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6.4 Analysis of cavity-decoupled chemical explosions

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Introduction

Cavity decoupling has long been acknowledged to be the most effective means of evading detection of an underground nuclear test, and is thus one of the most probable scenarios for a violation of the Comprehensive Nuclear Test Ban Treaty (CTBT). NORSAR has recorded and analysed seismic data from a series of underground cavity explosions in the Kopparberg region of Sweden, with the aim of quantitatively predicting the decoupling effect of underground cavities of known dimensions and shape.

A database of seismic waveform data has been compiled for seven such cavity explosions. A series of four explosions has taken place between December 2000 and June 2002 using varying quantities and compositions of explosives within a chamber of size 1000m^3 with an overburden of rock of approximately 100m. In addition, NORSAR also recorded a series of explosions between 1987 and 1989 which took place within smaller chambers on the same site. Only three factors differentiate these events; the quantity of explosive, the composition and arrangement of the explosives, and the size and configuration of the explosion chamber.

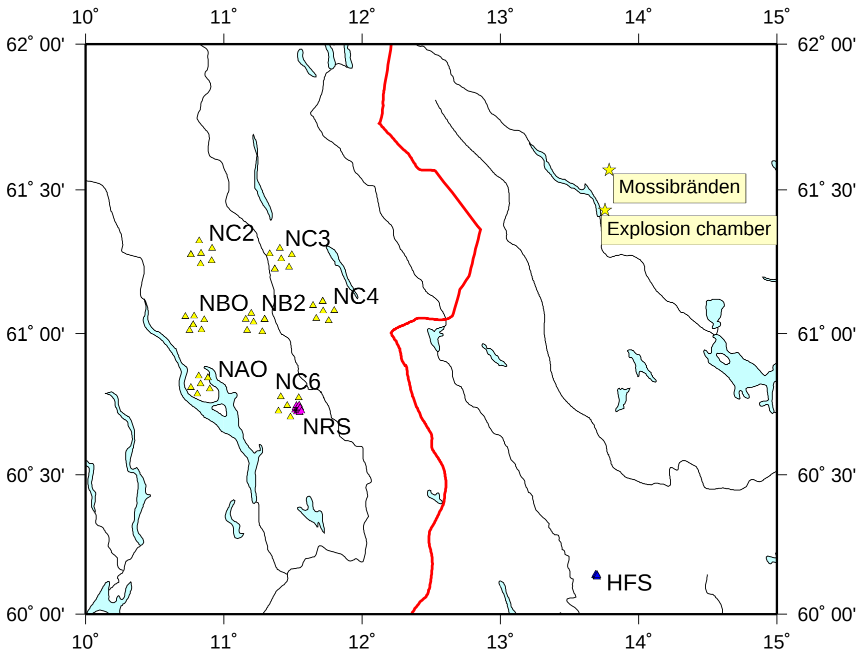

Fig. 6.4.1. *The location of the explosion sites relative to the HFS and NRS arrays and the NORSAR sub-arrays. The red line is the Norway-Sweden national boundary.*

The cavity explosion data has been complemented by records from a series of surface explosions at Mossibränden, a site approximately 15 km from the underground cavities. The distance between the surface and cavity explosions is small compared with the distance between the explosion sites and the NORSAR, NORES and Hagfors seismic arrays (see Fig. 6.4.1). This will largely eliminate path effects and allow a comparison of source properties.

Cavity decoupled explosions

The cavity explosions, which comprise two separate series of experiments, are listed in Table 6.4.1. The first six of these were recorded by the NORES array, which was unfortunately put out of action by lightning shortly before the June 2002 event; waveforms from the NRA0 instrument are displayed in Fig. 6.4.2. The signals resulting from the three events from 1987 and 1989 have far higher amplitudes than the later events, which probably reflects the differences in charge/cavity volume as displayed in Table 6.4.1. The signal from event 2001C150 (2500kg TNT in the 1000m^3 chamber) is indistinguishable from the noise without filtering of the data. The explosions were set off in chambers open to the access tunnels (unsealed explosions).

Table 6.4.1. Cavity decoupled explosions at the Älvdalen site. Origin times of the 1987-1989 events were estimated from arrival times at NORES. Origin times of the 2000-2002 events were determined from a station at the explosion site.

