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Reflection seismic imaging of the upper crystalline crust for characterization of potential repository sites: Fine tuning the seismic source

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September 2001

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Summary

SKB is currently carrying out studies to determine which seismic techniques, and how, they will be used for investigations prior to and during the building of a high−level nuclear waste repository. Active seismic methods included in these studies are refraction seismics, reflection seismics, and vertical seismic profiling (VSP). The main goal of the active seismic methods is to locate fracture zones in the crystalline bedrock. Plans are to use longer reflection seismic profiles (3−4 km) in the initial stages of the site investigations. The target depth for these seismic profiles is 100−1500 m. Prior to carrying out the seismic surveys over actual candidate waste repository sites it has been necessary to carry out a number of tests to determine the optimum acquisition parameters. This report constitutes a summary of the tests carried out by Uppsala University. In addition, recommended acquisition and processing parameters are presented at the end of the report.

A major goal in the testing has been to develop a methodology for acquiring high−resolution reflection seismic data over crystalline rock in as a cost effective manner as possible. Since the seismic source is generally a major cost in any survey, significant attention has been given to reducing the cost of the source. It was agreed upon early on in the study that explosives were the best source from a data quality perspective and, therefore, only explosive source methods have been considered in this study.

The charge size and shot hole dimension required to image the upper 1−1.5 km of bedrock is dependent upon the conditions at the surface. In this study two types of shot hole drilling methods have been employed depending upon whether the thickness of the loose sediments at the surface is greater or less than 0.5 m. The charge sizes and shot hole dimensions required are:

- Loose sediment thickness less than 0.5 m: 15 g in 90 cm deep 12 mm wide uncased shot holes
- Loose sediment thickness greater than 0.5 m: 75 g in 150 cm deep 20 mm wide shot hole that are cased to 16 mm

Both these shot holes can be drilled with handheld equipment making drilling possible even in difficult terrain with minimal damage to the environment. We refer to the combination of using small charge sizes and shot hole dimensions as the "slim hole method".

Geophones are preferably planted in 8 mm holes drilled in bedrock. If no bedrock is present it is better to plant the geophones at locations with thick soil cover rather than in soil cover that is only 20−40 cm thick. If the cover is only this thick then it should be mechanically removed.

One of the most important factors in producing high quality images is that the data are acquired with a high fold. High fold implies that the data are stacked together numerous times in order to increase the signal to noise ratio. Shot points should be located at every station to suppress the source generated noise. Shooting several times at the same station does not reduce source generated noise.

Sammanfattning

SKB genomför för närvarande undersökningar för att bestämma vilka seismiska metoder som ska användas och hur de ska användas före och under byggandet av ett djupförvar för använt kärnbränsle. De seismiska metoder som är aktuella är refraktionsseismik, reflektionsseismik och borrhålsseismik (VSP). Huvudsyftet med dessa seismiska metoder är att lokalisera sprickzoner i den kristallina berggrunden. Reflektionsseismiska profiler (3− 4 km) planeras att användas i de inledande stadierna av platsundersökningarna. Målet för dessa profiler är kartläggning av strukturer från 100 till 1500 meters djup. Innan sådana seismiska mätprofiler kan göras vid kommande platsundersökningar har det varit nödvändigt att göra ett flertal tester för att bestämma de optimala fältparametrarna för datainsamling. Denna rapport utgör en summering av de tester som utförts av Uppsala Universitet. Dessutom presenteras rekommenderade insamlings− och bearbetningsparametrar i slutet av rapporten.

En viktig målsättning i testerna har varit att utveckla en metodik för insamling av reflektionsseismiska data med hög upplösning på ett så kostnadseffektivt sätt som möjligt.

Den seismiska källan är vanligtvis huvudkostnaden i all seismik varför ett betydande arbete lagts ner på att reducera kostnaden för källan. I ett tidigt stadium av undersökningarna enades om att sprängmedel är den bästa källan vad gäller datakvalitet varför endast denna seismiska källa behandlas i denna studie.

För studier av de övre 1− 1.5 km av berggrunden är laddningarnas storlek och skotthålens dimension beroende av djupet till berggrundsytan i skottpunkten. I denna studie har två typer av borrningar gjorts beroende på om jorddjupet är mindre eller mer än 0.5 m. De laddningar och borrhål som behövs för seismiska signaler att penetrera till önskat djup är:

- Jorddjup mindre än 0.5 m: 15 g i 90 cm djupa och 12 mm vida hål. Vid jorddjup 0−0.5 m avlägsnas jordtäcket före borrning.
- Jorddjup mer än 0.5 m: 75 g i 150 cm djupa och 20 mm vida hål. Dessa hål har fodrats med rör.

Bägge dessa typer av skotthål kan borras med handburna utrustningar vilket möjliggör borrning i svår terräng och minimerar markskador. Användandet av små laddningar i borrhål med liten diameter kallar vi för klenhålsmetoden.

Geofonerna placeras helst i 8 mm:s borrhål direkt i berget där detta går i dagen. Om berg i dagen inte finns är det bättre att placera geofonerna i jord med större mäktighet. Om jordtäcket underskrider 0.5 m bör det mekaniskt avlägsnas.

En av de viktigaste faktorerna för att producera seismiska avbildningar av berggrunden av hög kvalitet är att data är insamlat med hög faltning (fold på engelska). Hög faltning innebär att registrerade signaler är adderade ett flertal gånger för att öka signal/brus förhållandet. Sprängning bör ske i varje punkt längs profilen för dämpa det källgenererade bruset. Sprängning ett flertal gånger i samma punkt reducerar inte det källgenererade bruset.

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1. Introduction

1.1. Background

One of the concerns of SKB in locating a disposal site for high level radioactive waste is the presence of sub−horizontal to moderately dipping fracture zones which groundwater can migrate through (SKB, 2001). These fracture zones are difficult to detect by surface geological mapping. Geophysical logging in boreholes has shown that fracture zones typically have low sonic velocities, densities and resistivities. They vary in thickness (width) from a few meters to over 100 m and are generally more hydraulically conductive than the surrounding rock (Ahlbom et al., 1992). Since the fracture zones have lower velocities and densities compared to the surrounding intact rock, it should be possible to image them with the seismic reflection method.

Early work in Canada showed that reflection seismics is one geophysical method which is well suited for detection of fracture zones (Mair and Green, 1981). With this background, an attempt was made to image a known fracture zone with high hydraulic conductivity at the Finnsjön study site. The zone dips gently to the west at depths of 100 to 400 m. The initial processing of the data failed to image this fracture zone. Analyses of the data and initial processing steps showed the importance of applying refraction statics, bandpass filtering and velocity analyses on this type of data (Juhlin, 1995). After reprocessing, a clear image of the gently dipping fracture zone was obtained (Figure 1−2). In addition, several other reflectors were imaged in the reprocessed section, both gentle and steeply dipping ones. It is likely that the source of these reflections are also fracture zones.

1.2. Overview of work carried out

The authors have been involved in five additional seismic reflection tests (Figure 1−1) since the Finnsjön study. From this work we have developed a methodology for acquiring and processing 2D high−resolution seismic data over crystalline rock. Special attention has been given to using the most efficient source since this is a major cost in the surveying. The preferred source is called the *slim−hole source* and consists of small charges of dynamite in small diameter shot holes.

The studies carried out were:

Ävrö seismic survey: This study consisted of two crossing lines using the same acquisition parameters as used at the Finnsjön site. The main goal of the seismic survey was to image known fracture zones.

Ävrö mini source test: The main goal of this test was to determine if the charge and shot hole size could be reduced while maintaining a good quality image of the upper 1 km.

Ängeby mini source test: This study involved further tests with reduced charge and shot hole dimensions as at Ävrö, but also included tests in glacial till.

Laxemar seismic survey: This study consisted of two full−scale crossing seismic profiles over the deep KLX02 borehole using the slim−hole method. The terrain was similar to that of Ävrö and Finnsjön with about 50% outcrop.

Gravberg seismic survey: This was a full−scale profile using the slim−hole method in glacial till in an area where strong reflectors are known to be present.

This report summarizes the above studies by reviewing the acquisition, processing and interpretation aspects of each study. The results are then discussed relative to cost time considerations in acquiring reflection seismic data. Based on our experience, we present strategies for acquiring and processing reflection seismic data with the goal of imaging the uppermost 1 km of crystalline crust. Finally, we summarize the most important conclusions from our work and present some suggestions for future work within this field.

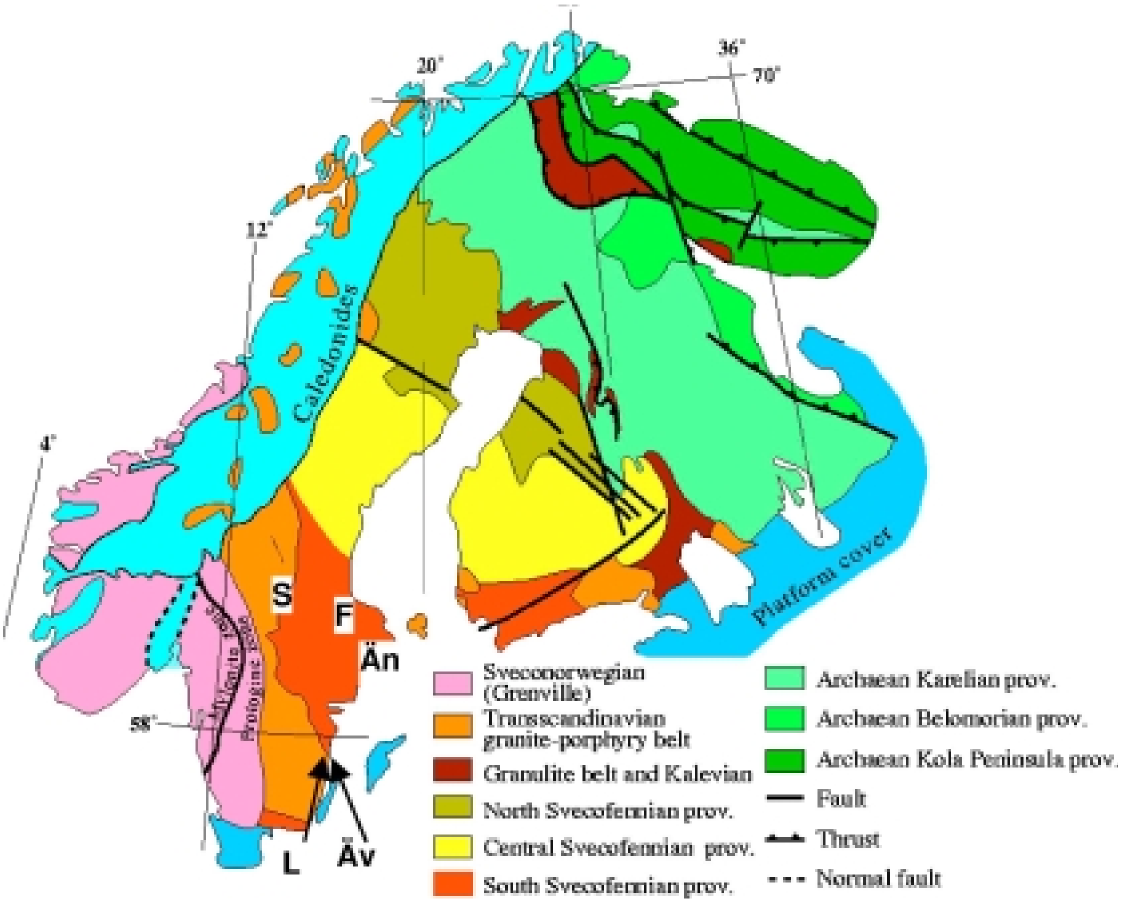

Figure 1−1. Location of study areas. F−Finnsjön, L−Laxemar, Äv−Ävrö, S−Siljan and Än− Ängeby. Map after Weihed et al.(1992).

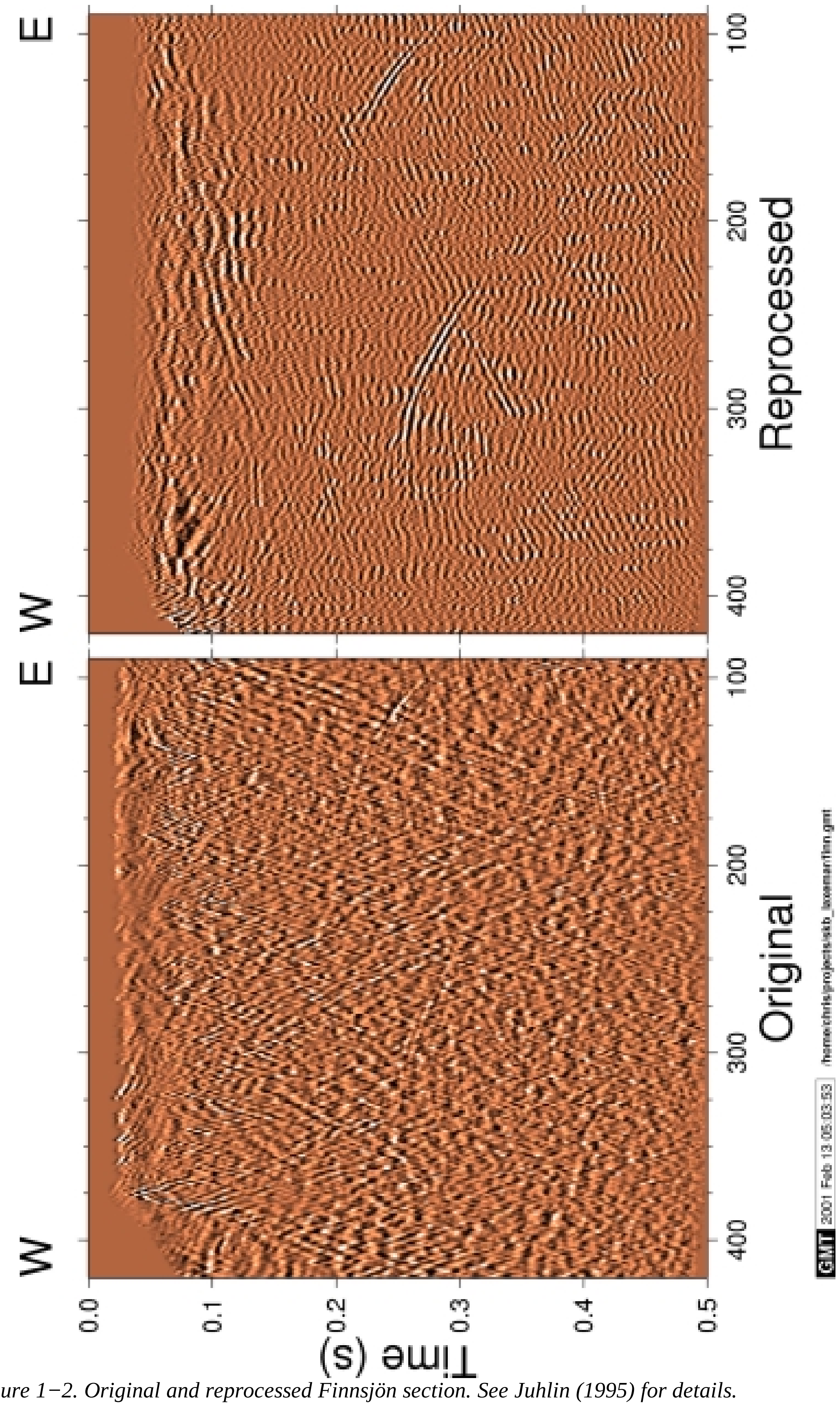

Figure 1−2. Original and reprocessed Finnsjön section. See Juhlin (1995) for details.

2. Experiments carried out

2.1. *Ävrö seismic survey*

2.1.1. Background and goals

Reprocessing of the Finnsjön data set confirmed that reflection seismics is a viable method for locating sub−horizontal fracture zones in crystalline rocks. Therefore, further testing was carried out by SKB and Uppsala University on Ävrö island (Figure 2−1). Two c. 1 km long crossing high−resolution seismic reflection lines were acquired in October 1996 in order to (1) test the seismic reflection method for future site investigations, (2) map known fracture zones and (3) add to the Swedish database of reflection seismic studies of the shallow crystalline crust.

