KRSC began its seismic network processing in 1982. Initially, this was done primarily by processing data from the KRSC network of seismological stations, but in recent years the analysis has been supplemented with data from IRIS stations (KBS, LVZ, KEV, ARU, ALE, NRI, etc.) and the Scandinavian seismic arrays (ARCESS, SPITS, FINESS, HFS, NORESS) for analyzing of the most interesting events. NORSAR has carried out similar analyses based primarily on the Scandinavian arrays, but in recent years supplemented with data provided by KRSC.

The seismicity of the Barents/Kara sea region is quite low, as discussed by Ringdal (1997). This is illustrated in Fig. 7.1.1 which shows the epicenters in northern Europe and adjacent areas determined in the Revised Event Bulletin of the GSETT-3 IDC during 1995-1997. Because of the high-quality coverage of regional arrays in Fennoscandia, a large number of seismic events (mostly mining explosions) are detected in this region. 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.

On the other hand, the figure shows that there are almost no recorded events in the region comprising the eastern part of the Barents sea, the Kara Sea, Novaya Zemlya and the northern part of Russia (excluding Kola). While the GSETT-3 network has a lower detection capability in this region compared to Fennoscandia, its capability is nevertheless around magnitude 3.0-3.5 and it is thus clear that seismic events of such magnitudes or larger occur rather infrequently in the region specified above. This is further illustrated in Fig. 7.1.2 which shows the low-magnitude events detected by the Barents regional array network since 1990. Only two additional events during 1995-97 have been located by this network.

Event location

The IASPEI-91 model is not suitable for the Barents region (Ringdal et al, 1997a), and it has therefore been necessary to study local travel-time curves using data from a set of strong explosions with known locations, including an underground calibration explosion carried out in the Khibiny Massif (29.09.1996, 350 ton), see Ringdal et al (1996).

We have attempted to fit a one-dimensional velocity model to agree with these results. This has resulted in the compilation of a model which is a combination of the NORSAR model for smaller depths (up to 200 km) and IASPEI-91 at greater depths. To validate the model we have relocated several large nuclear explosions at Novaya Zemlya, as well as the presumed earthquake on 1 August 1986 (see Asming et al, 1998). The study has shown that the locations by the regional network are within 5-10 km of the locations obtained by joint hypocentral determination (JHD) using world-wide data.

This documented consistency with precise global network locations is especially important since we are able to use the regional network to locate events far smaller than those which can be detected teleseismically. For example, the KRSC network was the only network with sufficient data to locate reliably the smallest recorded nuclear explosion on the Novaya Zemlya test site (m_b=3.8) on August 26, 1984 (Mikhailov et. al., 1996). The result is shown in Fig. 7.1.3. Our estimated epicentral coordinates of this explosion are 73.326 N, 54.763 E, thus placing the event (as expected) at the nuclear test site.

The table of low-magnitude events in Ringdal (1997) has been supplemented by more recent information as summarized in Table 7.1.1. The most important new information concerns the new location of the 26 August 1984 nuclear explosion mentioned above, a confirmation of the 25 August 1987 event as a 1 kiloton chemical explosion (Khristoforov, 1996), and the two seismic events on 16 August 1997, the second of which was located by Ringdal et al (1997b) (see also Richards and Kim, 1997).

Table 7.1.1. Low magnitude (mb<5.0) seismic events in the NZ region since 1980

Date/time	Location	m_b	Comment
26.08.84/ 03.30.00	73.326 N, 54.763 E	3.8	Located by Asming et al (1998)
01.08.86/ 13.56.38	72.945 N, 56.549 E	4.3	Earthquake according to Marshall et.al. (1989)
25.08.87 / 14.00.00	73.380 N, 54.780 E	3.2	Chemical explosion-974 ton (Khristoforov, 1996)
12.31.92/ 09.29.24	73.600 N, 55.200 E	2.7	Located by Scandinavian regional network
13.06.95/ 19.22.38	75.170 N, 56.740 E	3.5	Reported in REB, relocated by Ringdal (1997)
13.01.96/ 17.17.23	75.240 N, 56.660 E	2.4	Not in REB, located by Ringdal (1997)
16.08.97 02.11.00	72.510 N, 57.550 E	3.5	Reported in REB, relocated by Ringdal et al (1997b)
16.08.97 06.19.10	72.510 N, 57.550 E	2.6	Not in REB, located by Ringdal et al (1997b)

The smallest of the two events on 16 August 1997 was, as mentioned above, first reported by NORSAR, and represents a rather interesting example of low-level detection. Only one of the Fennoscandian stations (Spitsbergen) had an automatic detection of this event, and only the P-phase was detected. After analysis at NORSAR and KRSC, we quickly succeeded in locating this event on the basis of Spitsbergen P and S (visually detected, see Fig. 7.1.4), and a visual confirmation of both P and S at Kevo. Some weeks later, the Amderma data tapes became available, and the event could be further confirmed as being located at almost exactly the same point as the first event (Fig. 7.1.5 and 7.1.6). The SNR of both events as recorded by Amderma is remarkably high.