Origin ID	Explosion origin time	Explosion charge (kg)	Explosive	Chamber volume (m^3)[a]	Charge/ Chamber volume (kg/m^3)
1987C146	1987-146:10.47.38.2	5000	ANFO[b]	300	16.7
1987C259	1987-259:10.36.13.0	5000	ANFO	200	25.0
1989C263	1989-263:10.06.03.5	5000	ANFO	300	16.7
2000C348	2000-348:10.03.02.0	10000	TNT	1000	10.0
2001C150	2001-150:10.03.56.2	2500	TNT	1000	2.5
2001C186	2001-186:10.41.23.5	10000	TNT and ammunition shells	1000	10.0
2002C164	2002-164:08.59.25.1	10000	TNT / powder	1000	10.0

a. Not including access tunnel.
b. The ANFO explosive used in the 1987 and 1989 events had an explosion equivalent of 0.82 of TNT

In order to quantify the differences between these six events, we examine the power density spectra (PDS). For each component, three time windows were defined corresponding to the P arrival, the S arrival and pre-event noise. The P-window was defined beginning at the P-wave onset and ending 5 seconds later. The S-window consists of the 10 seconds immediately following the S-wave onset. A third 10 second window, ending 2 seconds before the P-wave onset, was defined to measure the background noise level.

For each event, the PDS was calculated for the three time windows for each vertical component trace. The PDS, averaged over all vertical component traces for the NORES array, is shown for the first six decoupled explosions in Fig. 6.4.3. In order to provide a common basis for comparison, we have converted all spectra to the characteristics of the HFS response which, unlike the NORES array response, is flat to velocity over the bandpass.

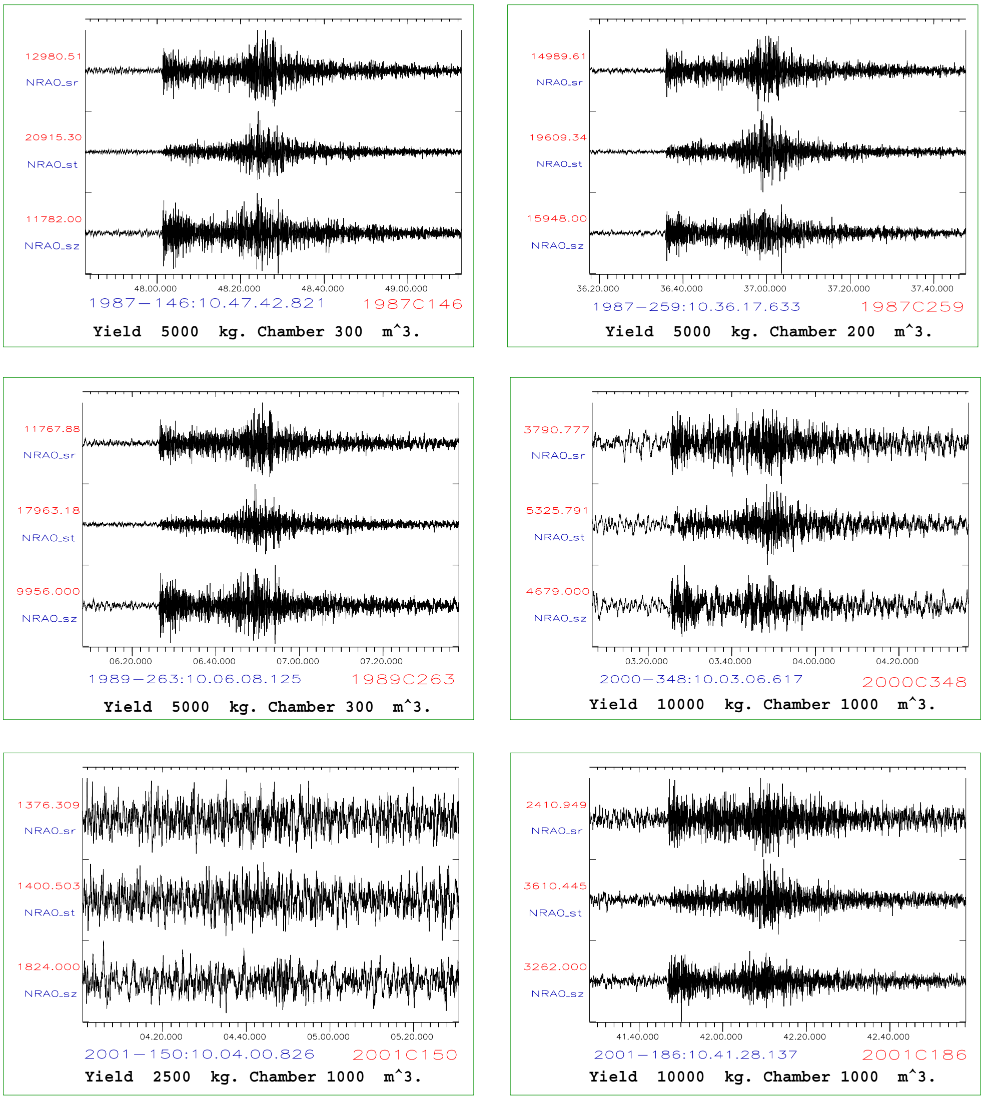

Fig. 6.4.2. *Unfiltered waveforms for the 6 decoupled explosions prior to June 2002 from the 3-component NRA0 instrument of the NORES array. North and East waveforms have been rotated into radial and transverse components. Maximum values of traces (counts) are indicated in red.*

