NORSAR

NORSAR Scientific Report No. 1-2002

Semiannual Technical Summary

1 July - 31 December 2001

Frode Ringdal (ed.)

Kjeller, February 2002

6.4 Monitoring the seismicity of the Spitsbergen Archipelago

6.4.1 Introduction

The work described in this paper is a part of the KRSC - NORSAR cooperative activity aimed at a detailed study of seismicity in the Spitsbergen region. Part of the motivation for the study is to improve the quality and availability of well-located reference events (“ground truth data”) for location calibration purposes, and to develop local velocity models for improved location accuracy.

Spitsbergen and the adjacent areas are parts of a geologically complex region with moderate to high seismicity. The main seismicity in the area is associated with the North-Atlantic Ridge, and especially the Knipovich Ridge situated at a distance less than 400 km from the archipelago (Sundvor and Eldholm, 1979, Mitchell et. al., 1990). In addition, some coal mines are located in the area of Spitsbergen, causing occasional induced seismicity. In this study we describe some of our observation of unusual features of seismic events and wave propagation in the area and our preliminary attempts to develop local travel time models.

6.4.2 Station Network and Geology

The Spitsbergen (Svalbard) Archipelago is characterized by a very complicated geological structure. The simplified map in Fig. 6.4.1 shows the delineation of the four major geologic units:

- local Tertiary basin sediments;

- Carboniferous through Cretaceous platform cover sequence;

- Devonian basin sediments;

- metamorphic basement rocks;

The complexity of geological structure and underwater topography causes difficulties in location and interpretation of seismic events. We will return to some illustrations of this problem later.

Local seismicity has been observed in Spitsbergen for a considerable time by a seismic network comprising digital and analog seismic stations (see Fig. 6.4.1). The analog stations BRB and PYR were operational from about 1976 to 1990, and were then closed down. Recently, a digital station has been reinstalled at the BRB location. The station KBS operated as an analog station until the 1980s, and is now a digital broad-band station. The array SPI is part of the International Monitoring System, and has been in operation since 1992.

Maps of seismic events in and near Spitsbergen for the period 1964 - 2001 are shown in Fig. 6.4.2. The locations for years 1964-1998 are taken from ISC bulletins whereas those for 1998-2001 are taken from NORSAR Reviewed Regional Seismic Bulletin. Even though the NORSAR regional bulletin covers a much shorter time interval than the ISC bulletin, the observed seismicity patterns in the two plots are remarkably similar. In particular, a segment of the mid-atlantic ridge to the west can be observed, and pronounced seismic zones in Nordaustlandet (northeast) and Heerland (southeast) can also be identified on both maps.

The temporary seismic network shown in Fig. 6.4.1 was installed in Spitsbergen in 1979 (Bungum et. al, 1982) and operated during that year. A map of seismic events detected and located by this network is shown in Fig. 6.4.3.

6.4.3 Travel time model

In 2001 a digital seismic station GBV 316B was installed in Barentsburg (Kremenetskaya et. al, 2001b). A large number of mining rockbursts and explosions have been recorded (distances 2-5 km from the station). Based on these events we have estimated P and S velocities in the upper layer and obtained values of 4.54 and 2.52 km/sec, respectively. Such values are usual for sediments.

We used the calibration event 28.01.2001 with known coordinates (78.066 N, 14.324 E) to extend the model to larger distances. This event, which has been described by Kremenetskaya et. al (2001b), was well-recorded by the SPI and KBS stations (Fig 6.4.4).

We tried to modify the BARENTS travel time model adding a layer of sediments with the velocities mentioned above and fitting the depth of this sedimentary layer as well as the Moho depth. As a preliminary result, which seems to provide the best fit to the data, we obtained the following:

Table 6.4.1. Velocity model SPITS0

Depth (km)	Vp (km/s)	Vs (km/s)
0-2	4.54	2.52
2-10	6.20	3.44
10-30	6.70	3.72
30-55	8.10	4.50
55-210	8.23	4.57
>210	Same as IASPEI 91	

This model is similar, although not identical to the model presented in Kremenetskaya et. al. (2001a). We re-located the event using the BARENTS model and the SPITS0 model. The results are shown in Table 6.4.2, and demonstrate that the location error decreases from 16 km using the Barents model to less than 1 km using the SPITS0 model. While this kind of performance cannot be expected on a general basis, it is nevertheless encouraging.