2.1.2. Location

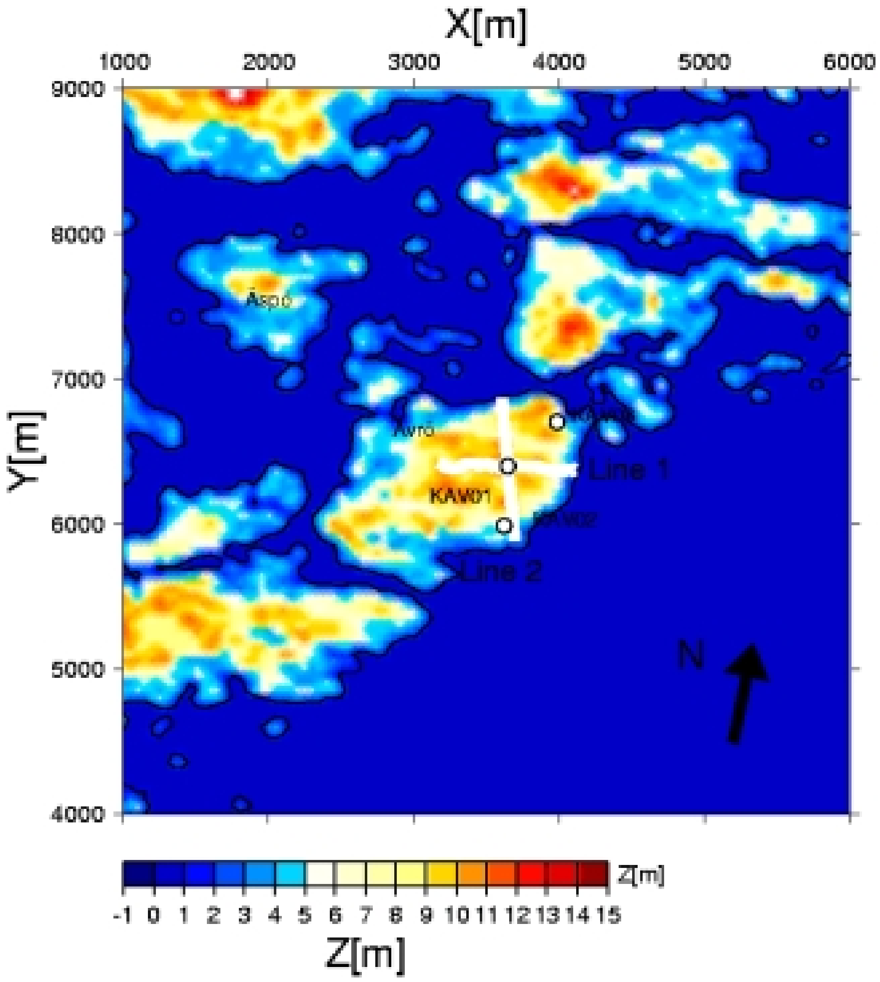

Figure 2−1. Location of the Ävrö seismic profiles. Topography is from the SKB database.

2.1.3. Acquisition

The two profiles were staked in August 1996, a W−E one (Line 1) with a station spacing of 5 m on average and a N−S one (Line 2) with a station spacing of 10 m on average (Table 2−1). Shot− and geophone points were placed, to the greatest extent possible, on bedrock. The drillers were instructed to drill at the nearest place to a staked point where there was a bedrock outcrop at the surface, but not further than 1 m parallel and 2 m perpendicular to the profile from the staked point. If no bedrock was found within this area the hole was drilled at the staked point. Geophone holes (8 mm diameter, 50 mm deep) were later drilled following the same instructions, but were not necessarily drilled close to the shotpoints. For this reason, staked points, shotpoints and geophone points do not match exactly.

Table 2−1. Acquisition parameters for the Ävrö seismic survey.

Parameter	*Line 1*	*Line 2*
Number of channels	100	100
Geophone spacing	5 m	10 m
Shot spacing	5 m	10 m
Nominal fold	50	50
Nominal spread	end on / shoot−through	end on / shoot−through
Geophone type	single 28 Hz	single 28 Hz
Minimum offset	20 m	20 m
Sample rate	1 ms	1 ms
Record length	5 s	5 s
Charge type	Nitro−Nobel booster	Nitro−Nobel booster
Charge size	100 g	100 g
Nominal charge depth	2 m	2 m
Field low cut	Out	Out
Field high cut	250 Hz	250 Hz
Number of shots	191	93
Line length	1 km	1 km
Recording system	SERCEL 348	SERCEL 348

2.1.4. Results

The data clearly image three major dipping reflectors (dips > 15°) and one sub−horizontal (dips < 15°) in the upper 200 ms (Figure 2−2). The dipping ones (south, east and north−west) intersect or project to the surface at or close to where surface mapped fracture zones exist (Juhlin and Palm, 1999). 3D effects are clearly apparent in the data and only where the profiles cross can the true orientation of the reflecting events be determined (Juhlin and Palm, 1999). To orient and locate all events observed on the lines requires acquisition of 3D data. Reflector B in Figure 2−2 (the south dipping reflector on Line 2) have a dip direction parallel to the plane of the N−S running Line 2. It can, therefore, be migrated properly and correlates with the top of a heavily fractured interval observed in borehole KAV01 at ca. 400 m (Juhlin and

Palm, 1999). Likewise, a sub−horizontal reflection at ca. 60 ms can also be migrated properly and it also correlates with a known fracture zone in borehole KAV01.

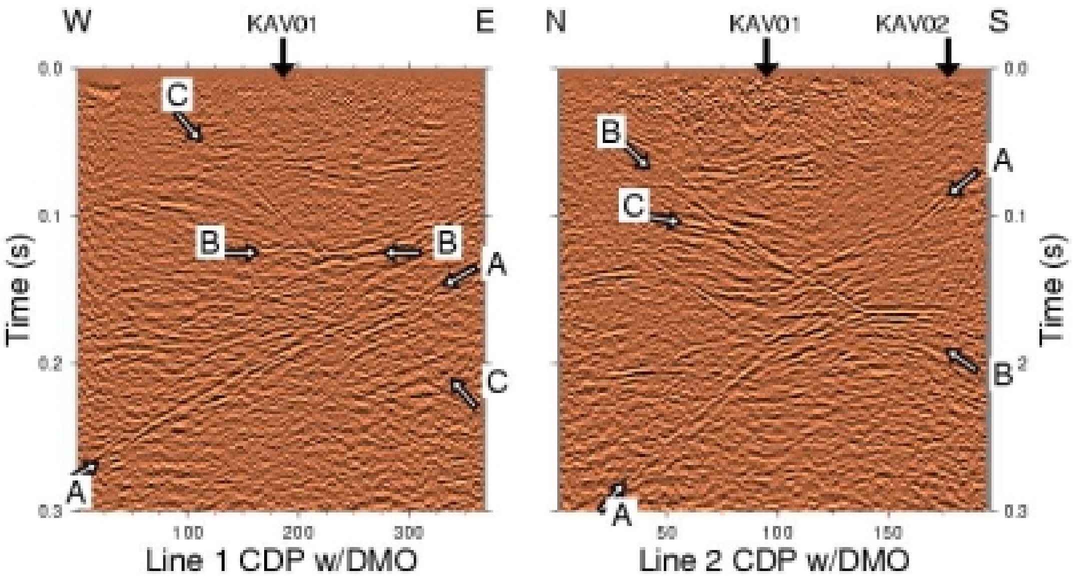

Figure 2−2. Processed section from Lines 1 and 2, Ävrö.

The processed images from this experiment have proven to be very useful when integrated with other geoscientific data (Markström et al., 2001).

Figure 2−3 shows the stacked sections from Lines 1 and 2 plotted to 1.6 s, corresponding to signals arriving from as far away as 5 km. Between 300 and 650 ms there are number of events which do not cross the entire section and are most apparent on the E−W section (Line 1). These events probably have a fairly localized origin and may originate from mafic bodies.

Below 650 ms there is a moderately SW dipping reflector at 700 ms and there are 3 deeper N dipping events at about 1.1, 1.2 and 1.4 s. The uppermost of these deeper events projects to the surface about 8 km to the south of Ävrö in the Baltic Sea. This projection assumes that the reflectors are planes. If they have a listric nature and steepen as they become shallower the uppermost one will intersect the surface closer than 8 km from Ävrö. The one at 700 ms projects to the surface about 5 km to the NE of Ävrö. Given the dipping nature (c. 20° dip) of these events, they are tentatively interpreted as fracture zones which extend deep into the upper crust.

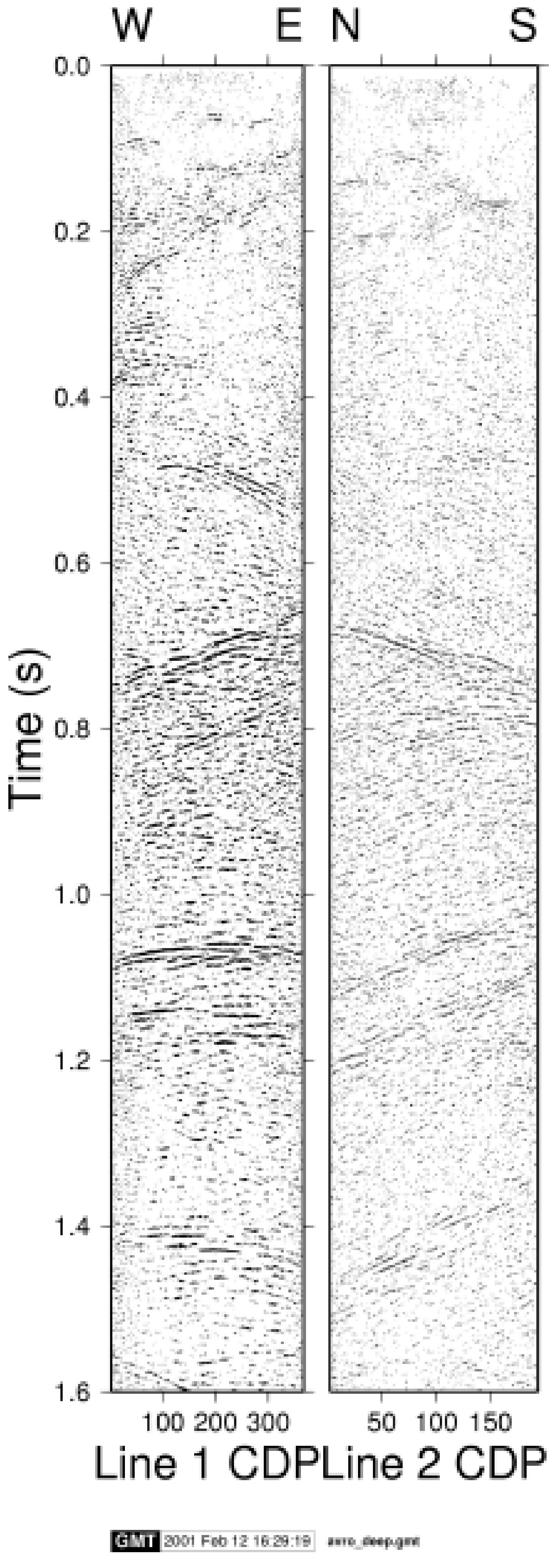

Figure 2−3. Lines 1 and 2 processed to 1.6 seconds, Ävrö.

2.2. Ävrö mini source test

2.2.1. Background and goals

The four moderately dipping reflectors imaged at later times from 700 to 1400 ms on the Ävrö seismic survey (Figure 2−3) indicated signal penetration to at least 4 km. This observation led to the idea that it should be possible to reduce the charge size and the shot hole dimensions and still image the uppermost 1000 m of crust. The reduced shot hole dimension would significantly reduce the cost of the seismic survey. This method of seismic acquisition will be referred to in this report as the slim−hole method.

The main goal for the first slim−hole test was to investigate if similar images of the upper 500 ms could be obtained along a short portion of Line 1 of the Ävrö seismic survey described in the previous section.

2.2.2. Location

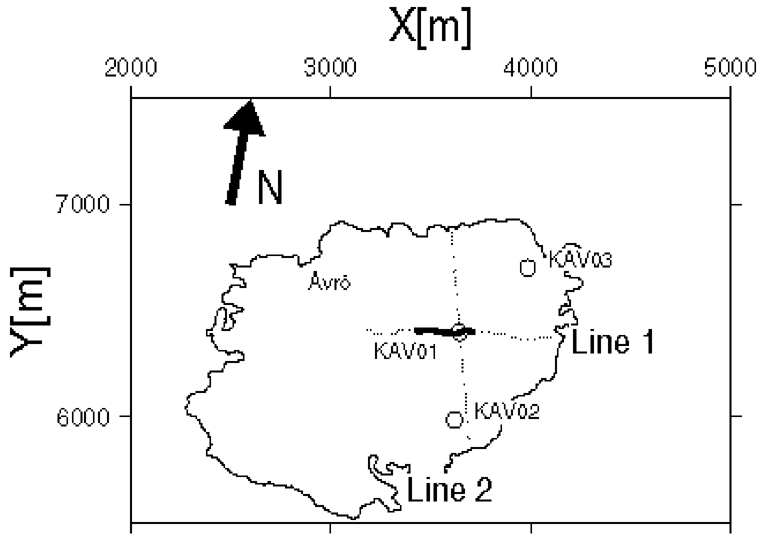

Figure 2−4. Location of the Ävrö mini−source test profile relative to Line 1 from the Ävrö seismic survey.

2.2.3. Acquisition

In order to test the slim−hole method, a 290 m long test profile was shot along part of Line 1 (Figure 2−4). Recording was done in parallel on thirty−three 28 Hz and thirty−three 60 Hz single geophones spaced at 10 m (Table 2−2). Two sets of thirty shots were fired along the line. The first set consisted of 7 grams in a single 12 mm wide 60 cm deep shot hole and the second set consisted of 14 grams distributed evenly in two 12 mm wide 60 cm deep shot holes. All holes were made by a Hilti TE 55, a 6 kg electric combi−hammer handheld drilling machine. All the shot holes were drilled directly into bedrock. At locations where the bedrock was not observed, the soil was removed by use of a powered shovel. All geophones were planted in 8 mm drilled holes in order to avoid the "ringing" that occurs when the soil layer is only 20−40 cm thick. Total drilling time for each shot hole was approximately 10 min. More details on the acquisition can be found in Appendix 1.

Table 2−2. Acquisition parameters for the Ävrö mini−source test.

Parameter	*28 Hz line*	*60 Hz line*
Number of channels	33	33
Geophone spacing	10 m	10 m
Shot spacing	10 m	10 m
Nominal fold	15	15
Nominal spread	shoot−through	shoot−through
Geophone type	single 28 Hz	single 60 Hz
Minimum offset	20 m	20 m
Sample rate	1 ms	1 ms
Record length	5 s	5 s
Charge type	Trotyl	Trotyl
Charge size	7/14 g	7/14 g
Nominal charge depth	1 x 60 cm / 2 x 60 cm	1 x 60 cm / 2 x 60 cm
Field low cut	8 Hz	8 Hz
Field high cut	250 Hz	250 Hz
Number of shots	30	30
Line length	320 m	320 m
Recording system	SERCEL 348	SERCEL 348

2.2.4. Results

Images

To be able to compare the results from the small charge test lines with the data from Line 1 in Juhlin and Palm (1999), which was recorded with 5 m source and receiver spacing, decimation of the latter data was necessary. Decimation implies that shot points and/or receiver points are excluded from the processing. Ideally, the same shot and receiver positions should have been used in the slim−hole test. However, due to acquisition logistics, it was not possible to use exactly the same shot point locations on the small charge test lines as were used on Line 1. Instead, for producing the decimated Line 1 stack, shots and receivers were limited to the CDP interval 100 to 212 and only every other receiver was included in the processing. Every other shot point was not chosen since this would have left gaps in the stacked section making comparison with the test series difficult. After decimation the data were processed in a similar manner as the small charge test data with minor modification depending on data character (Table A−1). However, the fold is still higher on the decimated Line 1 stack than on the small charge test stacks.