The results shown in Fig. 6.4.3 clearly show the effect of substantially greater decoupling for the larger chamber. The spectra for events 1987C146 and 1987C263 show great similarity, which is to be expected given that both occured in the same chamber using the same quantity and type of explosives. Event 1987C259, which occured in the 200m^3 rather than the 300m^3 chamber, has a spectrum which is similar to the 1987C146 and 1987C263 spectra at high frequencies but which differs significantly in the 3 to 8 Hz frequency band. Events 2000C348 and 2001C186 both took place within the 1000m^3 chamber using the same yield of explosives. However, the PDS for event 2000C348 is greater than that for 2001C186 by an approximate factor of 2 for all frequencies. The only difference between these two events was that pure TNT was used as the explosive for 2000C348 whereas TNT mixed with ammunition shells was used for event 2001C186.

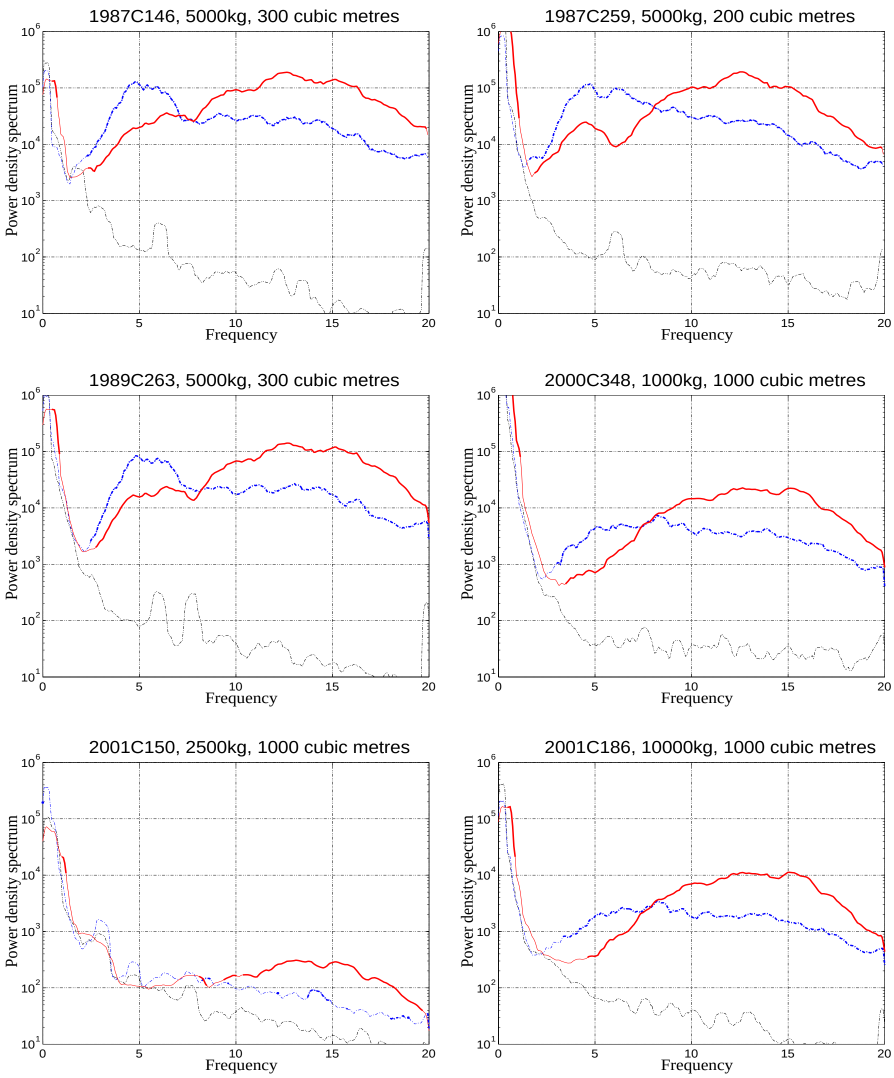

Fig. 6.4.3. *Power density spectra, averaged over all vertical component traces from the NORES array for six cavity explosions as indicated. Solid red lines indicate PDS for P-window (5 seconds following P), dashed blue lines indicate PDS for the S-window (10 seconds following S) and the dotted black line indicates PDS for the noise window (12 to 2 seconds before P). At frequencies for which the PDS for P or S window is less than 4.0 times that for the noise window, the signal spectrum is shown as a thin line.*

Using the average of vertical component traces from the NRS, NOA and HFS arrays, we compare the power density spectra from the P-arrival windows from all of the seven cavity explosions listed in 6.4.1. Performing a simple arithmetic mean on these spectra recorded at different locations is justified by the comparable source-receiver distances between the explosion sites and seismic arrays (see Fig. 6.4.1). Figure 6.4.4 demonstrates the greater PDS in the signal resulting from explosions in the smaller chambers. The 10000 kg of explosives used for the 2002C164 event consisted of 6600 kg powder and 3400 kg TNT in shells.