Table 6.4.2. Re-locating the calibration event 28.01.2001

Model	Latitude	Longitude	Error (km)
Ground Truth	78.066	14.324	0.0
SPITS0	78.072	14.317	0.7
BARENTS	77.93	14.045	16

6.4.4 Earthquakes in Heer Land

The Norwegian Government has recently approved the operation of a new coal mine in the Svea area close to the Heerland seismic zone. In a report to the Norwegian Parliament (JD Report No. 9 (1999-2000)) it was stated that “rockfalls” occurred several times in the Svea mine during experimental operation in 1997-1998. To clarify the situation regarding local seismicity we relocated a set of seismic events that occurred in this area using the travel time model mentioned above. The results are shown in Fig. 6.4.5 and Table 6.4.3.

Table 6.4.3. List of relocated Heer Land earthquakes

Number	DATE	TIME	Latitude	Longitude	ML
1	1997/04/28	06.09:48	77.7	17.1	1.8
2	1997/05/29	06.42:41	77.7	17.8	2.0
3	1998/02/03	05.40:33	77.8	17.6	1.5
4	1998/05/17	19.55:57	77.8	17.6	1.5
5	1998/09/10	21.57:37	77.8	18.1	1.8
6	1998/10/13	11.10:45	77.8	18.0	1.8
7	1998/11/11	07.37:37	77.8	17.9	1.8
8	1998/11/26	05.50:42	77.9	17.9	3.0
9	1998/11/26	14.12:36	77.7	17.7	1.9
10	2001/07/31	11.59:20	77.8	17.1	2.1
11	2002/01/20	08.53:21	77.9	16.9	1.6

Although the location errors here could amount to several kilometers (see below) it is possible to see that most of the earthquakes occurred in a compact zone. To contour this zone more exactly it would be desirable to install a set of additional seismic stations. This would also be useful in recording possible rockbursts associated with future mining operations.

6.4.5 Limits of the model application and possible sources of location errors

There are some indirect arguments in favor of the SPITS0 model in regions of Svalbard covered by sediments. Thus, some geologists estimate the thickness of sediments to be up to 2 km. In addition, the estimates of apparent velocities computed by sensors of the SPI array for very close events (2-5 km from the array) are in the range 4.4 - 5.2 km/sec which is more or less in agreement with the model.

It is clear that in a place with such complicated geological structure as Svalbard one should be very careful when using 1-D models. Thus, it is impossible to use the 1-D model SPITS0 to locate Svalbard events with more distant stations like ARCESS. An example is shown in Fig. 6.4.6.

One more striking example of location problems is the earthquake which occurred on 29.12.2001 at 14.24 GMT in Nordaustlandet. It was recorded by KBS and SPI, and the recordings are shown in Fig. 6.4.7.

Multiple onsets of P waves are clearly seen, especially for the KBS recording, where one can identify up to 4 different P onsets. In contrast to typical Pn and Pg onsets, say, for Khibiny explosions recorded at ARCESS, the amplitudes of the P onsets for this event are very different.

To explain such features, careful modelling, probably 3-dimensional, is required. We might expect that if the P wave has several onsets, then the S wave should have the same, too. But we have not been able to find them in the waveforms. The reason might be that first S onsets are masked by the coda of the P waves. It means that the error of estimation of time difference between P and S onsets could amount to as much as 5-10 seconds or more. And, therefore, the location error by a single station could amount to many tens of kilometers.

The result of locating this event is shown in Fig. 6.4.8. Lines of location do not cross at the same point. The backazimuth calculated by the SPI array using beamforming is significantly different from that corresponding to the estimated location.

For weaker events these first weak onsets of P waves might be unnoticeable, which of course could influence the location accuracy.

After having looked through recordings for events in typical seismic regions of the Svalbard Archipelago, we have found that such weak first P onsets are typical for almost all areas, except some events occurring in the ridge zone to the West of Svalbard.

6.4.6 Anomalies in P/S ratios

The complex geological conditions in the Svalbard area manifest themselves in extremely high variability of P/S ratios. We have noticed this in particular for events occurring in the ridge zone and around Bear Island.

Thus, for example, KBS recordings of two earthquakes occurring very closely to each other are shown in Fig. 6.4.9. (3.12.2001 at 1.45:49 GMT, 78.33 N, 8.24 E and 3.01.2002 at 22.50:40 GMT, 78.4 N, 7.6 E). The P/S ratios for these two events differ by about a full order of magnitude, even though the events are very close together and of similar magnitudes.