Figure 2−5a shows the complete stacked section from Line 1 without DMO. The framed area corresponds to that portion which is covered by the small charge test data. Figure 2−5b shows the Line 1 data when only those shots and every other receiver that fall within the range of the small charge test data are included in the processing. Adjacent CDPs have been summed to give the same CDP spacing as in the mini−source test. The difference between this decimated stack and the full fold stack is striking. Figure 2−5c shows the same data as Figure 2−5b, except that the data have been processed in a manner similar to that for the mini−source test data as shown in Table A−1. The small charge test data stacked sections for both the 28 Hz geophones (Figure 2−5d) and the 60 Hz geophones (Figure 2−5e) show a much clearer image at 300−450 ms (ca. 900−1350 m) than the decimated Line 1 stack (Figure 2−5c). Above 300 ms, the two images are comparable, with the Line 1 decimated stack probably being somewhat better due to the higher frequency content of the 100 gram source on Line 1. This apparent paradox of the larger charges producing higher frequencies can be explained by intrinsic attenuation where the high frequencies of the small charges are so weak that they get damped to below the noise level in the upper 300 ms. Below 450 ms the decimated Line 1 stack is also superior to the small charge test data stacks. The 60 Hz 14 gram test series gives the best overall stacked section. It is directly comparable to the 28 Hz 14 gram series since the same acquisition geometries were used for both data sets. A direct comparison with Line 1 is not possible since the acquisition geometries differ somewhat. However, in the upper 500 ms (c. 1500 m) the data are of comparable or better quality than the decimated Line 1 data. The single 7 gram charges resulted in poorer images than the 14 gram charge data.

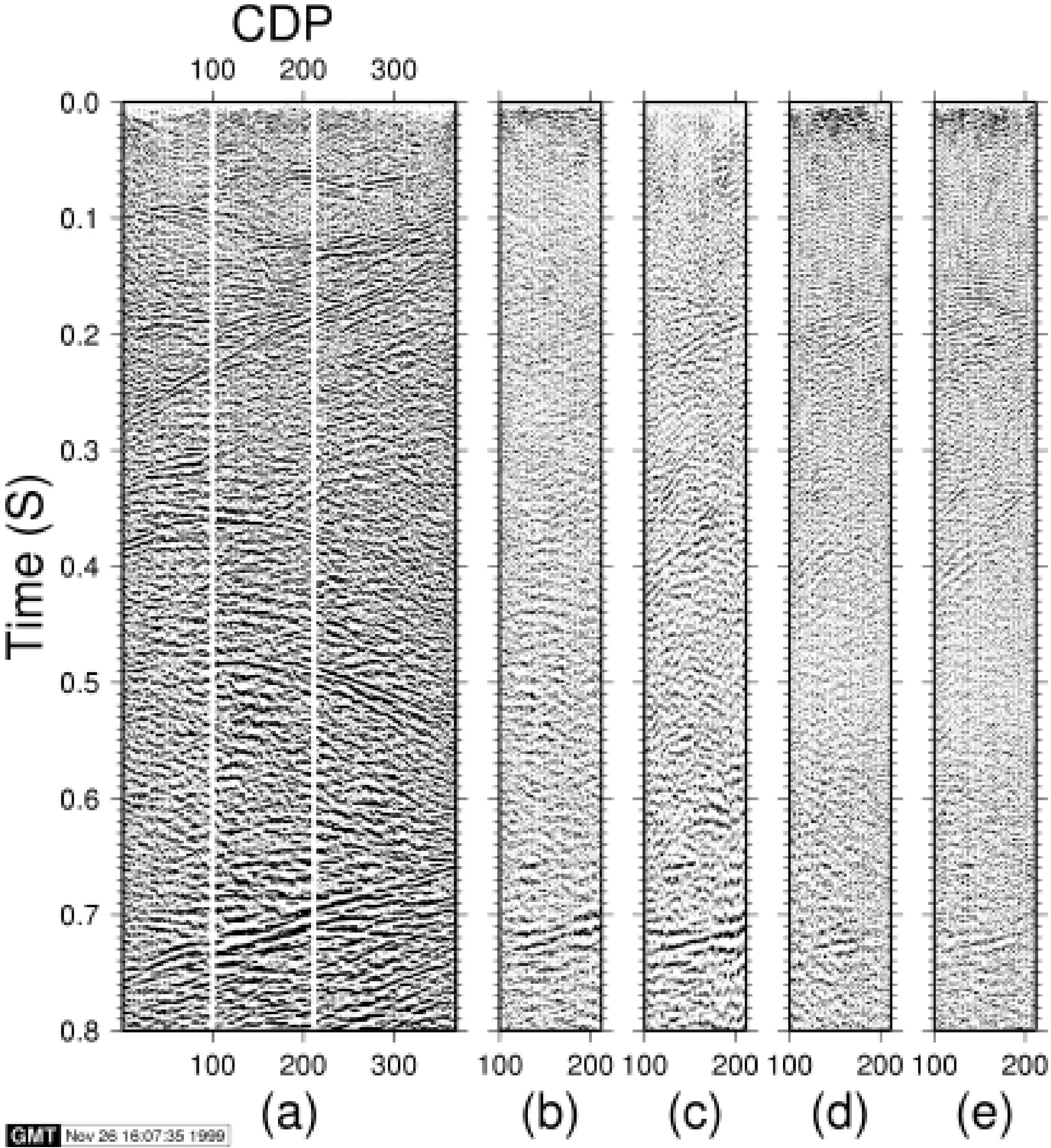

Figure 2−5. (a) Stacked section from Ävrö island Line 1 without DMO. (b) decimated stacked section from Line 1 using same processing parameters as in Figure 2−5a. (c) decimated stacked section from Line 1 using the processing parameters in Table A−1. (d) 28 Hz geophone stacked section from the small charge test data using the processing parameters in Table A−1(e) 60 Hz geophone stacked section from the small charge test data using the processing parameters in Table A−1 .

Spectral analyses

Average spectra were calculated from the 4 shot series (7 and 14 gram charges fired into 28 and 60 Hz geophones) and the 100 gram charges recorded on Line 1 with 28 Hz geophones. The analyses were done in 4 different time intervals (Table 2−3).

Table 2−3. Time intervals in which spectral analyses was performed.

0−200 ms	First arrivals and surface waves
200−400 ms	Most interesting time interval for SKB
600−800 ms	Clear Deep reflector
800−2000 ms	Mainly noise

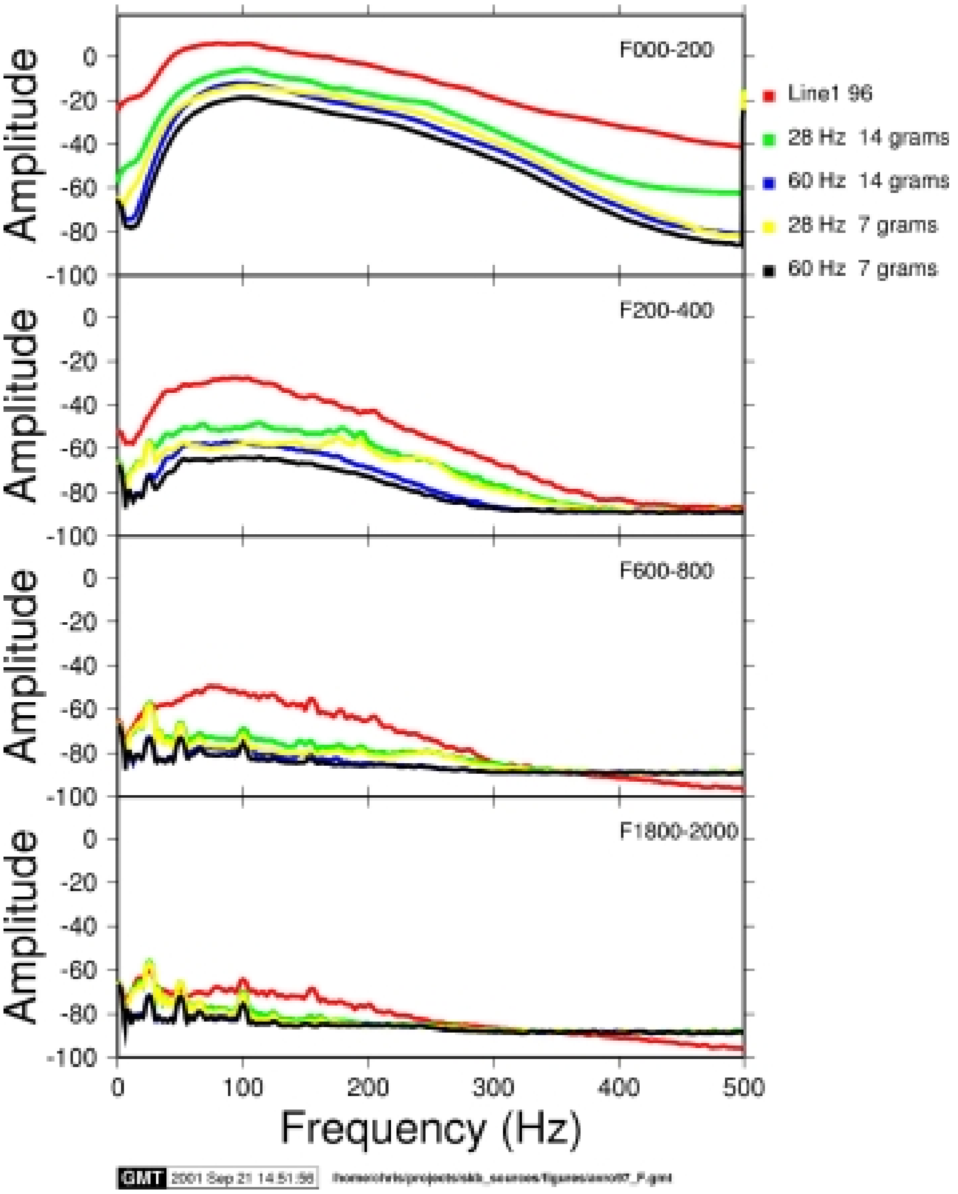

Figure 2−6. Average amplitude spectra for the windows defined in Table 2−3.

Amplitudes from Line 1, shot with 100 grams, are about 15−20 decibel (5−10 times) higher than using 14 gram shots (Figure 2−6). The amplitudes from the 14 gram shots are about twice (6 decibel) the ones from 7 gram shots. The amplitudes are closely proportional to charge size. In particular, note the following characteristics of the amplitude spectra in Figure 2−6.

- Frequencies 200−250 Hz, 28 Hz geophones. The amplitude ratio in relation to charge size is decreasing.
- Frequencies 60−250 Hz. The amplitudes recorded for 28 Hz geophones are almost always higher than for 60 Hz geophones.
- There is little seismic energy below 50 Hz, almost no source generated low frequency ground roll.
- Source generated noise and power disturbances (25, 50, 100 and 200 Hz) dominate the shot series data below 600 ms. The signals are just above the instrument noise level.

Amplitude decay analyses

Average true amplitudes were calculated from the 4 shot series (7 and 14 gram charges fired into 28 and 60 Hz geophones) and the 100 grams charges recorded on Line 1 with 28 Hz geophones. The analyses were done in the frequency bands, 0−500 Hz, 50−100 Hz, 100−200 Hz and 200−400 Hz (Figure 2−7). If the signal penetration is defined as the time when the amplitude ceases to decrease (Barnes, 1994) then the signal penetration for the 7 gram shots corresponds to about 600 ms on both the 28 and 60 Hz geophones and for the 14 gram shots to about 800 ms. Noise levels are about 6 dB (2 times) higher on the 28 Hz geophones than the 60 Hz geophones on the unfiltered data (Figure 2−7).

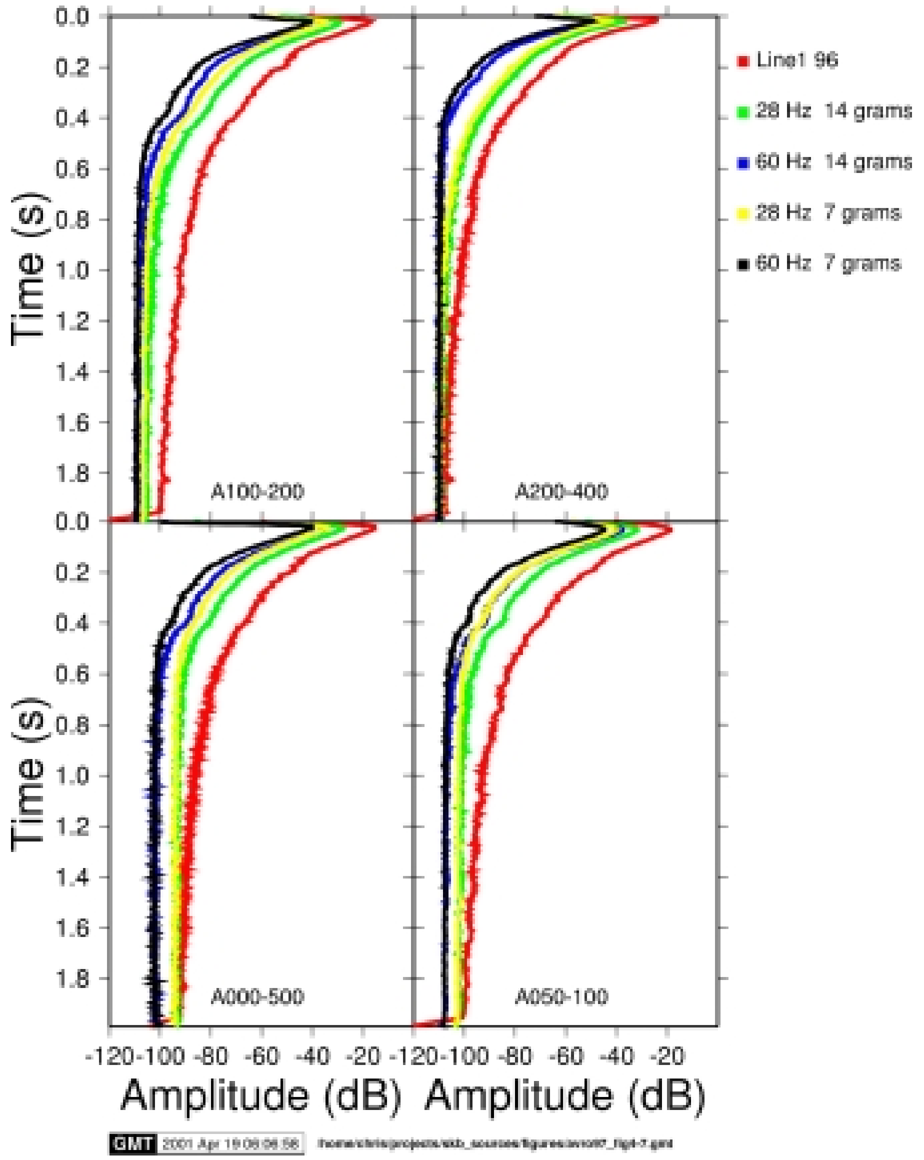

Figure 2−7. Average amplitude decay versus time for Line 1 and the test series for unfiltered data (A000−500), bandpass filtered 50−100 Hz (A050−100), 100−200 Hz (A100−200) and 200−400 Hz (A200−400). All shots from each data set have been included.

2.3. Ängeby mini source test

2.3.1. Background and goals

The aim of this project was to optimize the slim−hole method that is to be used in reflection seismic investigations of the uppermost 1500 m in typical Swedish terranes with frequent bedrock outcrops and thin glacial deposits. As shown in the previous section, such areas give excellent conditions for seismic recording down to depths of 2−3 kms using 14 gram charges of explosives in slim−holes. However, the great advantage with the slim−hole method is that a small handheld electric drill can be used to drill the shot holes. Based on the Ävrö mini−source study the estimated cost savings per length of profile was of the order of 4 times when compared to using drilling equipment carried by vehicles. The 14 gram shot test profile on Ävrö was, however, chosen in such a way that all shot points were on bedrock outcrops. A disadvantage with using small charges is, of course, the risk of using too small a charge size when profiling in a new area. A resulting "white section" can be interpreted in two ways: Either the uppermost crust is truly homogeneous or the signal/noise ratio is too small to image any discontinuities. One way to avoid this unwanted situation is to start a reflection investigation in a new area with 10−20 larger shots (50−100 grams) recorded to 2−3 seconds. Experiences from 500 kms of deep seismic reflection profiling in different areas of Sweden have shown that reflectors are generally present in the upper 2−3 seconds. If deeper reflectors are observed, such reflectors will confirm that the uppermost crust is truly homogeneous.