All of the spectra in Fig. 6.4.4 exhibit low power at low frequencies, although the ratio of low-frequency power density to high-frequency power density is lower for the events within the 1000m^3 chamber, indicating a higher degree of decoupling. The signal to noise ratio for event 2001C150 was very low for frequencies below 10 Hz and a low-frequency power to high-frequency power ratio cannot be estimated.

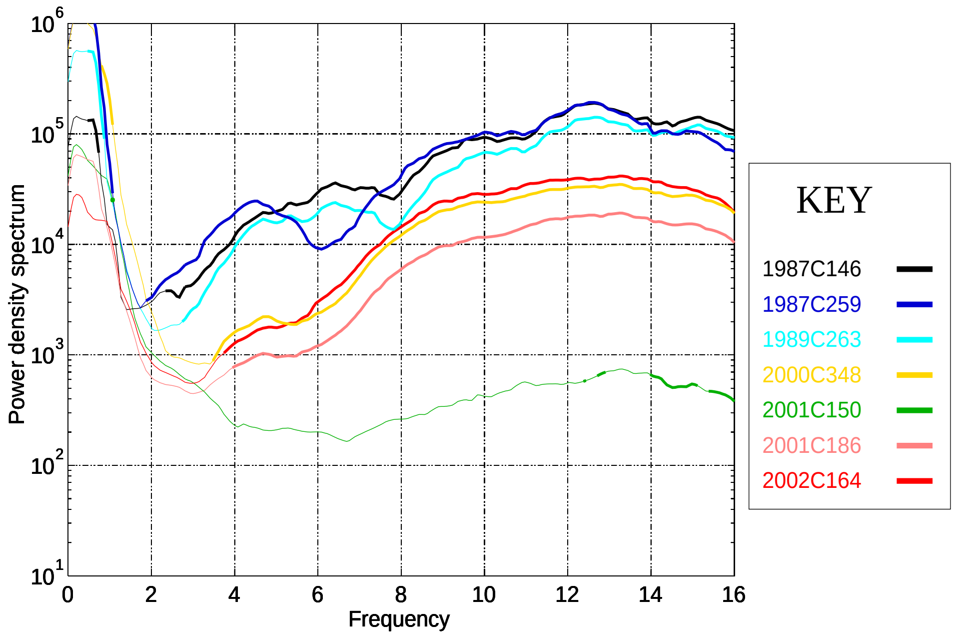

Fig. 6.4.4. *Power density spectra for the P time window averaged over all vertical component instruments for the arrays NOA, NRS and HFS. Thin lines indicate that the ratio PDS(signal)/PDS(noise) was below 4.0 for a given frequency. Events 1987C146, 1987C259 and 1989C263 only include instruments from the NORES array. Event 2002C164 only includes instruments from the HFS and NOA arrays.*

A comparison between the underground cavity explosions and surface explosions at Mossibränden

The Swedish Armed Forces regularly detonate outdated ammunition at ground level at a site approximately 15 km from the underground chambers (see Fig. 6.4.1). Seismic waveforms from 12 such events were added to the database to provide a comparison between underground explosions (where the explosive is completely surrounded by air) and detonations at the surface in the open air. The surface explosions at the Mossibränden site are listed in Table 6.4.2.

Table 6.4.2. Explosions at the Mossibränden site in Älvdalen, June and July 2001. Charges are TNT weights.

Origin ID	Date	Charge/ kg	Origin time as determined by NDC, NORSAR
2001S176	25 June 2001	18831	2001-176:13.46.17.7
2001S177a	26 June 2001	20327	2001-177:07.15.31.2
2001S177b	26 June 2001	20408	2001-177:13.00.11.1
2001S178a	27 June 2001	20101	2001-178:09.16.04.5
2001S178b	27 June 2001	20432	2001-178:13.40.12.4
2001S179a	28 June 2001	20793	2001-179:09.40.55.4
2001S179b	28 June 2001	20242	2001-179:13.50.31.6
2001S183	2 July 2001	21024	2001-183:11.36.00.6
2001S184a	3 July 2001	19044	2001-184:07.31.01.9
2001S184b	3 July 2001	20540	2001-184:13.01.00.0
2001S185	4 July 2001	19118	2001-185:09.36.05.6
2001S186	5 July 2001	20102	2001-186:08.46.05.1

In Fig. 6.4.5 we compare the waveforms resulting from one of the underground cavity explosions (2002C164) and one of the surface explosions (2001S186) filtered through several different frequency bands. The amplitudes resulting from the surface explosion are somewhat greater than those resulting from the decoupled explosion. This is particularly pronounced for low frequencies; in the 1.5-3.0 Hz frequency band, the signal from 2002C164 barely exceeds the background noise level whereas there is a clear signal at these low frequencies from the surface explosion. In the 3-6 Hz band there is a weak S-wave signal from the cavity explosion but no discernible P-wave arrival. In the higher frequency bands, the cavity explosion has a strong P-signal which is comparable to that from the surface explosion.