6.4.7 Conclusions

1. A preliminary 1-dimensional travel time model has been developed for Spitsbergen.
2. Taking into account the very complicated geology and underwater topography in and near Spitsbergen, it is necessary to use a 3-dimensional model or some kind of regionalization for improving locations;
3. Multiple onsets of P and probably S waves can strongly increase location errors. Such onsets are not uncommon for Spitsbergen earthquakes;
4. The complexity of the geology manifests itself also in a great variability of P/S ratios of earthquakes in the Spitsbergen region. Study of this variability could help to “calibrate”

the P/S ratio as a discriminant between earthquakes and explosions or find conditions under which such discriminants fail;

5. Study of all the unusual phenomena mentioned above would require the development of more advanced techniques for analysis of seismic events.

E. Kremenetskaya
S. Baranov
V.E. Asming
F. Ringdal

References

Asming, V.E., E.O. Kremenetskaya & F. Ringdal (1998): Monitoring seismic events in the Barents/Kara Sea region, *Semiannual Technical Summary, 1 October 1997 - 31 March 1998*, NORSAR Sci. Rep. 2-97/98, Norway.

Bungum, H, B.J. Mitchell and Y. Kristoffersen (1982): Concentrated earthquake zones in Svalbard, Tectonophysics, 82, 175-188.

Kremenetskaya, E., V. E. Asming and F. Ringdal (2001a): Seismic location calibration of the European Arctic. *Pure and Applied Geophysics*, 158 No. 1-2, 117-128

Kremenetskaya E., S. Baranov, Y. Filatov, V. Asming and F. Ringdal (2001b): Study of seismic activity near Barentsburg mines (Spitsbergen). In: Semiannual Tech. Summ., 1 October 2000 - 31 March 2001, NORSAR Sci. Rep. 2-2000/2001, Kjeller, Norway.

Stortingsmelding nr. 9 (1999-2000) Svalbard, JD Report No. 9 to the Norwegian Parliament (1999-2000).

Mitchell, B.J., H. Bungum, W.W. Chan and P.B. Mitchell(1990): Seismicity and present-day tectonics of the Svalbard region. Geophys. J. Int., 102, 139-149.

Sundvor E. and O. Eldholm (1979): The western and northern margin off Svalbard. *Tectonophysics*, 59, 239-250.