The Ängeby mini−source test study was carried out in a "new area" using a small handheld electric drill for shot holes to be used for charge sizes of the order of 50−100 grams. The intention was to drill deeper and larger diameter holes than used for the 14 gram shots on Ävrö and to combine closely spaced shot holes. The profile was chosen in such a way that parts of it crossed till with a thickness of more than 2 meters. Different techniques for making the shot holes in the till were tested. The study also included an investigation of the drilling aspects (time studies, bit wear) and a comparative analysis of the seismic energy generated from different shots. As in the Ävrö mini−source experiment, where only 14 gram shots were used, both 28 Hz and 60 Hz geophones were used.

2.3.2. Location

A 320 m long test profile with 10 m station interval was set up in the forest just NE of the village of Ängeby, 20 km NE of Uppsala. The profile was staked out by use of a 100 m tape measure. It was slightly curved to cross over as much bedrock outcrops as possible. Figure 2−8 shows the distribution of stations in till and bedrock. All positions of shot points and geophones were surveyed by use of a theodolite and distancer.

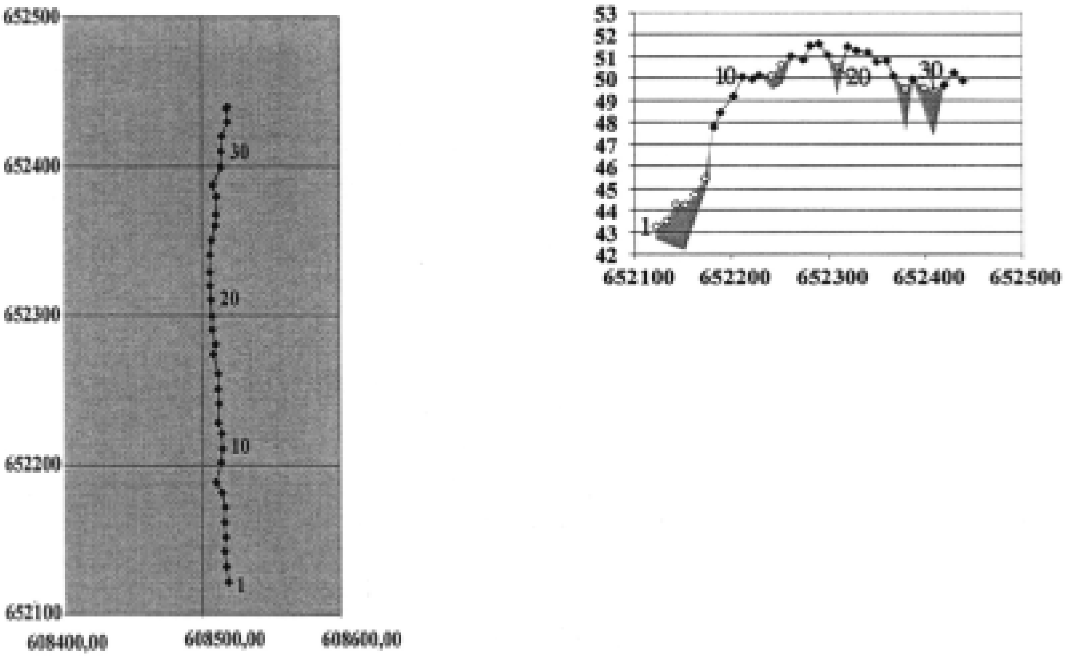

Figure 2−8. Elevation along the seismic profile with station numbers. Gray corresponds to estimated till thickness, white diamonds are stations on till and black diamonds are stations on bedrock.

2.3.3. Acquisition

The handheld electric drill used for drilling in bedrock and in till was the Hilti TE 55, the same one as used in the Ävrö mini−source test. For drilling deeper than 90 cm a minimum bit diameter of 20 mm was used. The drilling program was revised several times because of problems with the 20 mm bits. Drilling with 20 mm bits was much slower than with 12 mm bits, taking almost twice as much time per drilled length. This is due, in part, to that 20 mm bits have a different construction and, in part, to that there are more difficulties in bringing the drilling dust to the surface. At depths greater than 90 cm the drill often became rapidly stuck and had to be pulled up slightly and restarted. If the upward motion is not done quickly enough the bit steel is easily broken by twisting it. Therefore, the number of holes drilled to depths greater than 80 cm with 20 mm bits was reduced in relation to the original plan.

For drilling in till, 25 mm bits were used. Drilling with the Hilti machine to a predefined depth was easy, at least down to 90 cm. As long as the boulders were small enough and the depths were small the boulders were pushed aside. When the resistance was high the machine behaved as in bedrock. The drilling mud from boulders and bedrock filled in cavities in the till and the drilled hole was normally kept open long enough to set down a plastic casing.

For drilling deeper than 90 cm in till a Pionjär MB−61 was used. Most often the drilling was stopped at 35−70 cm at a boulder or at bedrock and only at four stations it was possible to drill deeper. Holes deeper than 90 cm were cased. Most of the holes in the depth range 35−70 cm that were kept open were used for smaller charges.

Data were acquired with the shot and geophone spacing expected to be used for future site investigations (Table 2−4). More detailed information concerning the acquisition and processing is given in Appendix 2.

Table 2−4. Acquisition parameters for the Ängeby mini−source test.

Parameter	*28 Hz line*	*60 Hz line*
Number of channels	33	33
Geophone spacing	10 m	10 m
Shot spacing	10 m	10 m
Nominal fold	30	30
Nominal spread	shoot−through	shoot−through
Geophone type	single 28 Hz	single 60 Hz
Minimum offset	20 m	20 m
Sample rate	1 ms	1 ms
Record length	5 s	5 s
Charge type	Trotyl	Trotyl
Charge size	variable	variable
Nominal charge depth	variable	variable
Field low cut	8 Hz	8 Hz
Field high cut	250 Hz	250 Hz
Number of shots	66	66
Line length	320 m	320 m
Recording system	SERCEL 348	SERCEL 348

2.3.4. Results

Images

Plots of stacked data from all shots and geophones, regardless of whether they were planted in till or bedrock, are shown in (Figure 2−9). Stacks using different combinations of shots and geophones in till and bedrock are shown in (Figure 2−11) (28 Hz geophones) and (Figure 2−10) (60 Hz geophones). There are only 14 geophones in till compared to 19 in bedrock. For both geophone types (28 and 60 Hz), the best images are obtained when all shot and geophone points are used. However, if only geophones in bedrock are used the stacks are only slightly inferior. The importance of using all stations as source points is demonstrated by comparing the sections where only source and geophone points in bedrock have been used. The fold becomes too low and the source generated noise prevails in the upper 300 ms. The same is also true when only shots and geophones in till are used with the resulting stacks being quite poor.

There is little differences between the two geophone types, the 60 Hz geophones give a slightly better image in the upper 400 ms and the 28 Hz ones below 400 ms.

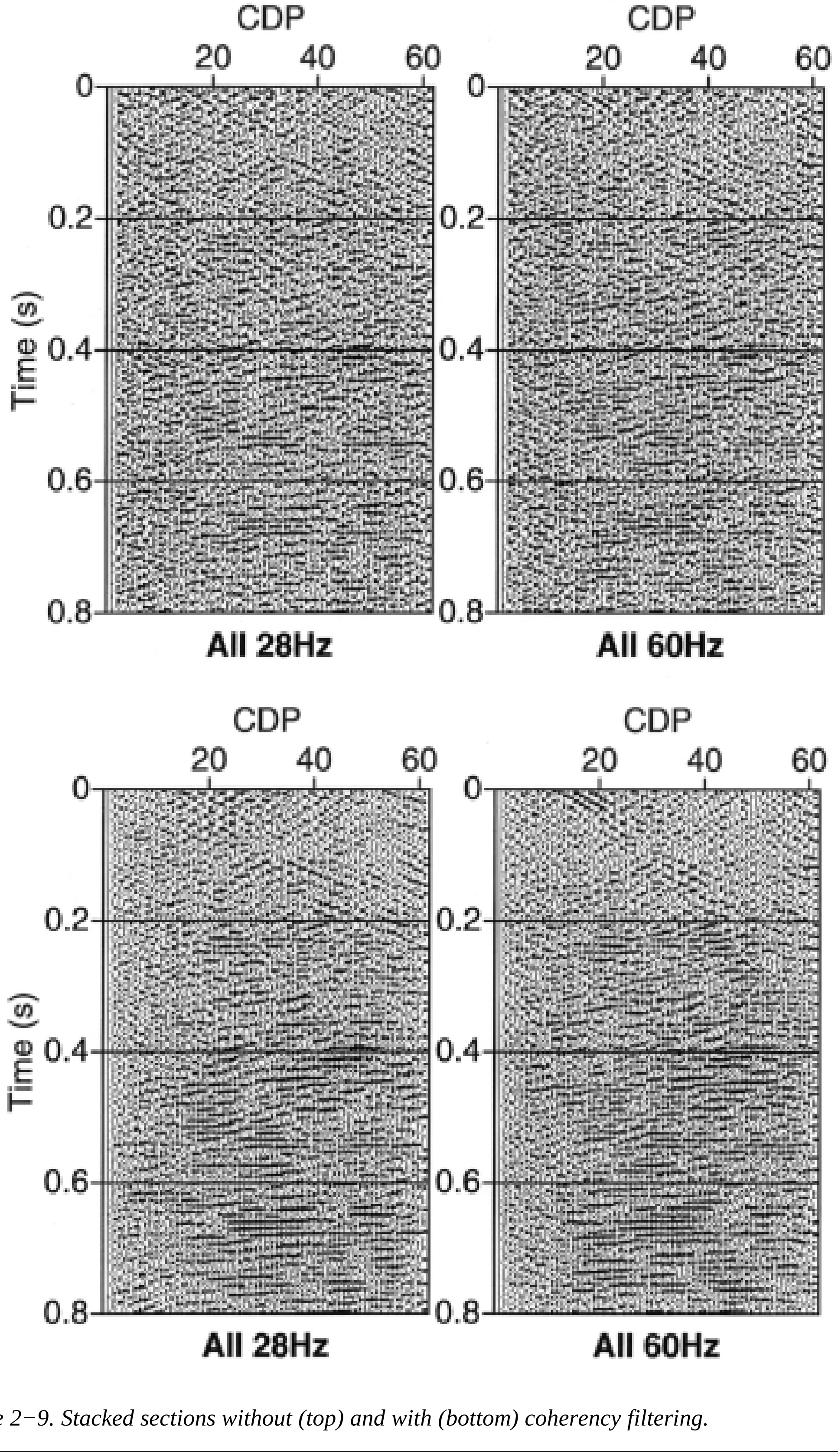

Figure 2−9. Stacked sections without (top) and with (bottom) coherency filtering.

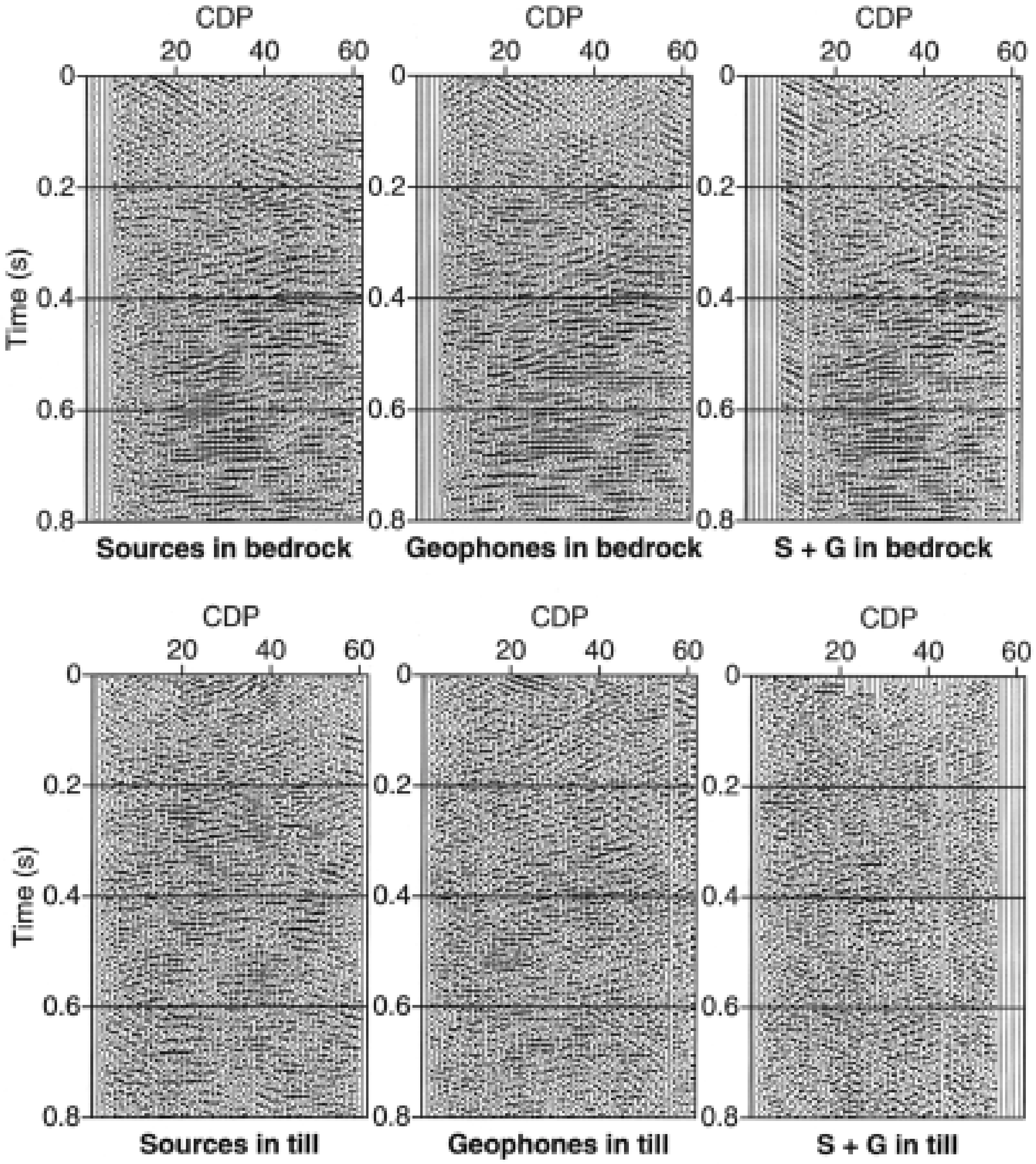

Figure 2−10. Stacked sections from the 60 Hz geophone data using different combinations of sources and geophones in till and bedrock.