The spectral properties of the energy resulting from these two events is seen more clearly in the power density spectra: see Fig. 6.4.6. The clear distinction between the two events is the energy in the P spectrum at low frequencies. The underground cavity explosion on the left has a peak of P-energy between 8 Hz and 16 Hz, with approximately an order of magnitude less energy below 8 Hz. By contrast, the surface explosion on the right has slightly more P-wave energy between 3 Hz and 8 Hz than at higher frequencies. There is less difference between the S-wave spectra for the two events.

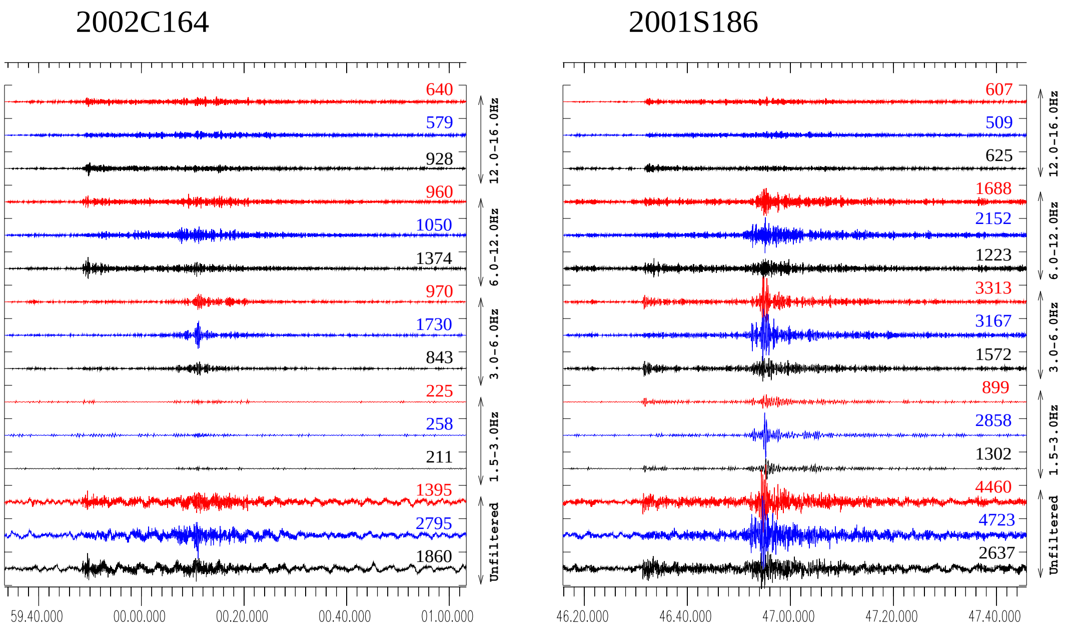

Fig. 6.4.5. *Waveform data from the 3-component HFSC2 instrument for events 2002C164 (cavity explosion: 10000kg powder and TNT in shells in a 1000m^3 cavity) and 2001S186 (surface explosion of 20102kg out-of-date ammunition). Vertical component traces are in black; rotated radial and transverse components are in red and blue respectively. All traces are scaled identically with the largest amplitude as indicated. Frequency bands for filtering are shown on the right hand side.*