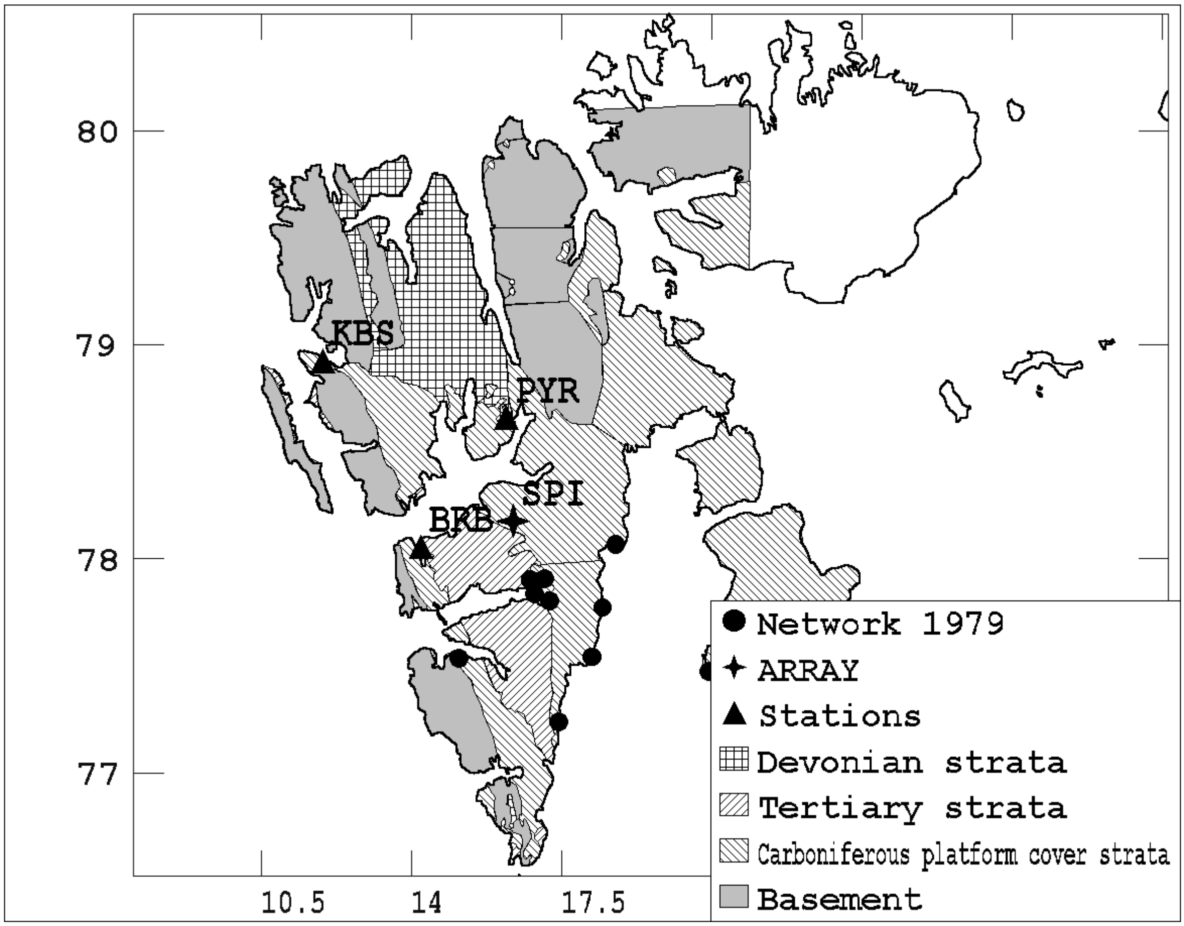

Fig. 6.4.1. Geology of the Spitsbergen Archipelago. Location of seismic stations are indicated.