Study of P/S ratios observed at NORSAR

NORSAR recordings of Novaya Zemlya events

The NORSAR large array has an extensive database of recordings from events near Novaya Zemlya, including some nuclear explosions with magnitudes similar to those of the 16 August event and the nearby presumed earthquake of 1 August 1986 (Ringdal, 1997). It is therefore of interest to compare the P/S ratios for these events, as recorded by individual sensors in the array. In the following, we give some comments on these observations.

Figures 7.1.7 and 7.1.8 show recordings at the center seismometer of each of 5 NORSAR subarrays for the presumed earthquake of 1 Aug 1986 and the nuclear explosion of 9 Oct 1977. These events have similar magnitudes (4.3 and 4.5) and are also at similar epicentral distance (~20 degrees) and azimuth.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 across the array for both events.
- For each sensor pair, the P/S ratios are quite similar, although P/S is slightly smaller on average for the presumed earthquake
- The variability in the P/S ratios is dominated by strong P-wave focusing effects across NORSAR

While it is seen that the P/S for the presumed earthquake is generally slightly smaller than for the explosion (as might be expected), it is in fact *larger* for one of the sensors (NBO00).

It may be concluded from these two figures that P/S in this frequency band is not a very powerful discriminant when using data recorded at a single array or station. Clearly, better performance might be expected if data from a large range of azimuths are available, but the overall performance of this discriminant is still questionable. Recent studies for Central Asia (Hartse et al, 1997), have shown that the P/S discriminant for that region appears to be 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 4 Hz, so we are restricted to considering the lower frequencies for Novaya Zemlya events.

NORSAR recordings of a Kola nuclear explosion

In order to illustrate the behavior of the P/S discriminant at higher frequencies (3-5 Hz), we show in Fig. 7.1.9 the pattern of P/S ratios across the full NORSAR array (22 subarrays, center sensors) for the nuclear explosion in the Kola Peninsula on 4 September 1972. This explosion had an epicentral distance of only about 10 degrees, and consequently we see a fair amount of high-frequency energy both for the P and the S phase.

It is clear from this figure that the P/S ratio varies considerably across NORSAR even in the frequency range 3-5 Hz. Fig. 7.1.10 shows a comparison of the two neighboring subarrays 02C and 03C, situated less than 30 km apart. The relative difference in P/S ratio is about a factor of

4 between these two seismometers. Thus, any P/S ratio factor at a single station of 4 or less will not be sufficient to separate different seismic sources.

Source scaling of the P/S ratio

To our knowledge, only one station at a regional distance, the NORSAR array, has available digital recordings of both large and small nuclear explosions from Novaya Zemlya. It may be 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 7.1.11 shows a selection of nuclear explosions recorded at 01A01, with magnitudes ranging from 3.8 (26 August 1984) to 6.0 (10 August 1978). The data have been filtered in the band 1.0-3.0 Hz. There is a remarkable and systematic increase in the P/S ratio with increasing magnitude. This demonstrates that comparing the P/S ratios of large and small events could easily give misleading conclusions.

An illustration, in an expanded scale, for two of these explosions is shown in Figure 7.1.12. The difference between these two explosions is in fact rather similar to the differences seen for the Kevo recordings shown by Richards and Kim (1997), which likewise compares a large and a small seismic event. Admittedly, the Kevo recordings are in a higher frequency band, but there is clearly reason for caution in interpreting the Kevo plots based on the results discussed above.

Because of the large epicentral distance of NORSAR from the test site, there is no appreciable high-frequency energy in the NORSAR recordings. Consequently, we have not been able to assess the possible source scaling of the P/S ratio for frequencies of 3 Hz and above. It would seem reasonable that such a source scaling might in fact be present also at these higher frequencies, but this needs to be further studied.

Conclusions and recommendations

This paper demonstrates that the excellent capabilities of the IMS network for the Barents/Kara Sea region can be further improved by taking advantage of the regional seismic network in northern Europe. The paper presents analyses of some other interesting seismic events occurring in the region in recent years, including the small (m_b=3.8) nuclear explosion on 26 August 1984. Further work should be carried out, especially using data from the Amderma station, to obtain additional information on the seismicity of the Barents/Kara sea region at low event magnitudes.