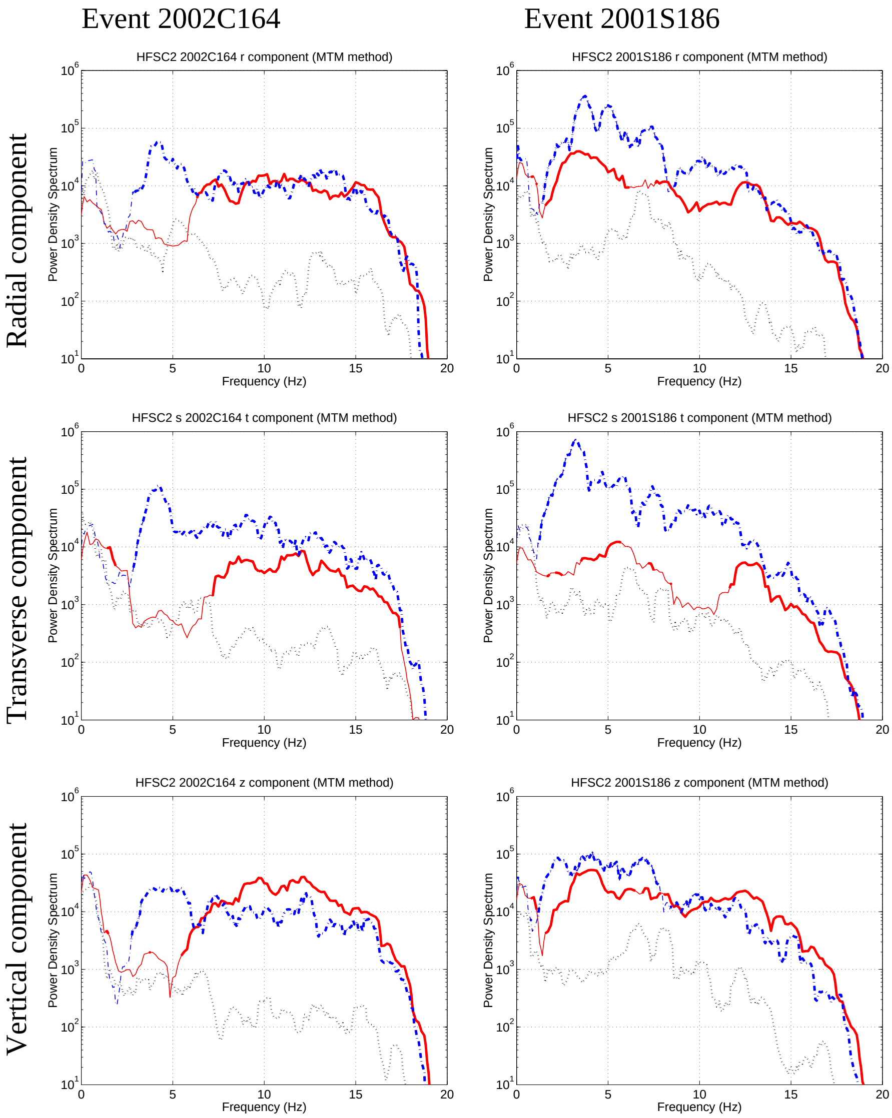

Fig. 6.4.6. *Power density spectra (PDS) of the radial (top), transverse (center) and vertical (bottom) components of the signals from events 2002C164 (decoupled, left) and 2001S186 (Mossibränden, right) from the HFSC2 instrument. The solid red line is the PDS for a 5 second interval starting at the P arrival, the dashed blue line is the PDS for a 10 second interval starting at the S arrival and the dotted line is the PDS for a 10 second interval ending 2 seconds before the P arrival (noise window). The dashed and solid lines are displayed with double thickness for frequencies where the signal to noise ratio is greater than 4.0 .*

A discriminant for cavity-decoupled explosions

The comparison between events 2002C164 and 2001S186 (Fig. 6.4.5 and Fig. 6.4.6) indicates that the primary difference between the underground cavity explosions and the surface explosions is relatively low P energy at low frequencies for the decoupled explosions. We applied the following step-wise procedure to find a quantity which summarises the visual discriminant in the vertical component spectra of Fig. 6.4.6, which can then be applied to all of the events in the database in order to find a systematic difference between the cavity (C) events and the surface (S) events.

For each event in the data-base, the following steps were carried out:

- Waveform data was obtained for every available vertical component station in the HFS, NRS and NOA arrays.
- For each trace, a P-window (5 seconds following the P-arrival), an S-window (10 seconds following the S-arrival) and a noise window, N (10 seconds ending 2 seconds before the P-wave arrival), were defined.
- Power density spectra were calculated over all time windows for all traces.
- Two frequency bands were defined: band 1 (3 - 8 Hz) and band 2 (8 - 14 Hz). Median values of the P, S and noise power density spectra were calculated for frequencies within these bands. For a given trace, we denote the median value of the power density spectra between frequencies f1 and f2 P(f1-f2), S(f1-f2) and N(f1-f2) for the P time window, S time window and noise time window respectively.
- For each trace, the ratios P(8-14):N(8-14), S(8-14):N(8-14), P(3-8):N(3-8) and S(3-8):N(3-8) were calculated. If one or more of these ratios was below 2.0, then the trace was excluded. For the remaining traces, the ratios P(8-14):P(3-8) and S(8-14):S(3-8) were evaluated and the mean and standard deviations calculated. The results are displayed in Fig. 6.4.7.

Fig. 6.4.7(a) shows a clear distinction between the decoupled explosions (blue bars) and the surface detonations (green bars) with the former having far higher ratios of P energy in the higher frequencies to P energy in the lower frequencies. This ratio is highest for three 10000kg explosions suggesting that they were the most effectively decoupled. The 2500 kg explosion (2001C150) was probably even more effectively decoupled, but was excluded from this analysis on the grounds of poor signal to noise ratio. This ratio is approximately an order of magnitude greater for the decoupled explosions than for the surface explosions.