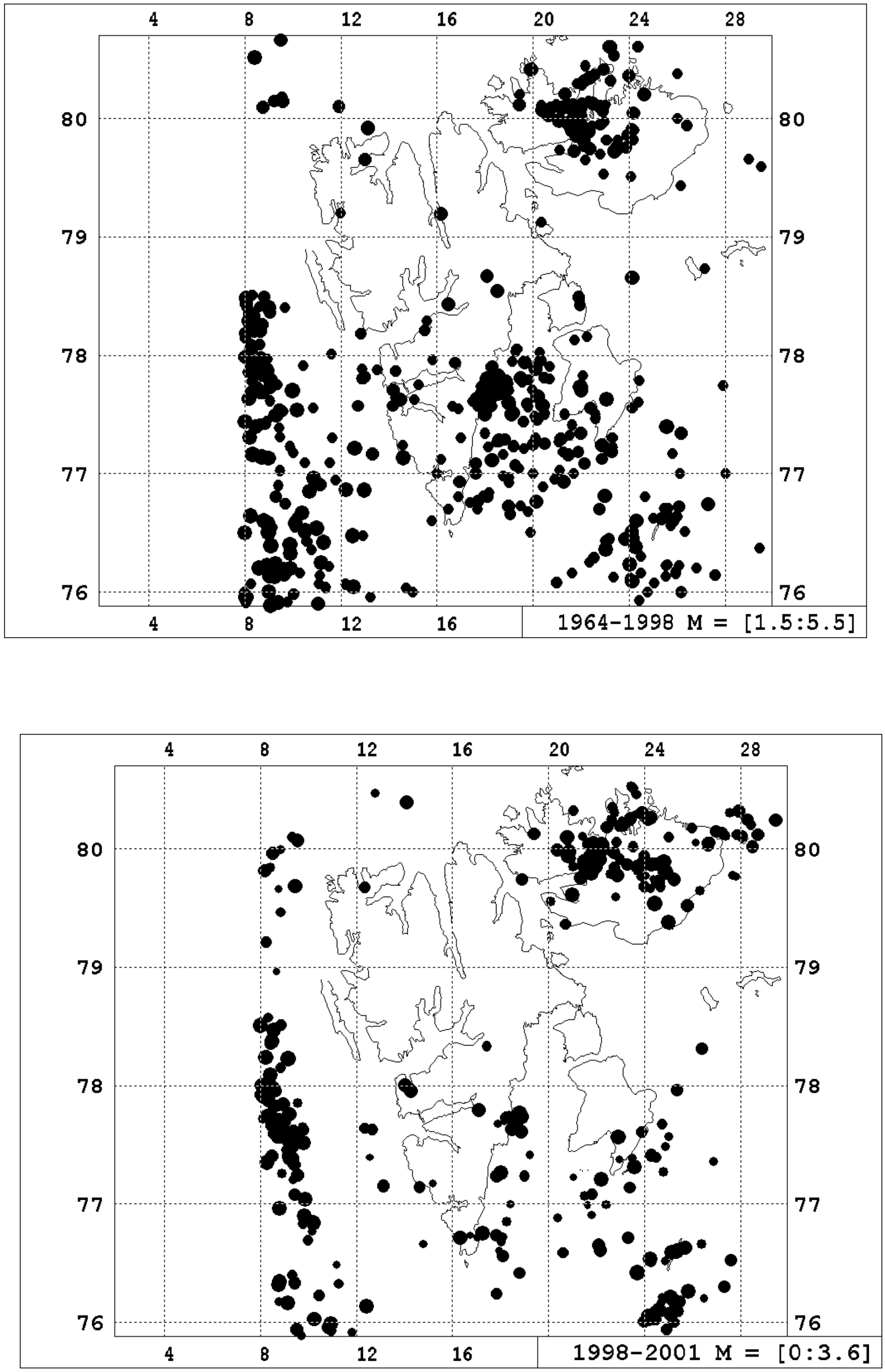

Fig. 6.4.2 Seismicity of Spitsbergen during 1964-1998 using ISC data (top) and during 1998-2001 using NORSAR Reviewed Bulletins (bottom).

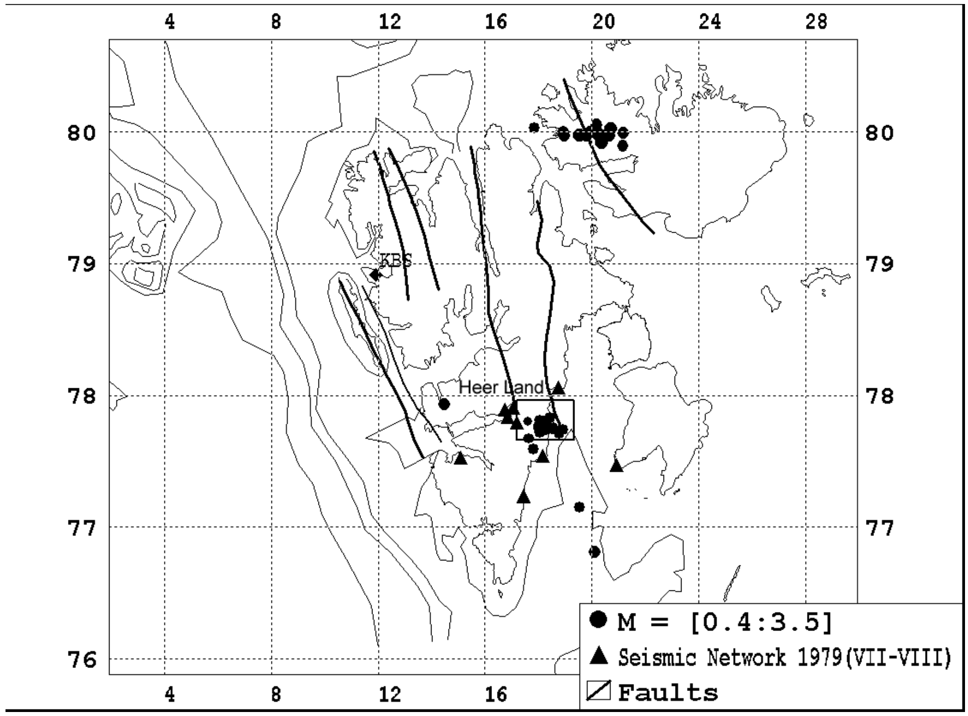

Fig. 6.4.3.Seismic events detected and located by the temporary network in 1979.