Case studies, some of which are discussed briefly in this paper, have demonstrated that traditional regional discriminants are not effective for separating between seismic source types at low event magnitudes in this region. In particular, the authors conclude that the P/S ratio, even at high frequencies, is rather unstable and should not be relied upon for regional event discrimination. The authors of this paper disagree with those scientists who have claimed 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 seismological evidence to confidently classify these events as explosions. In the opinion of these authors, the source type of these two events remains unresolved.

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Ringdal, F., Kremenetskaya E., V. Asming, I. Kuzmin, S. Evtuhin and V. Kovalenko (1996): Study of the calibration explosion on 29 September 1996 in the Khibiny Massif, Kola Peninsula. *Semiannual Technical Summary 1 April - 30 September 1996*, NORSAR Sci. Rep. 1-96/97, Kjeller, Norway.

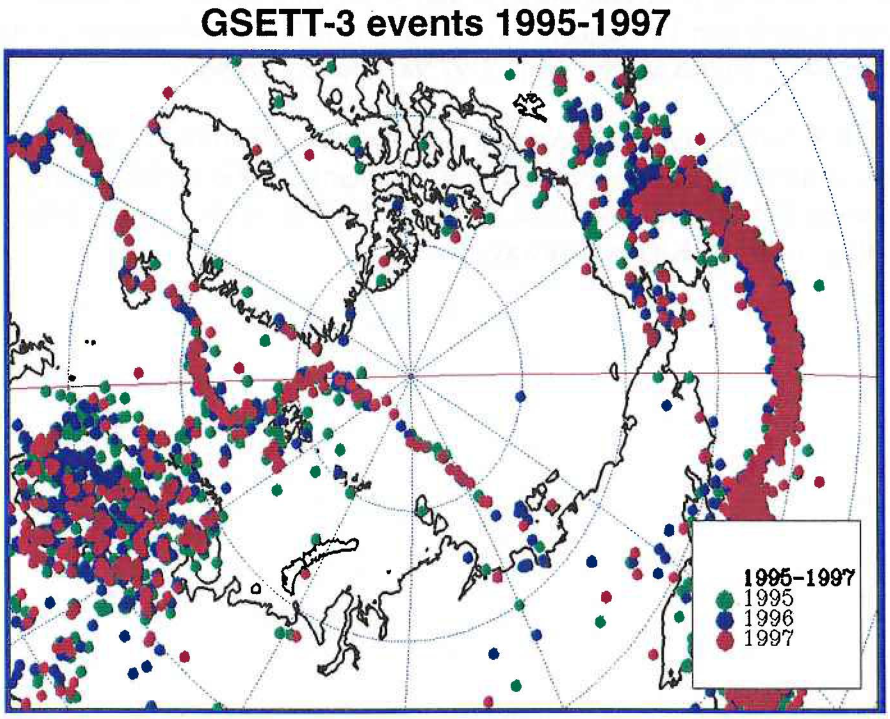


Fig. 7.1.1. Epicenters in northern Europe and adjacent areas determined in the Revised Event Bulletin of the GSETT-3 IDC during 1995-1997. Note the large number of seismic events (mostly mining explosions) in Fennoscandia and the high seismicity in the Spitsbergen area and offshore Norway (mostly earthquakes). Also note the low observed seismicity in the Barents/Kara sea region.

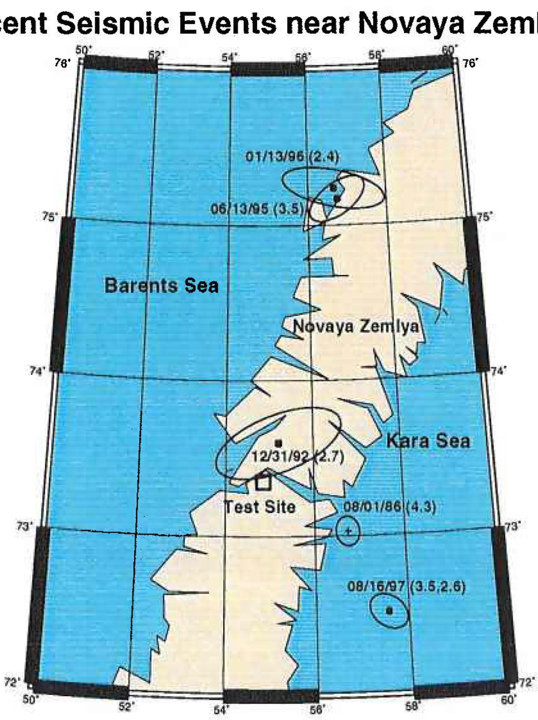


Fig. 7.1.2. Location of some recent low-magnitude seismic events near Novaya Zemlya using data from the stations in the regional array network in northern Europe.