Fig. 6.4.7(b) shows a similar pattern for the S waves but with a much smaller difference in the ratios. The P(high):P(low) ratio appears therefore to be a far better discriminant than the S(high):S(low) ratio. This is in accordance with expectations, since only P-energy is transmitted through the air surrounding an explosion and all shear energy is generated by conversion from P-energy. Given that S and P exhibit similar trends (i.e. decoupling produces both less P and less S at low frequencies), the P(high):P(low) ratio is probably a better discriminant than the S:P ratio.

The simplicity of this single ratio discriminant may lead to spurious conclusions being drawn and it therefore provides no substitute for a thorough examination of the spectra. For example, on the basis of the P(8-14):P(3-8) discriminant (Fig. 6.4.7a), event 1987C259 would appear to be more effectively coupled than events 1987C146 and 1989C263: two events which involved equal quantities of explosives but in a larger chamber. The low P(3-8) value for event 1987C259 is the result of a decrease in power between 5 and 8 Hz (Fig. 6.4.4) which is not shown by events 1987C146 and 1989C263. Below 5 Hz, event 1987C259 displays more P energy than the other two events.

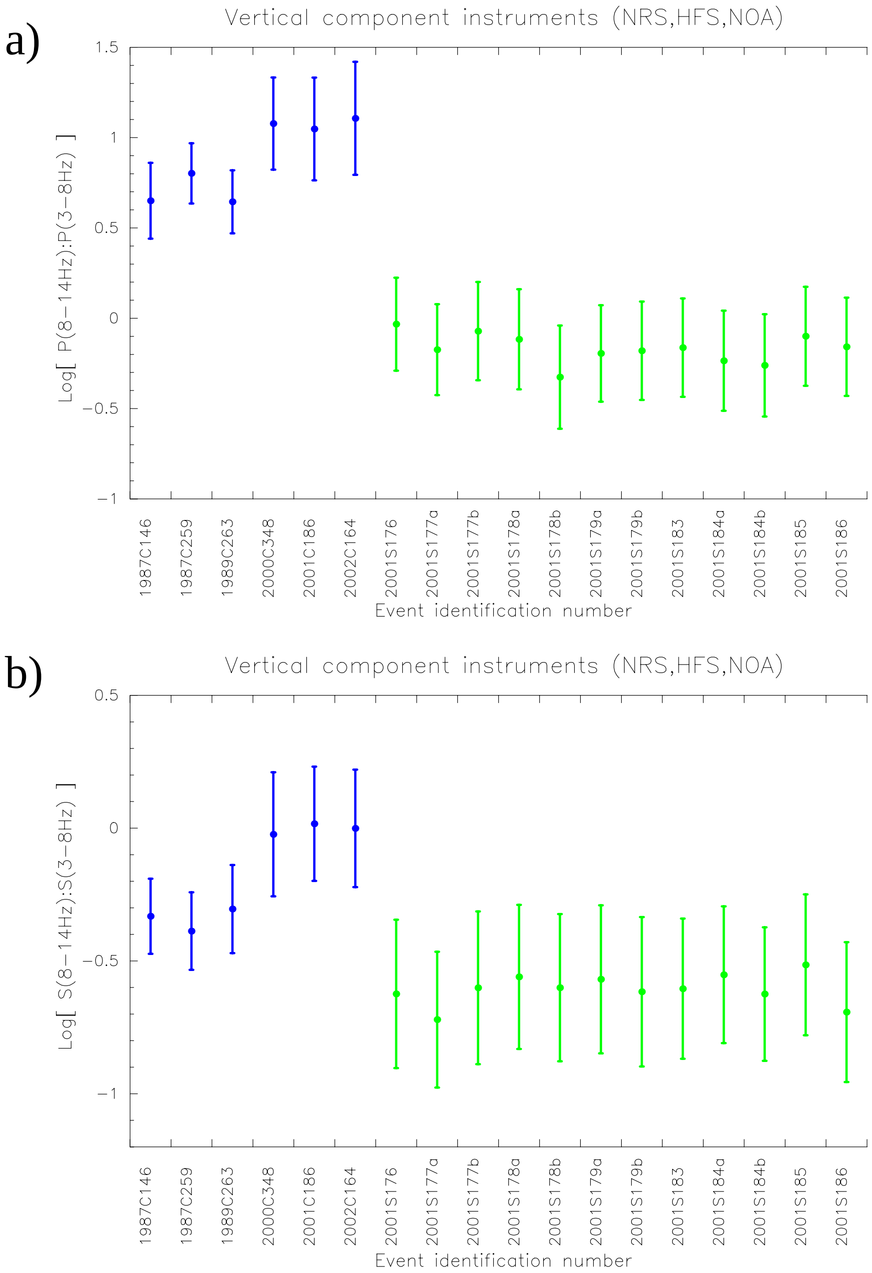

Fig. 6.4.7. *Mean values of (a) log(P(8-14)/P(3-8)) and (b) log(S(8-14)/S(3-8)) for all vertical component stations in the three arrays HFS, NRS and NOA for which the ratios P:N and S:N were greater than 2.0 in both frequency intervals. Error bars surrounding the mean values are standard deviations. Decoupled cavity explosions are denoted with blue bars and surface explosions from Mossibränden with green bars.*

Conclusions

Throughout the analysis, local site effects have been reduced as a result of averaging of values from many array stations. The synthesis below and the main conclusions of Fig. 6.4.7 are based on different wavepaths and distances, and it is therefore reasonable to assume that the findings are largely source related.