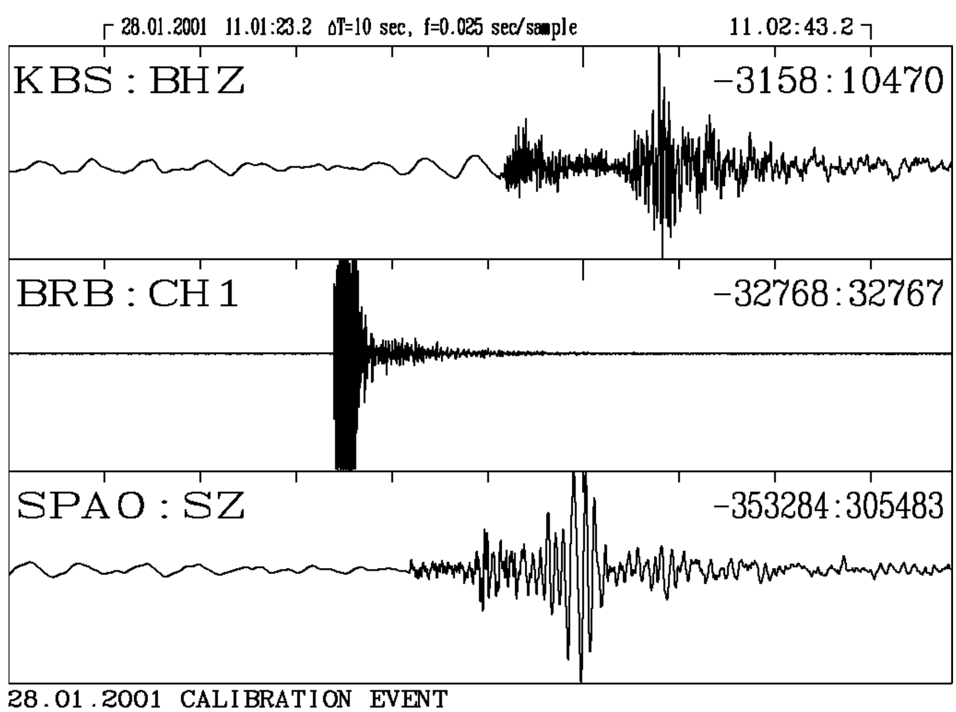

Fig. 6.4.4. Recordings of the calibration event 28.01.2001.

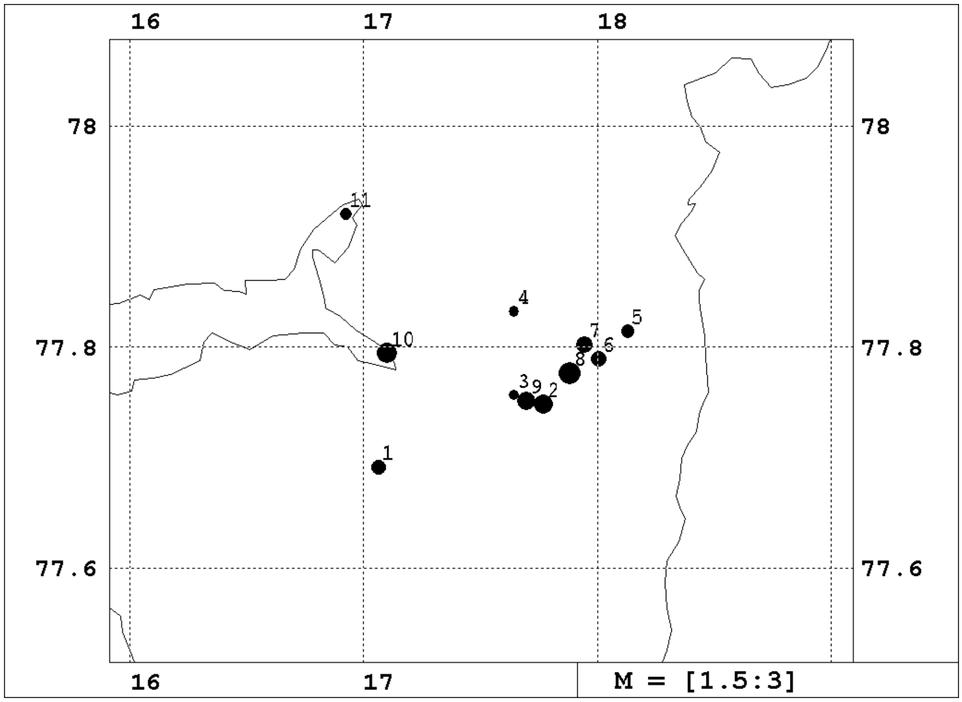

Fig. 6.4.5. Location of Heerland earthquakes.