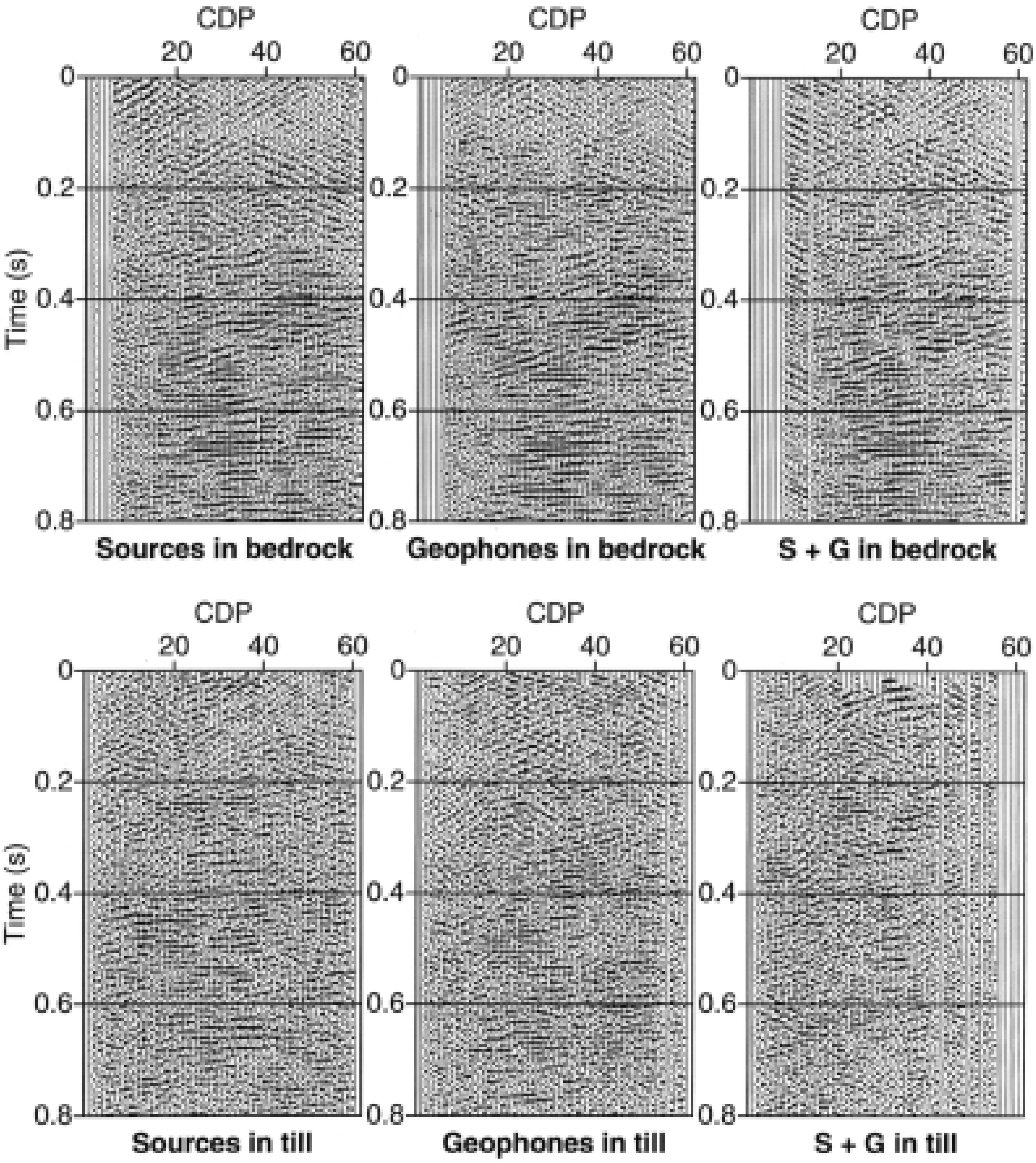

Figure 2−11. Stacked sections from the 28 Hz geophone data using different combinations of sources and geophones in till and bedrock.

Spectral analyses

Plots of amplitude versus frequency for different shot categories show the same trend for 28 and 60 Hz geophones, regardless of whether the first arrival or the 400−800 ms time window is used. An example of this is shown in Figure 2−12 for the shot category 12 mm holes in bedrock. For these shots fired in bedrock the seismic energy increases as charge size increases

In Figure 2−13 the shots have been divided into five groups. The figure shows that slightly more energy per gram of explosive is achieved from shots in 12 mm holes compared to 20 mm holes in bedrock. For shots in till it is only the deep (>1 m) cased holes that give energy well above noise level.

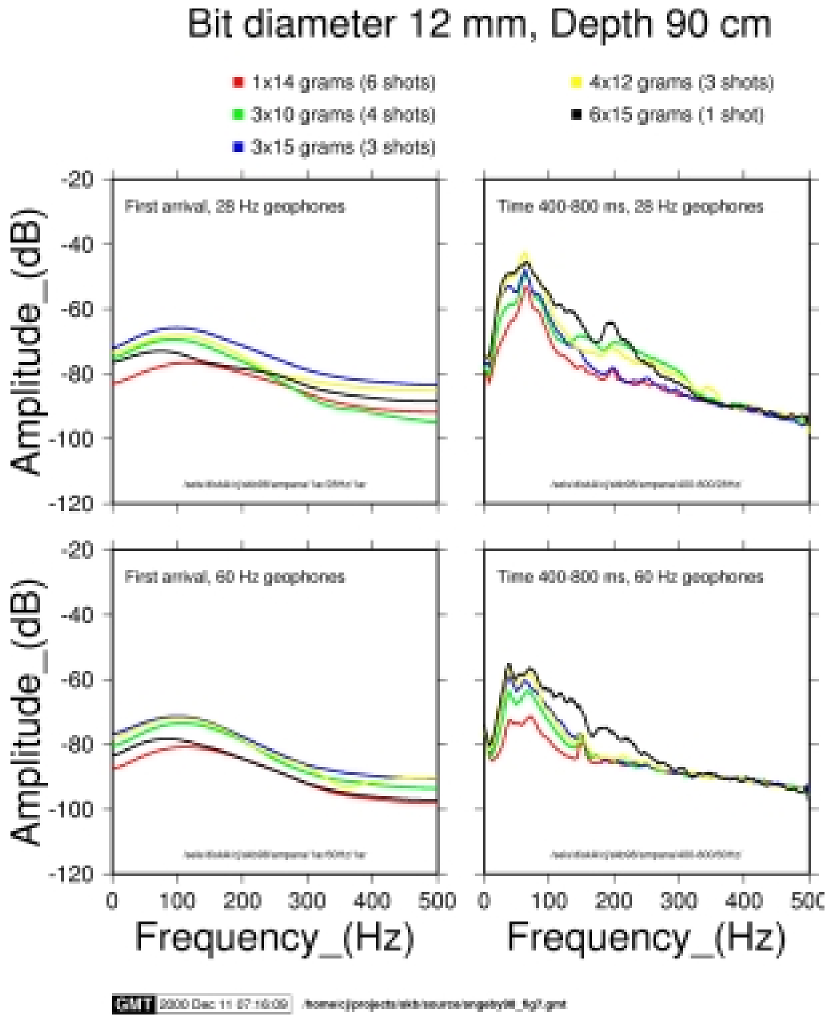

Figure 2−12. Amplitude spectra for various shot configurations using the first arrival window and the 400−800 ms time window for 28 Hz and 60 Hz geophones.

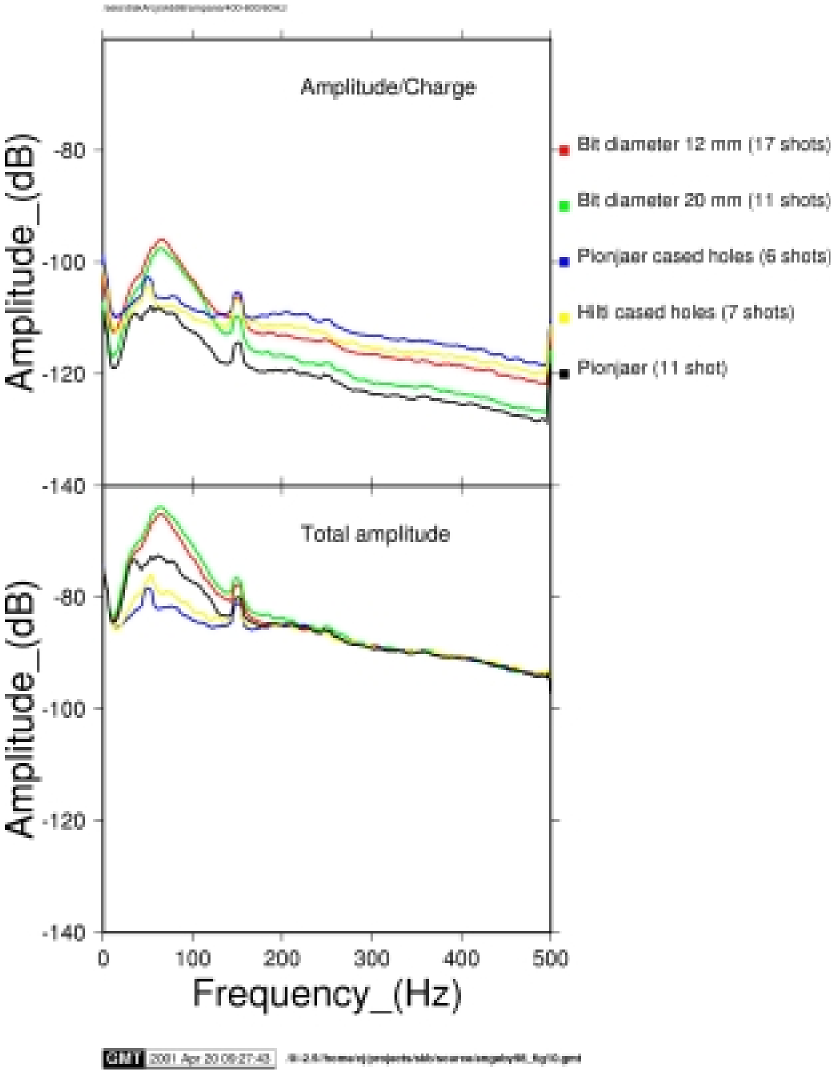

Figure 2−13. Total amplitude and amplitude normalized by charge size spectra for the major shot configurations using the 400−800 ms time window for 60 Hz geophones.

2.4. Laxemar seismic survey

2.4.1. Background and goals

The prime objective of this experiment was to perform a full−scale test of the slim−hole method using small explosive sources for mapping the upper kilometer of the crystalline crust. The shot holes were 12/20 mm in diameter and the charges were 15/75 grams in bedrock/till. Two deep boreholes had earlier been drilled in the survey area, depths of 1700 m (KLX02) and 1078 m (KLX01), that the surface seismic results could be correlated to. A secondary objective of the experiment was to map fracture zones in 3D that are present in the area and that intersect the boreholes. After the testing and development described in the previous sections, a good compromise between charge size and shot hole dimension had been determined to be 15 grams in 90 cm deep 12 mm diameter shot holes in bedrock outcrops and 75 grams in 150 cm deep 20 mm diameter (cased to 16 mm) shot holes in loose sediments.

2.4.2. Location

The Laxemar area was an ideal location to test the slim−hole source method due to its proximity to the Äspö Hard Rock Laboratory (Hammarström and Olsson, 1996) and the Ävrö area where previous studies had been carried out. In addition, two deep (1700 m and 1078 m) boreholes had been drilled in the area that could be used for calibration of the surface seismic data. Therefore, two crossing profiles were acquired over the 1700 m deep KLX02 borehole (Figure 2−14), a 2 km long NE−SW running one passing over the KLX01 borehole (Line 1) and a 2.5 km long NW−SE running one (Line 2), with the acquisition parameters that are expected to be used for future 2D site surveys.

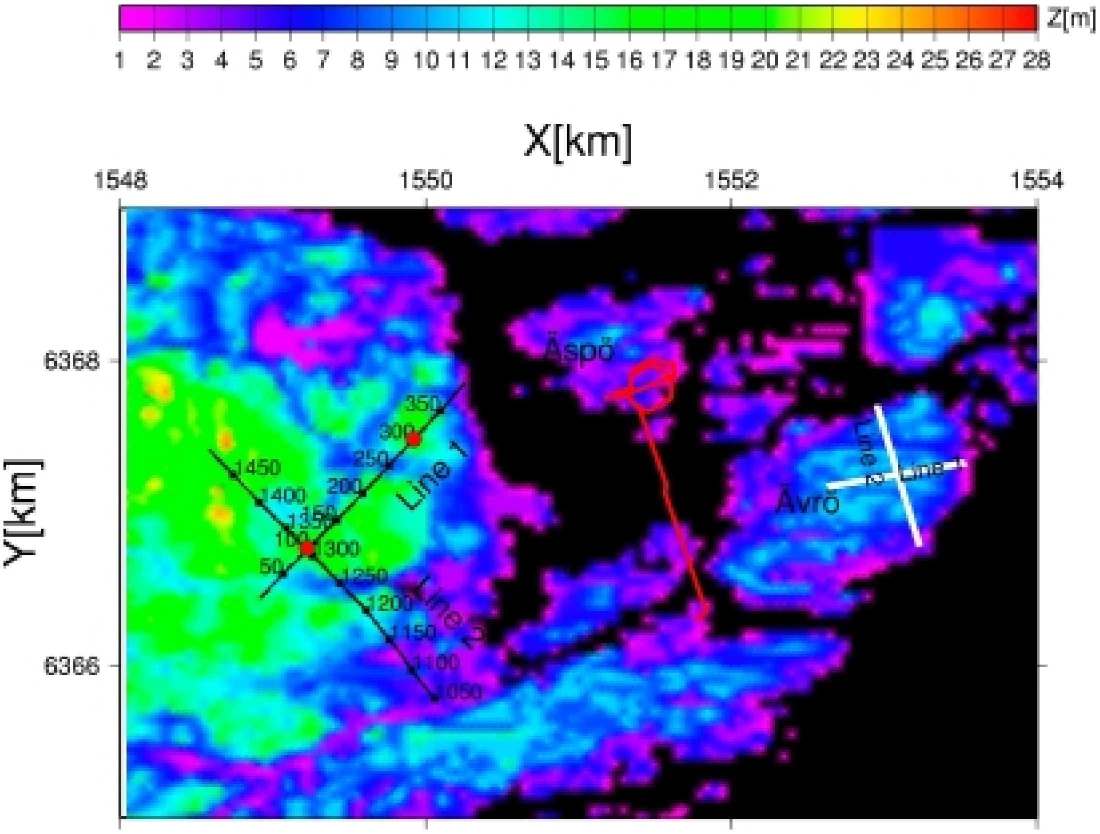

Figure 2−14. Location of the Laxemar (black) and Ävrö (white) seismic experiments and the KLX01 and KLX02 deep boreholes. Red line shows the location of the Äspö Hardrock Laboratory tunnel. Topography is from the SKB database.

2.4.3. Acquisition

The two profiles were acquired in December 1999. Both lines had an (average) station spacing of 10 meters (Table 2−5). Shot points and geophones were located to the greatest extent possible on bedrock. The shot holes were drilled at the closest suitable location to a staked point where bedrock was present, but not further away than 30 cm parallel and 1 m perpendicular to the profile from the staked point. If no bedrock was found within this area, even after removing 50 cm of soil, the shot hole was drilled at the staked point. In bedrock, 12 mm shot holes were drilled to 90 cm depth with an electric drilling machine powered by a gasoline generator. Charge sizes of 15 grams were used in these bedrock shot holes. In soil cover, 20 mm shot holes were drilled to 150 cm depth with an air pressure drill. These shot holes were cased with a plastic− or iron−casing having an inner diameter of 16 mm. Charge sizes of 75 grams were used in these loose soil sediment shot holes. Geophones were placed in a drilled hole in the bedrock if bedrock was found close to the station, otherwise they were placed directly in the soil cover. Bedrock shot holes were used on about 50 % of both profiles. All shot holes and geophone locations were surveyed with high precision differential GPS instruments in combination with a standard total station. This combination gave a horizontal and vertical precision of better than 1 percent of the station spacing (10 cm). The two lines cross each other near the 1700 m deep KLX02 borehole (Figure 2−14), with Line 1 also passing close to the 1078 m deep KLX01 borehole. The seismic data are of fairly good quality due to the thin soil cover. However, windy and rainy weather conditions had a negative effect on some shot records.

Table 2−5. Acquisition parameters for the Laxemar slim−hole profiles.

Parameter	***Value***	
Number of channels	100	
Geophone spacing	10 m	
Shot spacing	10 m	
Nominal fold	50	
Nominal spread	end on / shoot−through	
Geophone type	single 28 Hz	
Minimum offset	20 m	
Sample rate	1 ms	
Record length	5 s	
Field low cut	Out	
Field high cut	250 Hz	
Recording system	SERCEL 348	
	Bedrock	***Sediment***
Charge type	Trotyl	Trotyl
Charge size	15 g	75 g
Nominal charge depth	0.9 m	1.5 m
	Line 1	***Line 2***
Number of shots	196	221
Line length	2 km	2.5 km

2.4.4. Results

Stacked seismic sections of Lines 1 and 2 are shown in Figure 2−15. Where the two profiles cross, it is possible to orient several dipping reflectors and determine where they intersect the KLX02 borehole. Based on correlation with borehole data and surface geology, many of these reflectors appear to be related to fracture zones, some of which have high hydraulic conductivity. However, greenstones (mafic rocks) are probably the source to, or enhance, the stronger more sub−horizontal reflections. Some reflections present only on single lines may originate entirely from greenstone bodies. The signal has generally penetrated to 500 ms (1500 m) along both profiles. Stacking tests using geophones and shot on bedrock versus sediments show similar results to those for the Ängeby mini−source experiment (section 2.3). Stacks using only sources in bedrock and only sources in sediment produce nearly equal quality sections, but stacks using geophones only in sediment give much poorer quality sections than those using geophones only in bedrock. For a complete interpretation of the results see Bergman et al. (2001a, 2001b).