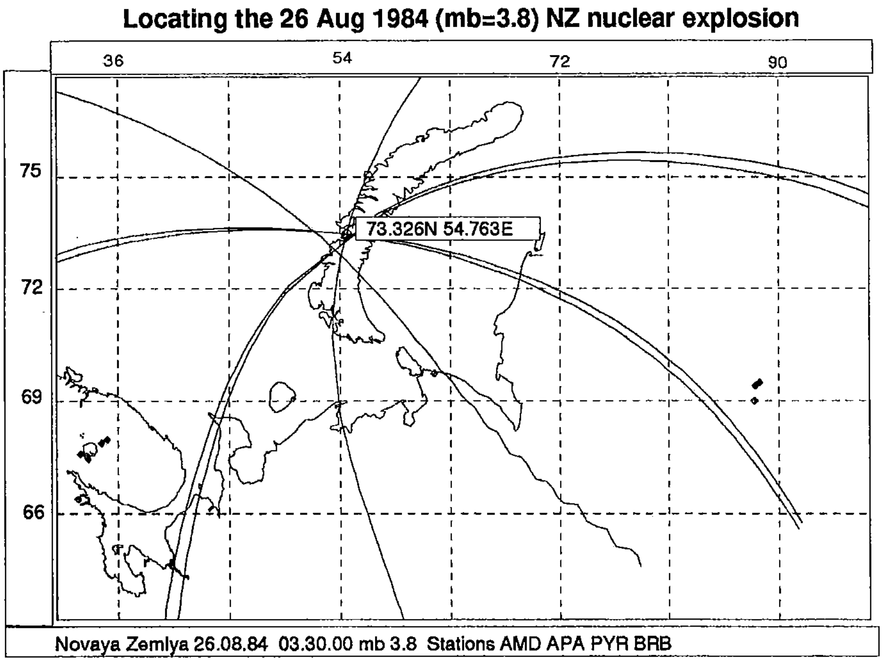


Fig. 7.1.3. Location of the smallest recorded Soviet nuclear explosion (26 August 1984, m_b=3.8) at Novaya Zemlya using data by the stations PYR, BRB, APA and AMD.

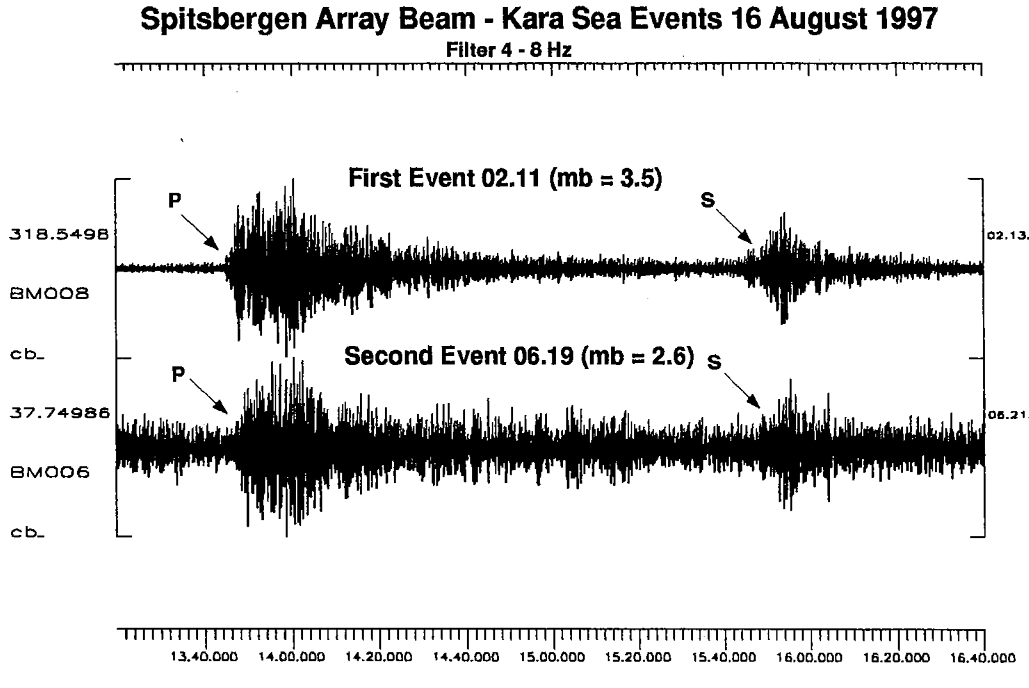


Fig. 7.1.4. Recordings by the Spitsbergen array of the two events on 16 August 1997. The traces are array beams steered towards the epicenter, and with an S-type apparent velocity in order to enhance the S-phase. The traces are filtered in the 4-8 Hz band. Note that the traces are very similar, although not identical. The scaling factor in front of each trace is indicative of the relative size of the two events.