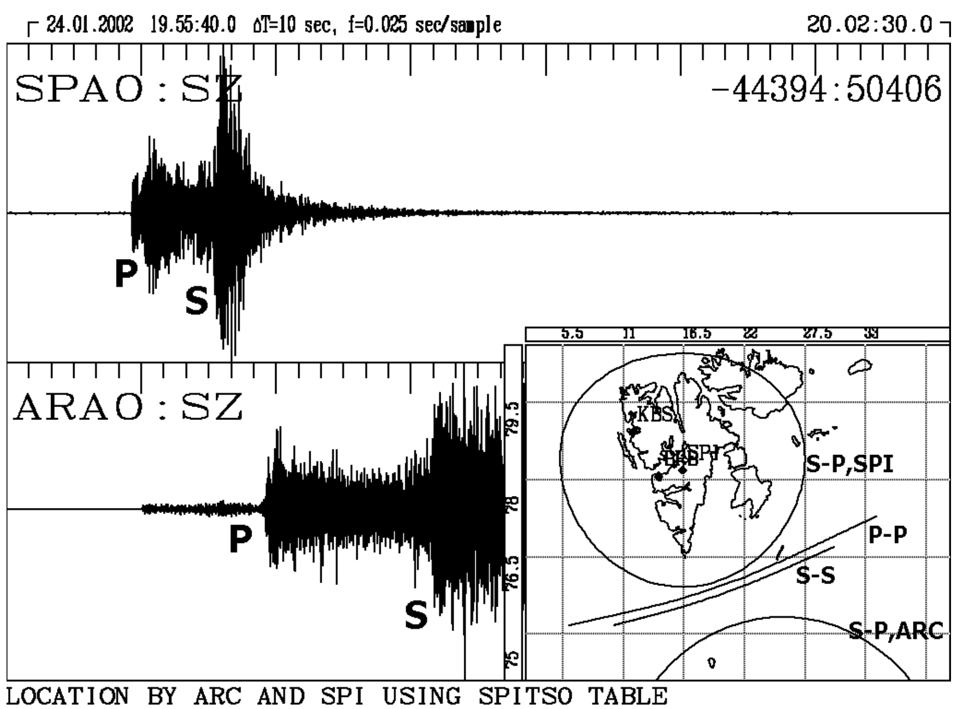

Fig. 6.4.6. Example of difficulty in obtaining location of event south of Spitsbergen using the SPITS0 model (isolines do not intersect).

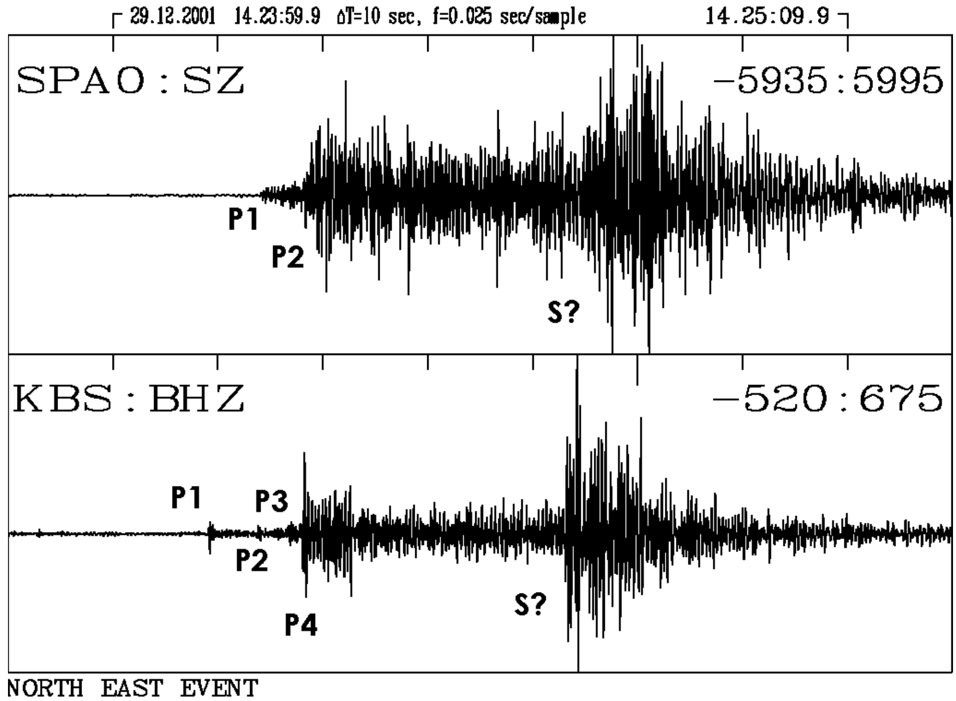

Fig. 6.4.7. Recording of the 29.12.2001 earthquake in Nordaustlandet.