- The recordings from explosions in the cavities at Älvdalen are characterized by a large amount of high-frequency energy (8-16 Hz) compared with the energy at lower frequencies (2-5 Hz). Such spectral characteristics are not observed for any of the other events included in the database. The effect is more pronounced for P than for S waves.
- The three 10000kg explosions in a 1000m^3 chamber appear to have been more efficiently decoupled than the 5000kg explosions in chambers of 200m^3 and 300m^3. The signals from the explosions in the smaller chambers were far stronger, in spite of significantly lower yields, and displayed a less pronounced high-to-low frequency energy ratio than the explosions in the larger chambers.
- The 2500kg explosion in the 1000m^3 chamber appeared to be very effectively decoupled, and was visible on our recordings only at frequencies above 8 Hz.

The Office of Technology Assessment report (OTA, 1988) estimates that a one kiloton explosion in granite at a depth of 828 meters would be decoupled by a spherical cavity with a radius of approximately 20 metres. It might be possible to scale this to a yield of 10 tons at a depth of 100 metres, as in Älvdalen, to obtain the cavity volume required for full decoupling. There are, however, large uncertainties associated with such scaling, in particular when it comes to the use of high-explosive materials and non-spherical cavities. The 10 ton explosions in Älvdalen were detonated in a cavity 5 meters high by 25 meters long, by 10 meters wide (~1000 m^3), and the explosive charge was made up of 10 simultaneous one ton charges detonated on the floor of the cavity (lifted from the floor on styropor ‘mattresses’). It is therefore uncertain whether the 10 ton shots were fully or only partially decoupled. As a qualitative indicator for the degree of decoupling it can be noted that the damages to the cavity are minor and limited to ‘surface scratches’, and the repeated use of the same cavity is warranted. On the other hand, both the 200m^3 and 300m^3 cavities have been closed for further use due to structural damage caused by the explosions. From the P-wave spectra shown in Figure 6.4.4 we make the following observations:

- The power spectral levels of the 2000C348 and 2001C186 10 ton explosions detonated in the 1000 m^3 cavity differ by a factor 2 ($\sqrt{2}$ in amplitude) over the entire observable frequency band. At high frequencies, the 2002C164 10 ton explosion has a similar spectral level to the (stronger) 2000C348 event, although it shows slightly lower power at lower frequencies.
- Between 8 and 16 Hz we find a factor 6 amplitude difference between the 2.5 ton and the weakest 10 ton explosion, both detonated in the 1000 m^3 cavity. Below 8 Hz, the 2.5 ton explosion had too low SNR to enable a comparison.

- The two 5 ton charges detonated in the 300 m^3 cavity had very similar spectra. Below 5 Hz, the 5 ton charge detonated in the 200 m^3 cavity had higher spectral levels than the 300 m^3 cavity shots. Between 5 and 8 Hz, the 200 m^3 cavity shot displays a reduction in power spectrum whereas the 300m^3 shots display an increase. Above 8 Hz the spectral levels were all similar.
- When comparing the spectral levels of the “smallest” 10 ton explosion detonated in the 1000 m^3 cavity with the 5 ton explosions detonated in the 300 m^3 cavity, we find the amplitudes of the 5 ton explosion exceeds the amplitudes of the 10 ton explosion by a factor 3-3.5 in the band 10-16 Hz. At 5 Hz, the amplitude difference is increased to a factor 7.

The spectral characteristics found for the decoupled explosions as shown in Fig. 6.4.7 may be influenced by the open tunnel during the explosions. This entails that it is presently unknown if these characteristics are reproducible in a sealed decoupled explosion.

These observations of the cavity explosions provide information that can be used to assess the full and partial decoupling effects. This is a topic that we plan to look into in the continuation of this project. For the newer events we have also collected high-frequency data that we will investigate in more detail. The high-frequency data was obtained using portable stations which were placed both alongside fixed instruments within the arrays and at selected sites closer to the source locations.

We also plan to assemble NOA, HFS and NRS recordings of earthquakes located at distances similar to Älvdalen and Mossibränden, but at different azimuths, in order to make comparative studies of their spectral characteristics.

Comparisons between records from decoupled explosions and ripple fired mining explosions are recognized as an important future target.

References

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