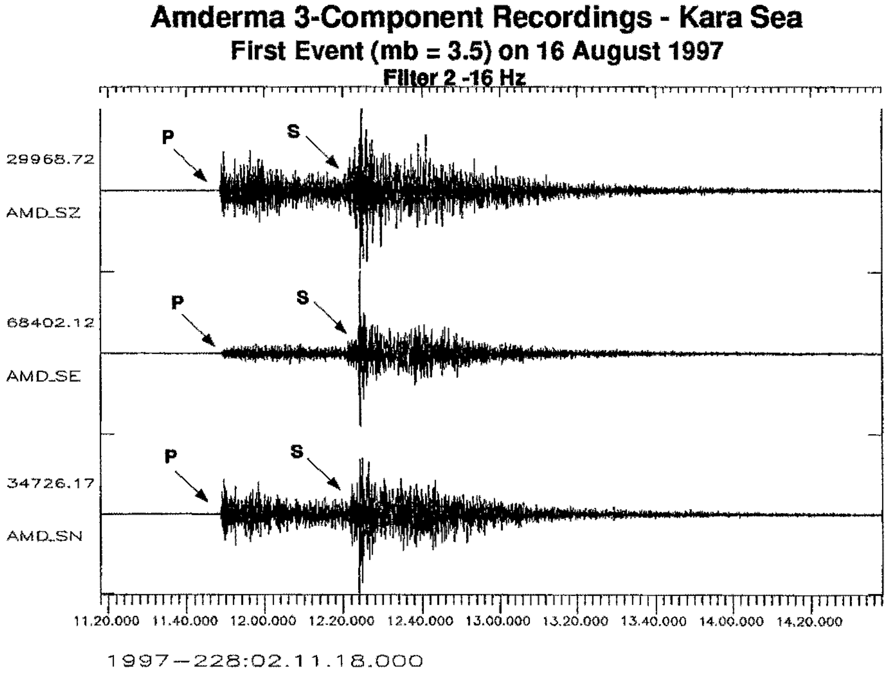


Fig 7.1.5. Recordings by the Amderma 3-component center station of the first seismic event on 16 August 1997. The traces are filtered in the 2-16 Hz band. The scaling factor in front of each trace is indicative of the event size.

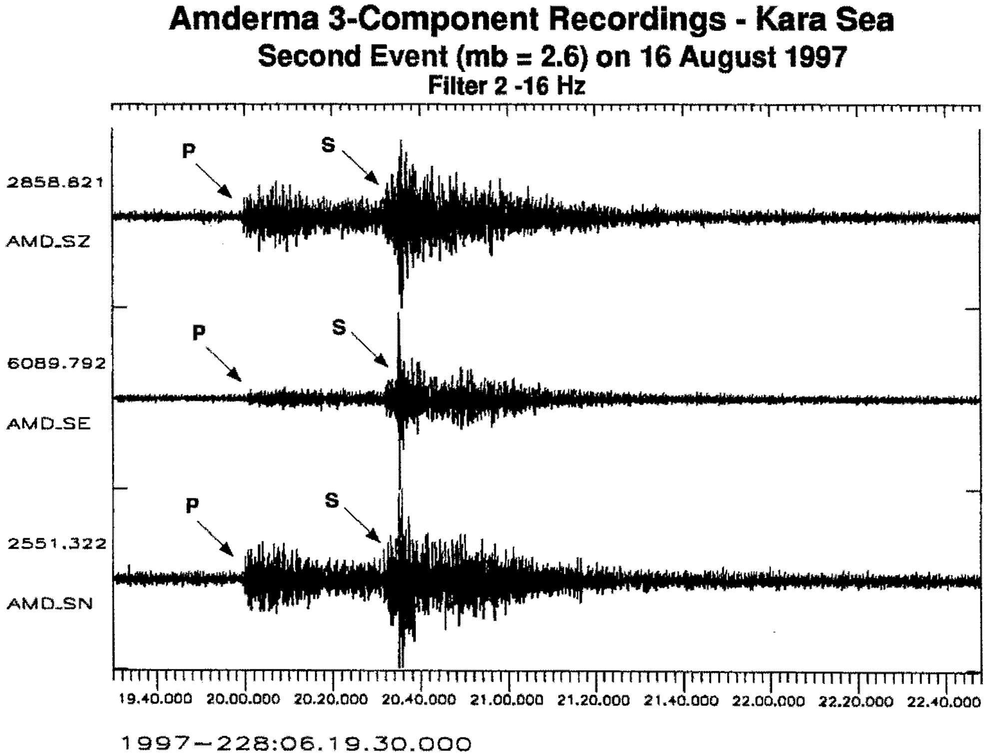


Fig 7.1.6. Recordings by the Amderma 3-component center station of the second seismic event on 16 August 1997. Note the high SNR even for this small (m_b=2.6) event.