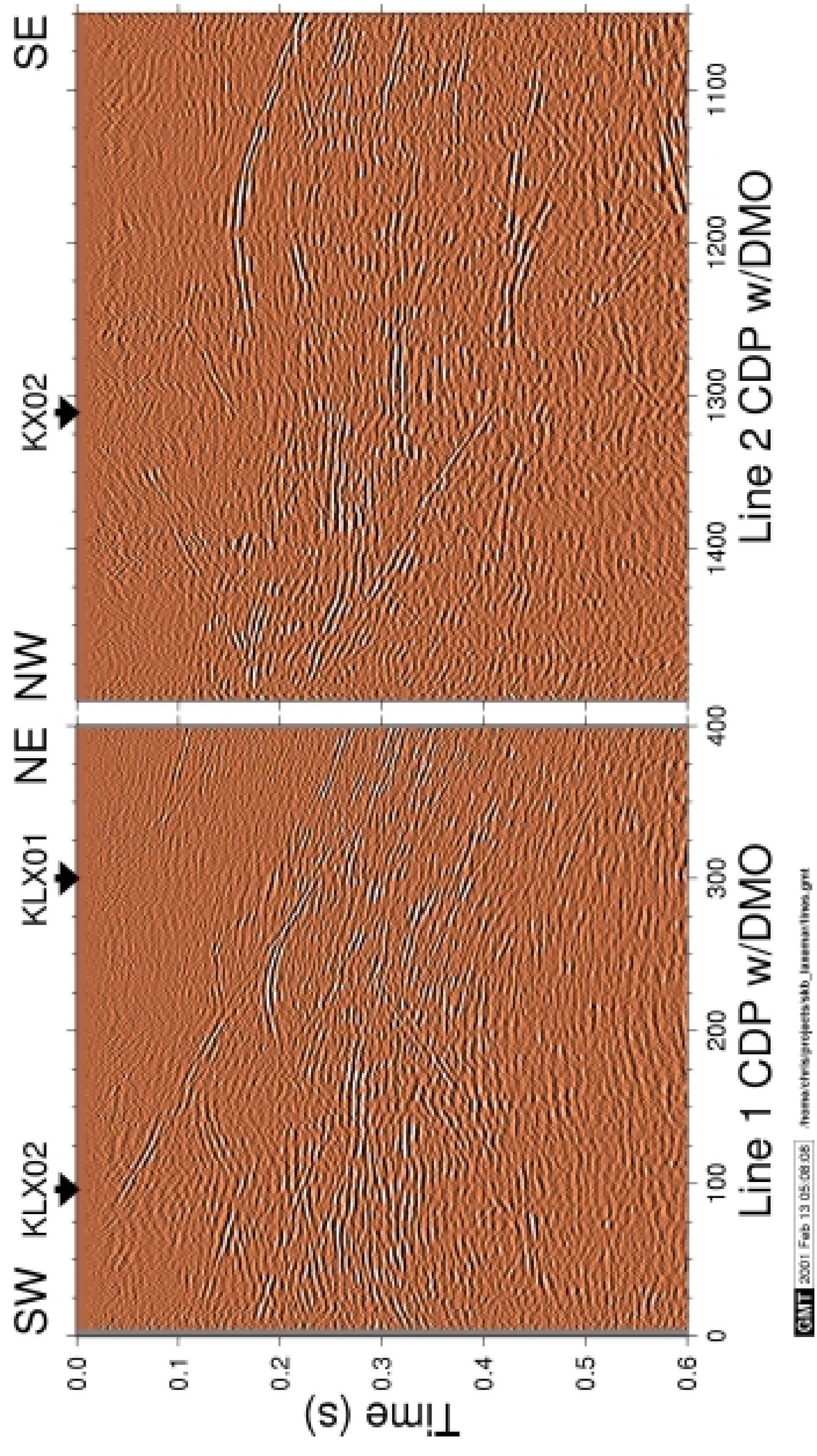

Figure 2−15. Stacked seismic sections of Laxemar Lines 1 and 2

2.5. Gravberg seismic survey

2.5.1. Background and goals

The full scale experiment using the slim−hole method at Laxemar, and the earlier tests leading up to it, had shown that it was possible to obtain high quality seismic images of the upper 1−2 km in areas with high percentages of bedrock outcrop, such as along much of the east coast of Sweden. An open question at this point was if it was possible to obtain high quality images in areas completely covered by a relatively thick layer of till. Seismic surveys in the mid−1980s had revealed several high amplitude reflectors in the upper 5 km in the Siljan Ring area in central Sweden (Juhlin and Pedersen, 1987). Subsequent deep drilling showed these reflectors to be dolerite sills (Juhlin, 1990). The surface seismic data were acquired using 5−10 kg charges in about 10 m deep shot holes in an area generally covered by 5−10 m of till. The combination of a known strong reflector at c. 1.5 km in an area covered by till made the Siljan Ring area an ideal location for testing the slim−hole method where outcrop is absent.

2.5.2. Location

A 3 km long profile was shot along part of the previous "deep" seismic survey in the vicinity of the 6.7 km deep Gravberg−1 borehole (Figure 2−16). Prominent high amplitude reflectors had been drilled at about 1.5, 2.7 and 4.7 km at this location with the uppermost one of these being the target of the new survey.

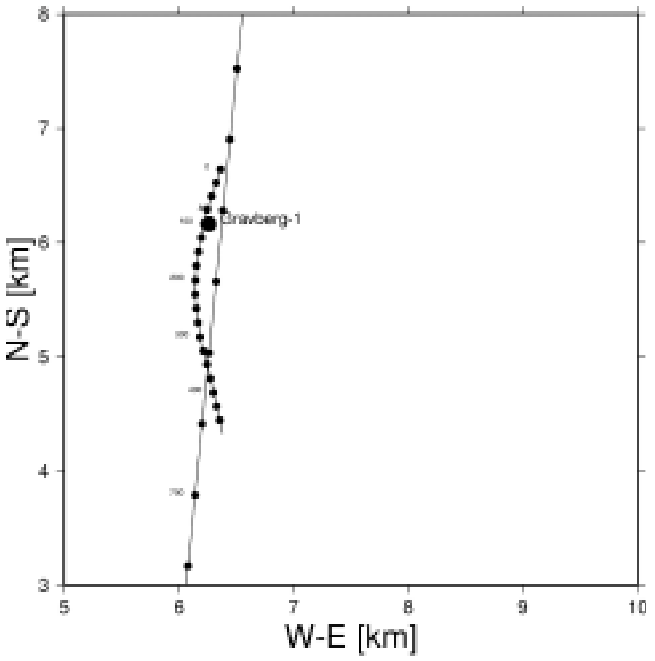

Figure 2−16. Location of the Gravberg slim−hole test profile relative to the deep Gravberg−1 borehole and the previously acquired deep seismic profile.

2.5.3. Acquisition

Two hundred 20 mm wide and 1.5 m deep shot holes were drilled over 4 long working days in May 2000. Since the profile lies along a gravel road a vehicle mounted drilling rig was used, but the holes could have been drilled with handheld equipment. A sturdy pipe was hammered into the shot holes and pulled out before casing was inserted instead of cleaning the holes with compressed air. This resulted in the casing being better set to the bottom of the shot hole and no cavity was created at the bottom of the hole. Plastic casing with an inner diameter of 16 mm was used in the majority of the shot holes, a few shot holes had iron casing.

Data were acquired in the time period 24−30 July 2000 under ideal weather conditions. Three different charge sizes were used along the profile with the following pattern over six shot points: (1) two 32 gram shots, (2) two 74 gram shots, and (3) two 116 gram shots. The first shot hole of each pair was generally tamped with sand and the second with sand and water. The pattern was then repeated for each set of 6 shot holes along the line.

Table 2−6. Acquisition parameters for the Gravberg slim−hole profiles.

Parameter	*Value*
Number of channels	100
Geophone spacing	10 m
Shot spacing	10 m
Nominal fold	50
Nominal spread	end on
Geophone type	single 28 Hz
Minimum offset	20 m
Sample rate	1 ms
Record length	4 s
Field low cut	Out
Field high cut	250 Hz
Recording system	SERCEL 348
Charge type	Trotyl
Charge size	32, 74 and 116 g
Nominal charge depth	1.5 m
Number of shots	191
Line length	3 km

2.5.4. Results

Standard processing parameters were applied to the data resulting in a stacked section with signal penetration to about 3 km with dolerite sills being imaged at about 0.6 and 1.0 s (1500 and 2700 m) at the location of the Gravberg−1 borehole (Figure 2−17). The geometry and location of the reflections on the stacked section agrees well with results from the earlier "deep" seismic survey (Figure 2−18). Even though the resolution is higher, both in time and space, no new reflections were observed on the slim−hole profile.

Separate stacks were produced for each charge size and the images compared. The 116 gram stack gave the best image of the deeper strong reflector at 1.0 s, but otherwise there is very little difference in the upper 0.6 s (1.5 km) between the different stacks. Note that in producing the separate charge size stacks that only one third of the total number of shots was used in producing each stack, a reduction in fold to about 17. This reduction resulted in significantly poorer quality images for the separate charge stacks compared to the full fold stack in Figure 2−17. Comparison of stacks using charges tamped with only sand versus those tamped with sand and water also showed very little difference between one another.

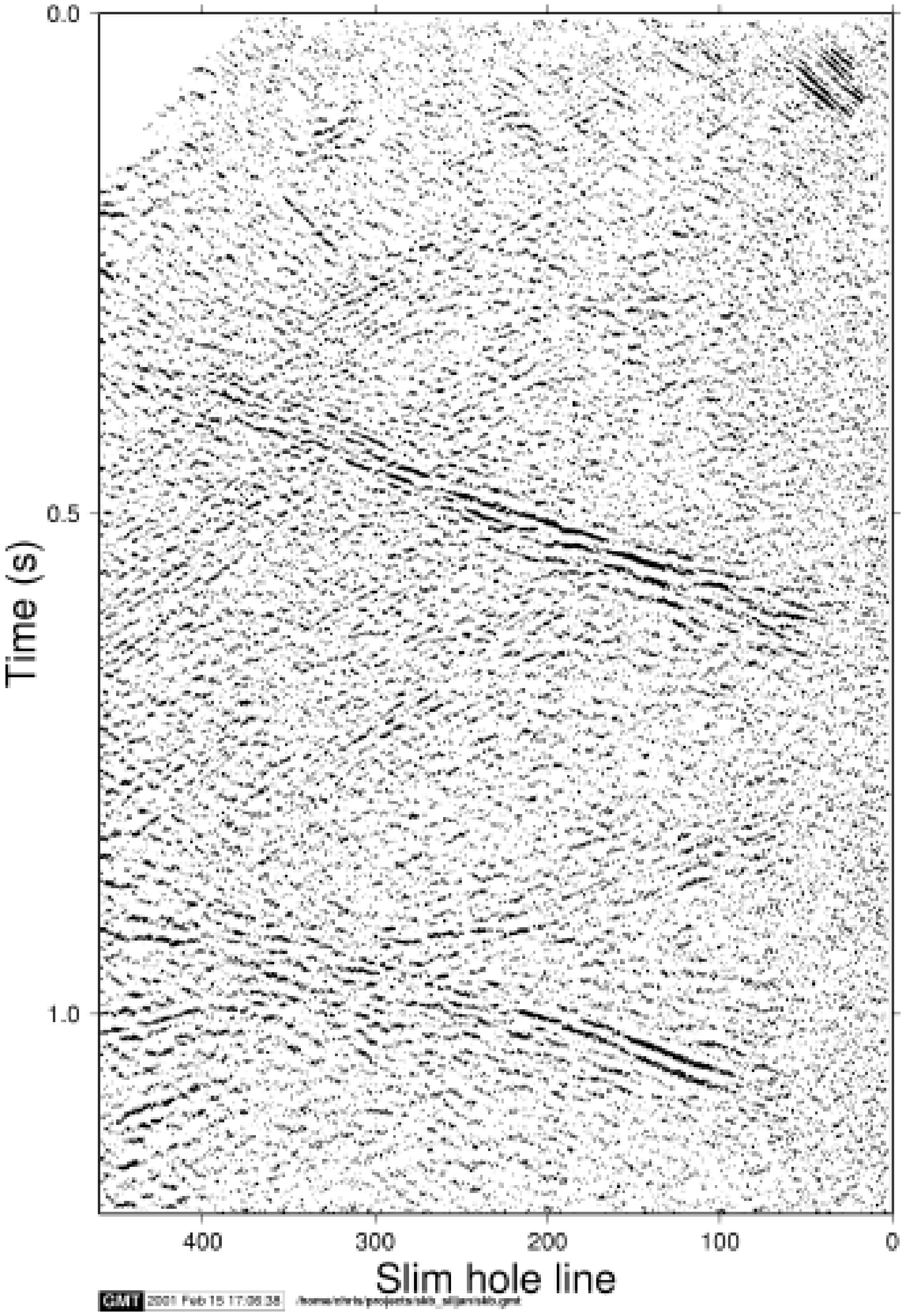

Figure 2−17. Stacked section from the Gravberg slim−hole test profile. The deep Gravberg−1 borehole is located at CDP 100.

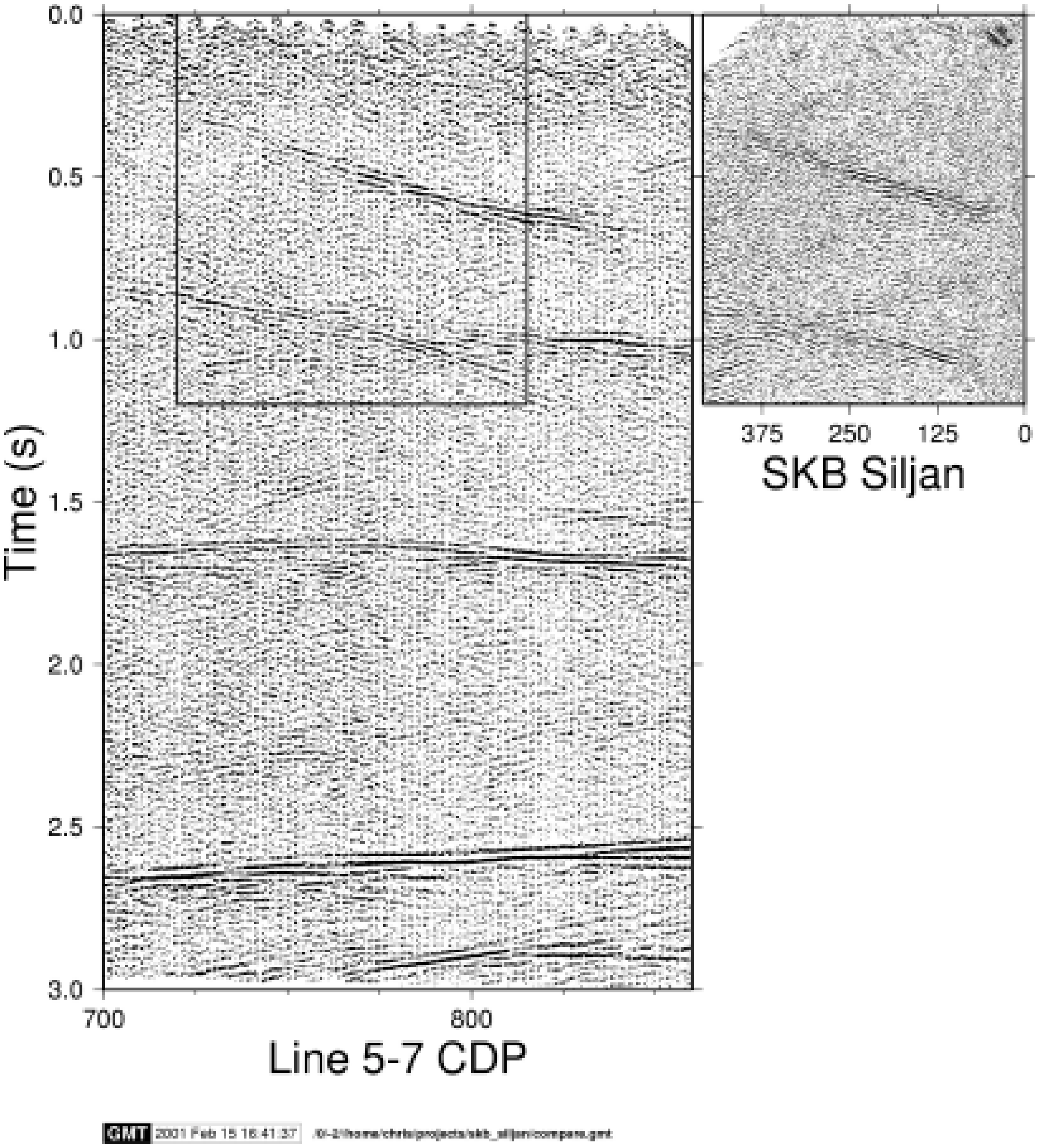

Figure 2−18. Stacked section of the previously acquired deep seismic profile and the slim−hole Gravberg profile.