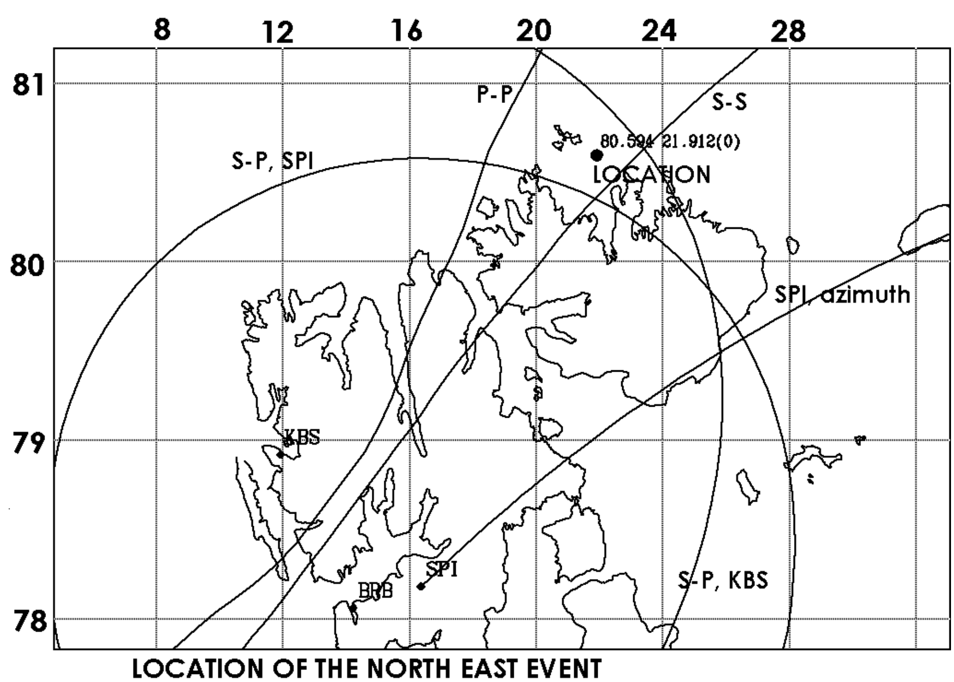

Fig. 6.4.8. Example of difficulty in obtaining location of an event in Nordaustlandet using the SPITS0 model (isolines do not intersect).

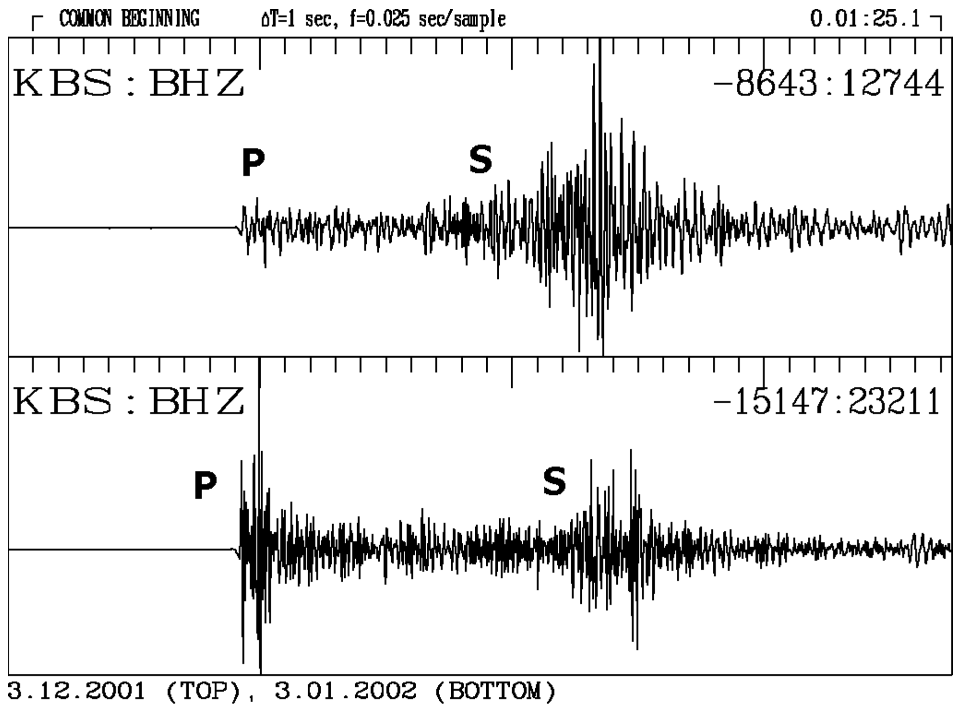

Fig. 6.4.9. Example of differences in P/S ratios for earthquakes located closely together. (3.12.2001 at 01.45.49 GMT; 78.33N 8.24E; and 3.01.2002 at 22.50.40 GMT; 78.4N 7.6E).