Earthquake (mb=4.3) 1 Aug 1986 (1.0-3.0 Hz)

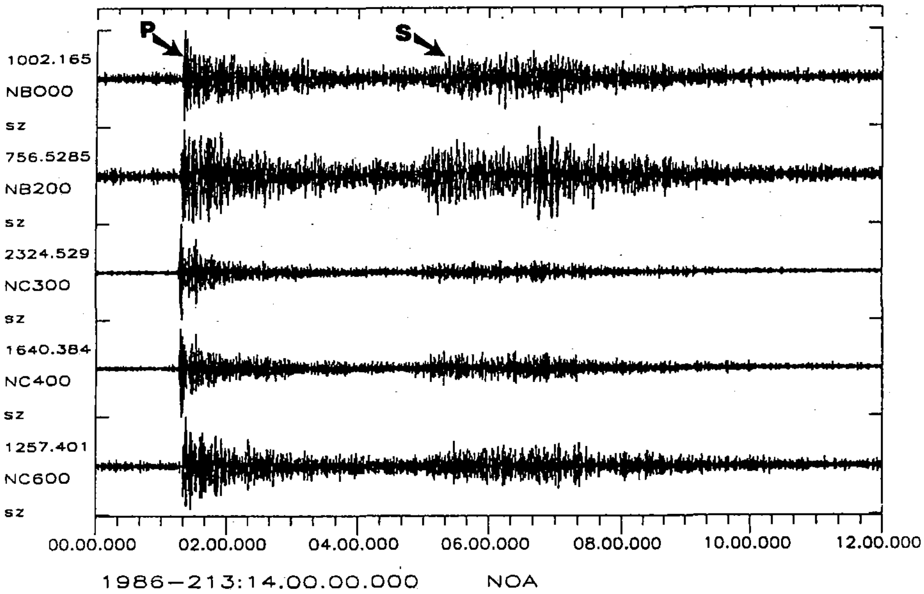


Fig. 7.1.7. Selected NORSAR SP seismometer recordings for the Novaya Zemlya presumed earthquake of 1 August 1986. Note the strong variation in relative strength of the P and S phases across the array.

Nuclear explosion (mb=4.5) 9 Oct 1977 (1.0-3.0 Hz)

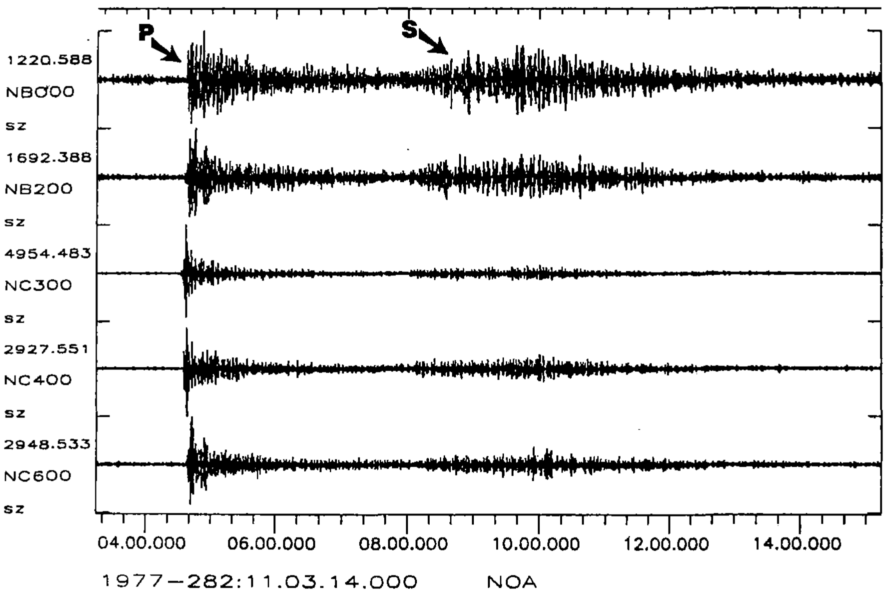
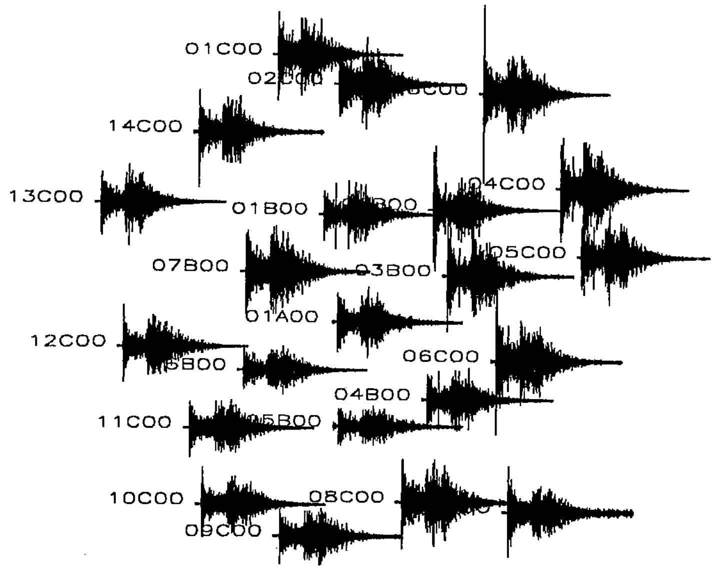