3. Discussion

The experiments carried out show that it is possible to obtain high quality images of the upper 1−1.5 km in crystalline rock using the slim−hole method. Below about 1.5 km (500 ms), the image becomes poorer due to lack of penetration by the smaller source. Comparison of stacked data from the Ävrö and Laxemar surveys to 1.6 s shows that the deeper reflections below 1 s are not imaged as well on the 15−75 gram charge slim−hole Laxemar data as on the 100 gram larger diameter shot hole Ävrö data (Figure 3−1). The reflectors at about 1.0 s, which are interpreted to represent the same structures on the two data sets, dip at about 10° to the north and project to the surface about 10 km to the south of Laxemar. Sub−horizontal reflections such as these are often observed on seismic data in Sweden in the upper 2−3 s. It is important to image these reflections in order to verify that the signal has penetrated sufficiently deep. If images are obtained at traveltimes of 1−3 s (3−9) km then one can be confident that the upper 500 ms (1.5 km) contains high quality data even if no reflections are present. The lack of reflections can then be interpreted to imply homogeneous rock or, at least, that there are no thick sub−horizontal fracture zones over large areas in the upper 1.5 km.

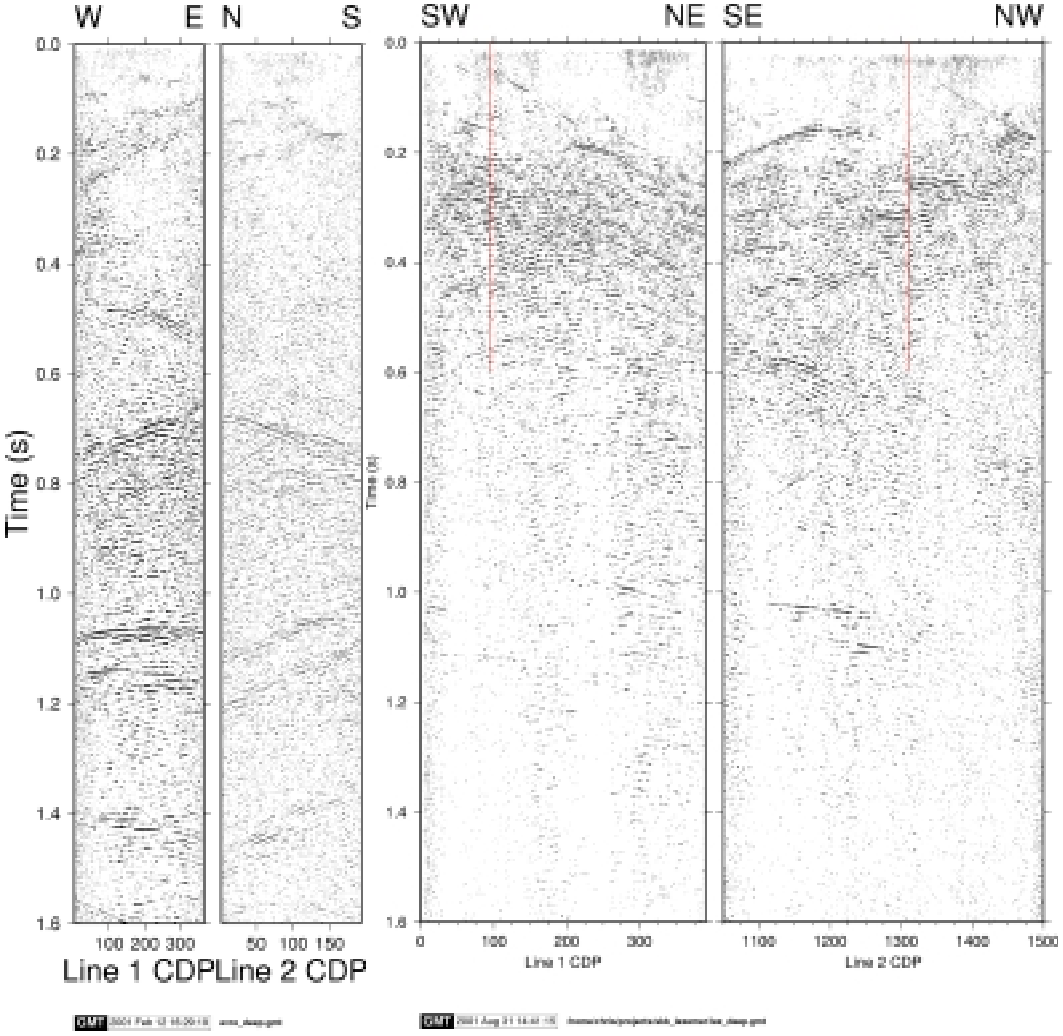

Figure 3−1. Stacked sections to 1.6 s from the Ävrö(left) and Laxemar (right) profiles.

3.1. Time considerations

Drilling of shot holes is not only an expensive component of a seismic reflection survey, but also a time consuming part. For a large field survey, the time required for drilling must be carefully planned. Daily drilling production rates for the Laxemar seismic survey are given in (Table 3−1). Two drilling machines were active, one for sediment shot holes and the other for bedrock. However, both machines were not dedicated solely to the project and were used for other purposes in the area at the same time. Therefore, the maximum daily production rates should be viewed as typical values for what a drilling machine can produce for a single day. The tests in Ängeby gave the average drilling time for a shot hole in bedrock to be about 20 minutes including overhead for non−drilling activities. This corresponds to 24 shot holes that can be drilled by one machine per 8 hour day. The maximum production rate at Laxemar of 25 shot holes per day in bedrock is consistent with this estimate.

Drilling rates for shot holes in sediment were generally slower than for bedrock at Laxemar with a maximum of 19 shot holes per day. At Gravberg, daily production rates averaged 50 holes per day in till. However, a vehicle mounted unit was used and the drillers worked very long days. For planning purposes, it is probably best to use 20 shot holes per day in bedrock and 15 in sediment/till per 8−hour day per drilling machine.

Table 3−1. Daily production rates for drilling of shot holes.

	Number of drilled holes	
Date	***Sediment***	***Bedrock***
15/11	6	17
16/11	15	25
17/11	19	21
18/11	7	20
19/11	13	20
22/11	13	16
23/11	2	19
24/11	12	11
25/11	12	11
26/11	17	5
29/11	1	9
30/11	13	11
1/12	10	10
2/12	14	15
3/12	7	5
6/12	13	11
7/12	15	7
8/12	5	

3.2. Cost considerations

The cost per shot for some of the experiments are shown in Table 3−2. Personnel, generator, fuel, drilling machine and bits are included in the drilling costs when using handheld equipment. Shooting costs include caps and explosives. When drilling in bedrock with the slim−hole method a thin soil cover has to be removed and this cost is included in the calculation. The cost is calculated as if soil removal is necessary at every other shot point. All costs are exclusive of mobilization and demobilization. The drilling costs for 1996 Ävrö seismic survey are based on if the ROC 512 drilling rig had been used to drill all 300 shot holes. The actual costs were higher than this since the drilling contract was split between two companies.

At Ängeby the material costs per drilled meter of hole was about 400:− for 20 mm bits and about 160:− for 12 mm bits. Personnel costs can vary significantly, a cost of 300:− per hour is used for the cost estimates here. This gives a cost of about 300:−per each 90 cm deep 12 mm hole and 900:− per each 1.5 m deep till hole. The higher cost of the till holes is due to longer drilling times (30 minutes versus 20 minutes) and that two people are required to operate the till drilling machine.

The higher costs for drilling in bedrock with the slim−hole method at Ängeby compared to Ävrö (for when shot holes with the same dimensions and depths are compared) can be explained by the rock being more difficult to drill at Ängeby resulting in longer drilling times. The longer drilling times at Ängeby compared to Ävrö also resulted in the material costs being higher there. For drilling in till the cost difference between the slim−hole method and the vehicle mount larger drilling rigs is much smaller than for drilling in bedrock. This is due to the higher material costs and that two people are required to operate the drilling machine efficiently.

Table 3−2. Estimated comparative source costs in SEK.

		Drilling	***Shooting***	***Soil removal***	***Total***
1996 Avrö seismic survey		1300:−	100:−		1400:−
1997 Ävrö mini−source		140:−	70:−	120:−	330:−
1998 Ängeby mini−source	Bedrock	260:−	70:−	120:−	450:−
	Till	900:−	120:−		1020:−

3.3. Environmental considerations

By using the slim−hole method the effects on the environment by a seismic survey are reduced compared to using vehicle mounted drilling rigs. Since heavy equipment need not be driven in the forest, there is a large reduction in damage to vegetation, as well as less scars being left in the ground after the survey. In addition, by using smaller charges, less pollutants are spread by the source.

4. Recommended field parameters

Surface conditions can be divided into the following categories

1. "Ävrö type": about 50% bedrock outcrop, the remaining bedrock is covered by 1−2 m of loose sediments or soil, i.e. clay and sand, with some till
2. Loose sediments: mainly clay, sand and gravel of varying thickness, but reaching up to 100 m thickness in some areas, little or no outcrop
3. Thin till: 5−10 m of till on top of bedrock, little or no outcrop
4. Thick till: till which is greater then 10 m thick, no outcrop

We have only carried out full−scale tests of the slim−hole method in categories 1 and 3. However, based on our experience from these type areas we can even recommend acquisition parameters for categories 2 and 4 (Table 4−1). Note that even in "Ävrö type" areas that about 50% of the shot points will require 20 mm holes drilled to 1.5 m with 75 g charges. Although, charge size and depth are important factors for the quality of the final processed image, the most important factor is a high fold, assuming that the signal is penetrating to the target depth. High fold can only be obtained by having a large number of shot points along the line. Stacks using only shots fired in bedrock or shots fired only in till both have poorer images in the uppermost parts due to a reduction in fold by about one half. This is equivalent to shooting at every other station rather than at every station. Although it is expensive, it is necessary to shoot at every station in order to acquire the best possible image for a given station spacing.

All data presented have been acquired with the SERCEL 348 recording system. The minimum sampling interval is 1 ms with this system and a field high cut of 250 Hz has been used in order to avoid temporal aliasing. In the Ävrö seismic survey, crossline data were also recorded on ABEM Terraloc systems in order to test the potential of using low−fold 3D data (the results were negative). These data show that significantly higher frequencies than 250 Hz are present in the data. How useful these higher frequencies are for improving the seismic image is not known, but with a target depth of 1 km and 10 m station spacing the improvement would probably be marginal if a faster sampling rate was used. However, it is recommended that data be recorded at 0.5 ms, if possible, in order not to loose the higher frequency component of the data.

Stacks using data recorded on 60 Hz geophones have given somewhat better images in the upper 500 ms (1.5 km) than those from 28 Hz geophones. However, the improvement is fairly small and does not warrant any requirement that 60 Hz geophones be used.

Stacking tests have been made on existing data using minimum offsets ranging from 20 m (that used in the actual acquisition) to 100 m. Very small differences are observed in the stacks with minimum offsets up to 80 m. Stacks with a minimum offset of 100 m start are poorer in the upper 100 ms. However, our tests were done on data that had been processed with all offsets. It may be that the offset range 20−80 m is important for refraction static calculations. Therefore, we recommend a minimum offset of 20 m until further studies are carried out.

If the dynamic range of the acquisition system is high enough then the field low cut filter can be left out. If surface waves appear to be a problem then a field low cut filter can be considered. The slim−hole method, in general, generates only low amplitude surface waves and the high frequency geophones also have damping effect on them. These surface waves may provide useful information on the near surface and should not necessarily be removed in the field.

Table 4−1. Recommended acquisition parameters for various surface conditions.

Parameter	***Value***			
	Ävrö type	***Loose sediments***	***Thin till***	***Thick till***
Charge type	To be decided			
Charge size	15/75 g	75 g	75 g	116 g
Nominal charge depth	0.9/1.5 m	1.5 m	1.5 m	1.5 m
Number of channels	>100			
Geophone spacing	10 m			
Shot spacing	10 m			
Nominal fold	>50			
Nominal spread	end on			
Geophone type	single 60 Hz or single 28 Hz			
Minimum offset	20 m			
Sample rate	<1 ms			
Record length	4 s			
Field low cut	Out			
Field high cut	>250 Hz			
Recording system	Digital			
Profile length	>3 km			

The length of a profile is dependent upon how deep dipping structures are to be imaged (Figure 4−1). Since many structures appear to dip at about 45° and the target depth is down to 1 km then in order to image these structures the profiles must extend 1 km beyond the limits of the target area. In order to obtain reliable images down to 1 km within the target area a minimum of 1 km of profile is required in addition to the 1 km extensions on the sides. This implies that profiles should be at least 3 km long in order to obtain unbiased images down to 1 km over a 1 km long section.

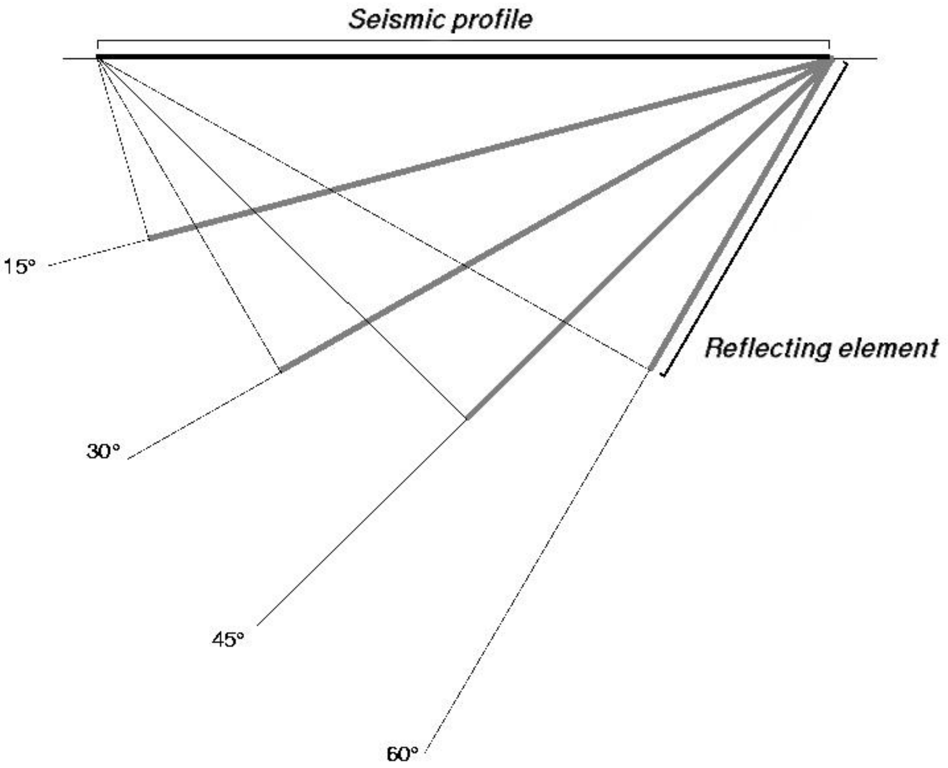

Figure 4−1. For a fixed profile length, the length of the reflecting element imaged decreases as the dip of the reflector increases.

5. Recommended processing parameters

Several studies have shown that processing is an important component in producing the final image that is to be interpreted (e. g. Juhlin, 1995; Wu and Mereu, 1992; Wu, 1996). Good static corrections are one of the most important factors in obtaining high quality images. It is especially important to have good first break picks in order to get the best possible initial refraction static corrections. In addition, the presence of both dipping and sub−horizontal reflections and the long−offsets used relative to the depth of the targets generally require that DMO (dip−moveout) be applied to obtain better images of the upper 300 ms. When the data are processed without DMO it is not possible to image two reflectors with differing dip at the same sub−surface location. Application of DMO allows, in theory, reflectors of all dips to be imaged simultaneously. Spectral whitening and choice of bandpass filter, as well as velocity analyses, are other important steps in the processing chain. Recommended processing steps are given in Table 5−1.