Fig. 7.1.8. Selected NORSAR SP seismometer recordings for the Novaya Zemlya nuclear explosion of 9 October 1977. Note the similarity to Fig. 7.1.7 as to the relative strength of P and S phases pair-wise for the same instruments, as well as the similarity in variation across the array.

NORSAR amplitude pattern



P and S waves (3.0-5.0 Hz)

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

Fig. 7.1.9. Amplitude pattern across NORSAR for the P and S phase of the Kola nuclear explosion on 4 September 1972 (distance 10 degrees). The data have been filtered in the 3-5 Hz band. Note the strong variation in P/S ratios.

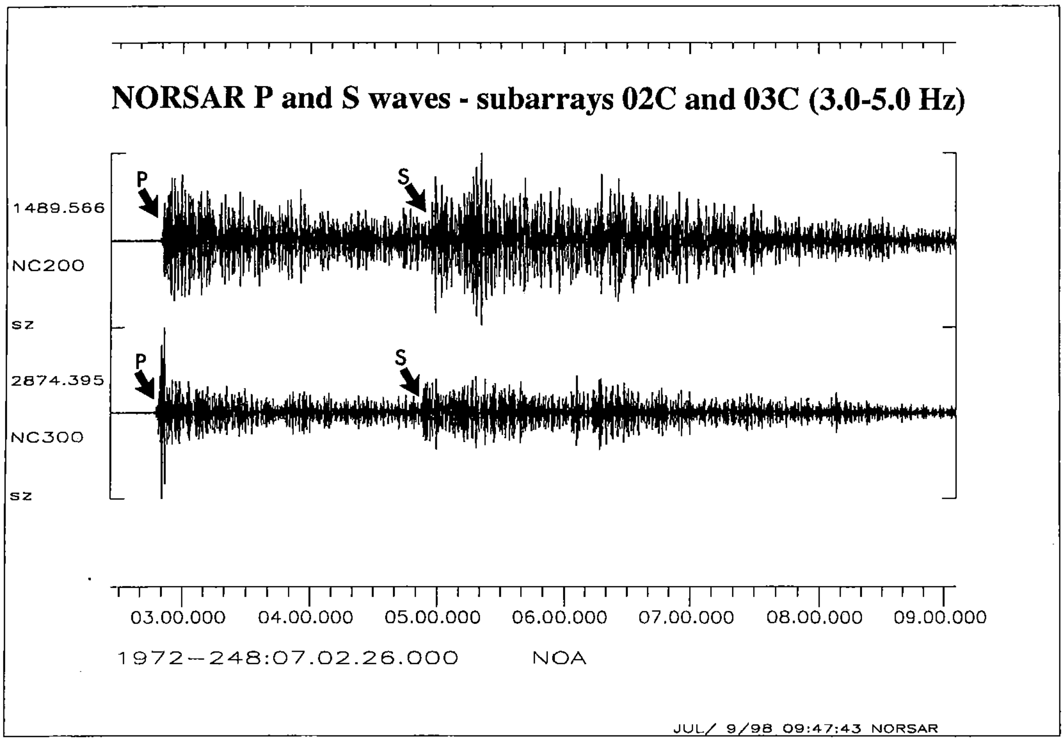


Fig. 7.1.10. NORSAR recordings at subarrays 02C and 03C (center sensors) of the Kola Peninsula nuclear explosion in Fig. 7.1.9 (filter band 3-5 Hz). The P/S ratios differ by a factor of 4.