Table 5−1. Recommended processing parameters.

Step	Process	Domain	Velocity Analysis	Stack control	Comment
1	Read raw data	CSG			
2	Spike and noise edit	CSG			
3	Pick first breaks	CSG			
4	Geometric spreading correction	CSG			multiply by time is generally sufficeint
5	Attenuation correction (optional)	CSG		1	some correction must be done at early arrival times
6	Refraction statics	CSG			
7	Surface consistent deconvolution	CSG			spectral whitening is also an option, sometimes this step must be skipped
8	Bandpass filter	CSG	1	2	many tests need to be made
9	Residual statics − Pass 1	CMP		3	
10	Trace top mute	CMP		4	remove first arrivals from data
11	AGC − Apply and save	CRG			
12	Velocity filtering	CRG		5	signals are more consistent in CRGs
13	AGC − remove	CRG	2		
14	Residual statics − Pass 2	CMP		6	
15	Trim statics (optional)	CMP		7	use a very short allowable shift otherwise you are cheating
16	AGC or trace equaliztion	COG			some kind of equalization generally must be done
17	NMO	COG	3		"true" velocities should now be used
18	DMO	COG		8	
19	Stack	CMP			alpha trimmed is generally better
20	F−X Decon	stack			or some other coherency filter
21	Trace equalization	stack			
22	Migration	stack			
23	Trace equalization	stack			

CSG − Common shot gather
CMP − Common midpoint gather
CRG − Common receiver gather
COG − Common offset gather

Good refraction static corrections is, perhaps, the most important step in the processing. This step is dependent upon that geometry has been applied correctly and that the first breaks are picked sufficiently accurately. The importance of verifying that the geometry is correct and that the refraction statics show significant improvement in the coherency of both shot and receiver gathers cannot be overemphasized.

6. Conclusions

From our studies we can conclude the following concerning high−resolution seismic acquisition on crystalline rock:

- If possible, shot holes should be drilled in bedrock within an ellipse centered on the station and that has a major axis perpendicular to the profile that is 20% of the station spacing and a minor axis that is 6% of the station spacing. If no bedrock is found within this ellipse the shot hole should be drilled in the loose sediments at the station.
- Shot holes in loose deposits (soil and till) should not be blown clean with compressed air. Instead, a pipe should be used to clean them before setting casing.
- Geophones should also be placed in drilled holes in bedrock, if possible, under the same constraints as for the shot holes.
- Soil and loose sediments should be removed if their thickness is less than 20−40 cm at the geophone positions.
- Profiles should extend 1 km further on each side of the target limit in order to image 45° degree dipping structures to 1 km depth.
- It is important to acquire the sesmic data under good weather conditions.
- Larger charges of 100−200 g can be fired by shooting several slim−holes in parallel. When a new area is being investigated, these larger charges should be fired at the start of the field work.
- Proper reconnaissance is necessary prior to starting field work in order to position in an optimal manner for both geological and logistical reasons.
- Surveying with differential GPS and total station measurements provides a high enough accuracy for reflection seismic processing.
- 60 Hz geophone are preferable to 28 Hz geophones, but the difference in data quality is marginal. Positioning and planting the geophones optimally is much more important.
- A 1 ms sampling rate is adequate, but 0.5 ms would be preferred.
- Sand and water combined is the optimum tamping method.
- A minimum of 96 channels is recommended for 2−D surveys.
- Having high fold in the data is more important than using larger charges. In order to have high fold, shots should be fired at every station.

7. Future Work

Although we recommend using single geophones for each station to increase resolution, we have not specifically tested the trade−off between resolution and increased signal to noise ratio using an array of geophones for each station. This would require future field work where various arrays are tested against single geophones along the same profile.

Another aspect which has not been tested is the precision in the surveying that is necessary to get reliable images. The combination of GPS and total station used to date has given coordinate accuracy on the order of cms. This may be overkill, however, it is not obvious what the minimum accuracy required is. Testing of this can be done using existing data and synthetic data by perturbing the coordinates and redoing the processing with various degrees of introduced errors.

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Appendix 1: Acquisition and processing details for the Ävrö mini−source test

Positioning

The test measurements were performed with a stationary spread of 320 m from station 1045 to 1109 along Line 1 in Juhlin and Palm (1999). The stations were easily located as either remaining stakes, shot holes or small drilled geophone holes. Since the coordinates of the station points, shot and geophone holes were known from the earlier profile, the new positions of the shot holes and geophone points could be established to sufficient accuracy by use of tape measure and compass.

Soil removal

At 12 of the 33 stations where the soil cover was less then 0.5 m it was removed by use of a skid steer loader GEHL 5625 equipped with a power shovel. The cleaning of soil from the bedrock was done in 30 minutes including transport between the stations. After soil removal all 33 receiver stations were located on bedrock.

Drilling

All holes were made by a Hilti TE 55, a 6 kg electric combihammer drilling machine. The shot holes were drilled with 12 mm bits down to 60 cm depth in the bedrock. Total drilling time for a hole was approx. 10 min. Three shot holes were drilled at each station. At the westernmost station nine holes were drilled with one meter separation, three to 60 cm, three to 70 cm and three to 90 cm depth. Total drilling time to 90 cm was approx. 15 min. For a total of 97 shot holes four 95 cm and six 40 cm drills were used up.

The geophone holes, two at each station for 28 and 60 Hz geophones, were made by a 8 mm bit down to 3−6 cm.

For the power supply of 230 V a 3kW Honda generator was used consuming 35 liters of petrol for all the drilling.

Loading procedure

A plastic trotyl based explosive was punched into thin hard plastic pipes of 11 mm diameter. The length of the charges varied from 39 to 155 mm, corresponding to 5 to 20 grams. To the pipe lengths 25 mm was added for the electric caps. The explosives were tamped with a fluid mixture of drill cuttings and water. For the second shot series, using two nearby holes, the caps were connected in series.

Recording

All recordings were done during a period of excellent weather conditions with almost no wind and no rain.

Test shots

For testing purposes, at the westernmost station, recordings from the following charge sizes (gram) and depths (cm) were obtained:

Depth	Charge size
60	5, 10 and 15 grams
70	5, 10 and 15 grams
90	5, 10 and 20 grams

A simple field processing of the nine test shots showed that 5−10 g at 60 cm and 10−15 g at 90 cm gave strongest coherent energy around 340 ms. This reflection is the most easy to detect on raw shot plots. After the test it was decided to shoot one shot series with 7 g in one 60 cm shot hole at each station and another series with 14 g in one 90 cm shot hole. The 90 cm holes were intended to be done by deepening the already predrilled 60 cm holes. However, it was found impossible to continue drilling in these holes that were drilled some days earlier because of small amounts of water in the holes. After drilling a few centimeters cuttings and water mixed to a very sticky material and the drill became stuck. Instead of drilling new holes to 90 cm, a third hole was drilled to 60 cm approx. 10 cm from one of the other holes. The charges were later divided into two 7 gram charges and fired simultaneously.

Shot series

The two shot series (7 and 14 grams) were fired into a fixed spread of 33 stations and 66 channels (28 and 60 Hz geophones at each station). In the processing, the nearest 3 stations for both geophone groups were excluded.

The shot series with a single 7 gram charge was fired with a mean time interval of one shot every 11 minutes and the two 7 gram charges in series were fired every 14 minutes.

Table A−1. Main Processing steps for small charge test data on Ävrö island.

1	`Read SEG2 data`
2	`Add geometry`
3	`Trace edit`
4	`Pick first break`
5	`Refraction statics`

6	`Bandpass filter`
	`70−140−300−420 Hz  0-  200  ms`
	`60−120−300−450 Hz  100−400  ms`
	`50−100−300−450 Hz  300−600  ms`
	`40− 80−240−360 Hz  500−800  ms`
	`30− 60−180−240 Hz  700−2000 ms`

7	`Velocity analysis`
8	`Residual statics`
9	`Split data into subsets for 28 resp. 60 Hz.`
10	`Sort to CDP domain`
11	`AGC: 100 ms window`
12	`NMO`
13	`Stack: 5% alpha trimmed mean`

Appendix 2: Acquisition and processing details for the Ängeby mini−source test

The drilling schedule used is shown in (Table A−2). For calculation of the total time for the drilling operation the actual drilling time has been increased by 60 % to include moving the generator, electric cables and drill, cleaning bedrock from moss and roots, drilling small geophone holes, fueling the generator, record keeping, etc.

The material costs per drilled meter of hole was SEK 394 for 20 mm bits and SEK 158 for 12 mm bits. Personnel costs can vary significantly, but if a cost of SEK 250 per hour is used then the cost per 12 mm hole is about SEK 300.

Table A−2. Drilling program, times required to perform the shot holes and the charges used.

Drilling equipment	*Geol. material*	*Bit diameter (mm)*	*No. of holes * depth (cm)*	*Drilling time (min)*	*No. of shot points in different shot categories*	*Charge (grams)*
Hilti	Bedrock	20	1*115	50	1	1*40
Hilti	Bedrock	20	5*100	205	1	5*12
Hilti	Bedrock	20	4*100	164	1	4*25
Hilti	Bedrock	20	2*100	82	1	2*25
Hilti	Bedrock	20	5*80	180	1	5*20
Hilti	Bedrock	20	3*80	108	2	3*17
					4	3*10
Hilti	Bedrock	20	2*80	72	1	2*14
Hilti	Bedrock	12	6*90	126	2	6*15
Hilti	Bedrock	12	4*90	84	3	4*12.5
Hilti	Bedrock	12	3*90	63	4	3*15
					4	3*10
Hilti	Bedrock	12	1*90	21	6	1*14
Hilti	Till	12	1*90	12 (1)	1	1*14
Hilti	Till	25	4*90	76 (2)	2	4*15
Hilti	Till	25	4*60	64 (2)	2	4*10
Hilti	Till	25	1*90	19 (2)	4	1*14
Pionjär	Till	25	1*200	47 (2)	1	1*100
					1	1*75
					1	1*50
Pionjär	Till	25	1*90	20 (2)	1	1*50
Pionjär	Till	25	4*30−60	52	2	4*14
Pionjär	Till	25	1*35−70	13	9	1*14

(1) Only one hole was possible to drill to 90 cm with 12 mm bit and keep open in till out of many tries.

(2) Including time for casing.

Charging procedure

Plastic explosives with a detonation velocity of 6500 m/s were used. In 12 mm holes in bedrock and cased holes in till the charge diameter was 11 mm. In 20 mm bedrock holes and uncased holes in till the charge diameter was 17 mm. The charge length was determined by the desired amount of explosives for each hole and cut accordingly. The charges used in the different shot holes are shown in (Table A−2). The explosives were tamped with fine grained sand and water. For shots consisting of two or more charges in nearby holes, the caps were connected in series.

Recording

A spread of 66 channels was used (33 single 28 Hz and 33 single 60 Hz geophones). The geophones were placed either in drilled holes in bedrock or in till after removing 10−20 cm of the top soil. Recordings were done using Sercel field units and Prosol PC central unit.

Four shots, out of total of a 30 using more than one hole, produced falling stones resulting in noisy records. None of the 25 shots using only one hole caused any observable noise in the records.

Table A−3. Processing sequence for the Ängeby mini−source test.

Read SEG2 data	
Add geometry	
Pick first break	
Elevation statics	
Refraction statics	
Velocity analysis	
Residual statics	
CDP stacking	**Spectral analysis**
Spectral whitening: 30−40−120−140 Hz	Chose data from geophones in bedrock, 28 or 60 Hz geophones, shot category
Bandpass filter: 30−50−150−220 Hz	True amplitude recovery
NMO	NMO
CDP stacking	Trace muting
FX−Decon (Coherency filtering)	Forward FFT
	Stack all traces

Processing

The processing objectives were to:

- Produce stacked seismic sections for studying the reflectivity as a function of time with regards to:
    - geophones (28 and 60 Hz).
    - shot location (till or bedrock)
    - geophone placing (till or bedrock)
- Analyze true amplitudes from shots of different categories. The analyses were done in two different time intervals:
    - 0−20 ms after linear move out correction, corresponding to first arrivals.

- 400−800 ms after normal move out correction, Corresponding to a wide reflective time window.

CDP stacking

Only 2 or 3 shot records showed reflected energy before processing the data. The following stacked sections were produced for both the 28 Hz and 60 Hz geophones using data from:

- All shot points and geophones (1684 traces, max fold 58)
- Only shot points in bedrock (902 traces, max fold 34)
- Only geophones in bedrock (971 traces, max fold 37)
- Only shot points and geophones in bedrock (498 traces, max fold 29)
- Only shot points in till (782 traces, max fold 27)
- Only geophones in till (713 traces, max fold 29)
- Only shot points and geophones in till (309 traces, max fold 17)

Exactly the same processing steps (Table A−3) were applied to each processing stream. For the important static corrections only the data put into the stream were used for the residual statics correction, however, all data were used for the refraction static correction.

Spectral analysis

All analysis were made for geophones in bedrock since these geophones show the highest signal/noise ratio, the lowest influence from surface waves and are more free from noise bursts. Spectra was created for all combinations of:

$$\frac{\text{28 Hz geophones}}{\text{60 Hz geophones}} \, x \, \frac{\text{First arrivals}}{\text{Time interval 400−800 ms}} \, x \, \frac{\text{Individual shots, all traces stacked}}{\text{Shots in same category stacked}}$$

In spite of the fact that individual shots in the same category show great variation all shots in each category have been used in the spectral analysis with one exception. In the time interval 400−800 ms four shots were excluded. These shots produced groups of falling splintered bedrock, partly within the time interval of interest.

Appendix 3: Processing parameters for the Laxemar slim−hole test

Table A−4. Main processing steps for slim−hole test at Laxemar

1 Read SEG2 data − 2000 ms
2 Spike and noise edit
3 Pick first breaks
4 Scale by t**2
5 Refraction statics
6 Surface consistent spiking deconvolution

Design gate 0 m: 200−500 ms, 500 m: 350−600 ms

Operator 40 ms

White noise added 1%

7 Bandpass filter

70−140−300−420 Hz	0−200 ms
60−120−300−420 Hz	100−400 ms
50−100−300−420 Hz	300−600 ms
40−80−240−360 Hz	500−800 ms
30−60−180−240 Hz	700−2000 ms

8 Sort to receiver domain
9 Residual statics − Pass 1
10 Trace top mute

0 m: 1 ms

100 m: 18 ms

1000 m: 183 ms

11 AGC − Apply and save− 50 ms window
12 Velocity filtering − median method

Remove 3000 m/s

13 AGC − remove
14 Sort to CDP domain
15 Velocity analyses
16 Residual statics − Pass 2
17 Trim statics − 2 ms maximum shift
18 Sort to common offset domain
19 AGC − 50 ms window
20 NMO
21 Common offset F−K DMO velocity − average DMO velocity
22 AGC − 50 ms window
23 Trim statics − 2 ms maximum shift
24 F−X Decon
25 Trace equalization 100−1000 ms
26 Kirchoff Depth migration same velocity as DMO 5500 m/s
27 Trace equalization 200−500 m

Appendix 4: Processing parameters for the Gravberg slim−hole test

Table A−5. Main processing steps for slim−hole test at Gravberg.

1 Read SEG2 data − 4000 ms
2 Spike and noise edit
3 Pick first breaks
4 Scale by t**2
5 Air−blast attenuation
6 Refraction statics
7 Spectral whitning

    Balancing frequencies

    25−40−160−200
8 Bandpass filter

50−80−200−400 Hz	0−150 ms
40−60−180−360 Hz	150−300 ms
35−50−150−300 Hz	300−700 ms
30−40−120−240 Hz	700−2000 ms
25−40−100−200 Hz	2000−4000 ms

9 Residual statics − Pass 1
10 Trace top mute

    Fb_pick+10 ms
11 Sort to CDP domain
12 Velocity analyses
13 AGC 50 ms window
14 NMO
15 Stack
16 Residual statics − Pass 2
17 Trim statics − 1 ms maximum shift
18 Trace equalization 400−800 m