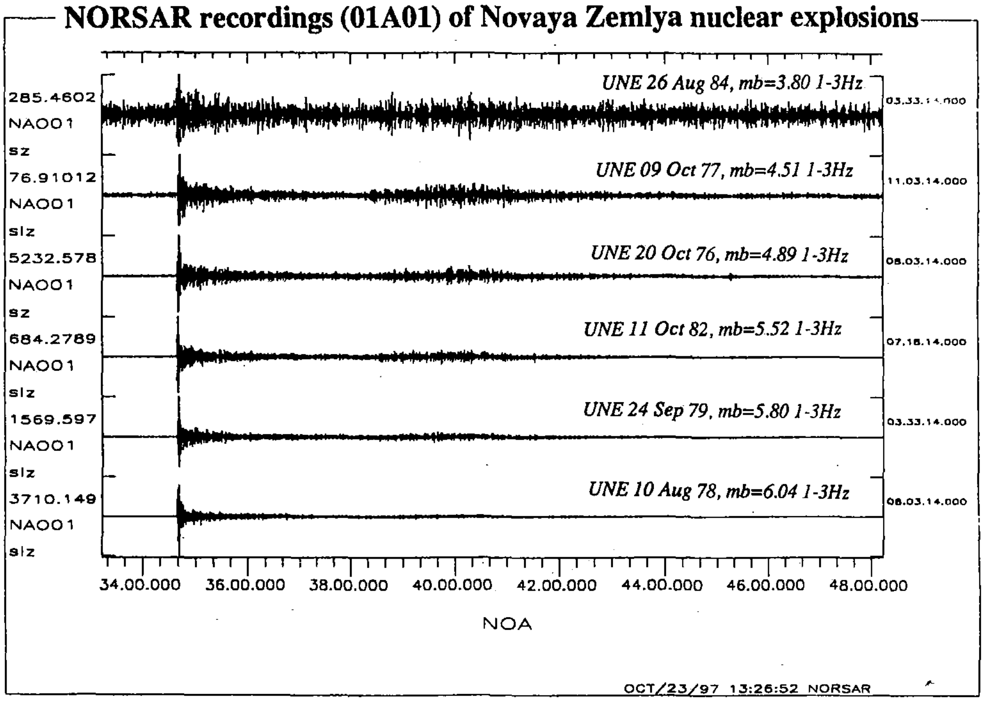


Fig. 7.1.11. NORSAR recordings (seismometer 01A01) of six Novaya Zemlya nuclear explosions of varying magnitudes. The data have been filtered in the 1-3 Hz band. Note the systematic increase in P/S ratio with increasing magnitude.

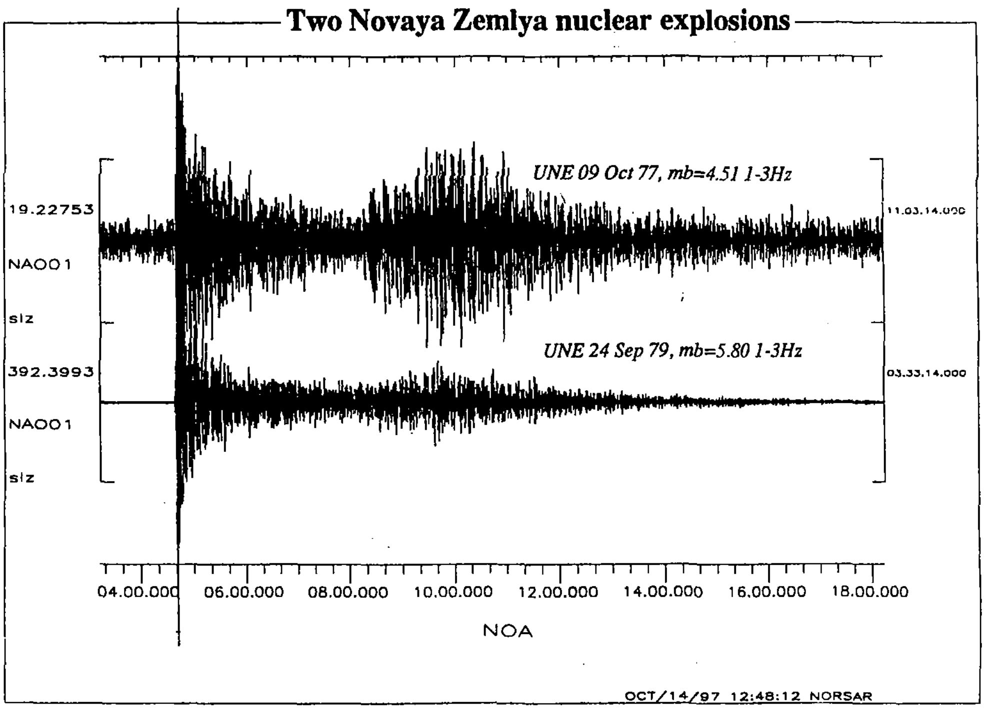


Fig. 7.1.12. NORSAR recordings (seismometer 01A01) of two of the Novaya Zemlya nuclear explosions shown in Fig. 7.1.11. The top trace shows a small explosion (m_b=4.5), whereas the bottom trace shows a large explosion (m_b=6.0). The vertical scale has been amplified to highlight the difference in P/S ratio between the two events.