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Estimate of bedrock topography using seismic tomography along reflection seismic profiles

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Abstract

Seismic tomography has been applied to the reflection seismic data collected in Forsmark during Spring 2001. Simultaneous with the tomography, delay times of the seismic waves passing trough the loose unconsolidated sediment covering the bedrock were calculated. From the delay times the thickness of the sediments have been estimated. A basis for the delay time to depth conversion was refraction seismic measurements performed in Autumn 2003. The estimated cover thickness correlates well with data from drilling in the area. The estimated cover thickness varies between 0 and 20 m.

Sammanfattning

Seismisk tomografi har blivit tillämpad på de reflektionsseismiska data som samlades in under våren 2001 i Forsmark. Samtidigt med den seimiska tomografin har en beräkning av tidsfördröjningen av de seismiska vågorna vid passagen genom jord/morän-täcket över berggrunden erhållits. Från dessa tidsfördröjningar har en uppskattning av jord/morän-täckets tjocklek gjorts. Som grund för tids-djup konversionen används hastigetsinformation av jord/moräntäcket som framtagits vid en refraktionsseismisk mätserie utförd under hösten 2003. De beräknade jorddjupen stämmer väl överens med jorddjup från några borrningar i området. Jorddjupet varierar mellan 0 och 20 m.

Contents

1 Introduction

Seismic data were acquired in the Forsmark area in the northeastern Uppland during late Spring in the year 2001 by Uppsala University under contract from SKB /Juhlin et al, 2002/. Approximately 16 km of high-resolution reflection seismic data were acquired along 5 different profiles. For each of the about 1300 shot points the seismic waves were recorded at 100 geophones resulting in about 130 000 individual recordings of the wave fields. In addition 10 portable seismographs were deployed in the area that recorded the seismic wave field from the shots, resulting in about 13 000 recordings. However, due to a variable data quality only about 4700 recordings were used in the 3D tomography documented in /Juhlin et al, 2002/.

The objective with this study is to use the large amount of recorded data along the seismic profiles to produce an estimation of the thickness of the loose sedimentary cover. The method to reach this objective is to use a new seismic tomography technique developed at Uppsala University /Bergman et al, 2004/.

The study was carried out by Uppsala Universitet according to acticity plan AP PF-400-03-84 (SKB internal controlling document).

2 Methodology

In seismic tomography the travel times of the first arriving seismic waves that reach the geophones (receivers) from the detonations (source) are used.

The first arriving waves travel directly from the source to the receivers and do not need to be reflected in the bedrock. The travel times depend on the distance between source and receiver, and the seismic wave velocities in the bedrock and the cover thickness. Which path the wave follows, and consequently the depth it reaches, also depends on the seismic wave velocities in the bedrock. The velocity is generally lower near the surface than at deeper levels, however, a deeper trajectory results in a longer traveled distance.

To determine the velocity in the bedrock, the wave front expansion is calculated and through this procedure the fastest path is found. Next the velocities of all parts of the bedrock are calculated for which the difference in calculated and measured travel times is minimized. Since waves from different source – receiver pairs pass the same parts of the bedrock the calculation of the bedrock velocities have to be performed using all waves simultaneous, i.e. a system of equations has to be solved.

New wave front expansions, quickest paths and the optimal velocity of the bedrock are calculated iteratively until sufficient agreement between calculated and measured travel times is achieved for all of the data.

To keep the optimization of the velocities of all parts of the bedrock, numerically stable smoothness criteria have to be put in the system of equations. However, the seismic velocities can vary dramatically between bedrock and loose unconsolidated sediments with a velocity of the bedrock of about 4000–6500 m/s and that of sediments from as low as 200–300 m/s up to c 3000 m/s. The constraints of a smooth velocity variation will inherently result in poor solutions in the sediment – bedrock contact regions.

To overcome this difficulty a time delay term was incorporated into the system of equations. This term absorbs the delay produced in the passage through the loose cover and allows the velocities to be solved for as if there was only bedrock /Bergman et al, 2004/.

The time delays are used to estimate the thickness of the cover. From these delay times bedrock topography can be constructed.

3 Input data

The tomography calculations used data from the reflection seismic measurements in 2001 /Juhlin et al, 2002/. Travel times for the first arriving waves were determined for every source-receiver pair where the signal to noise ratio was high. A total of 115 000 traveltimes were used from the five profiles (Table 3-1).

The tomography was carried out one profile at a time. For the calculations every profile was confined to a model area with borders as tight as possible to minimize the time of the calculations (Figure 3-1). Refractions seismic were done at three locations, close to borehole KFM04, close to borehole KFM01 and at the southern end of reflection seismic profile 3. For the refraction seismics a geophone spacing of one meter was used.

Table 3-1. Seismic data used in the study.

Profile	Sources (used)	Geophones (used)	Number of used traveltimes	% of all data	Model size X (m)	Model size Y (m)	Number of model cells
1	260 (260)	301 (296)	22650	87.1	3000	200	264008
2	217 (216)	268 (268)	18042	83.1	2500	500	550000
3	143 (143)	205 (205)	13185	92.2	250	2100	231000
4	196 (193)	248 (248)	14437	73.6	300	2500	330000
5	507 (507)	527 (525)	47167	93.0	1500	4700	3102000

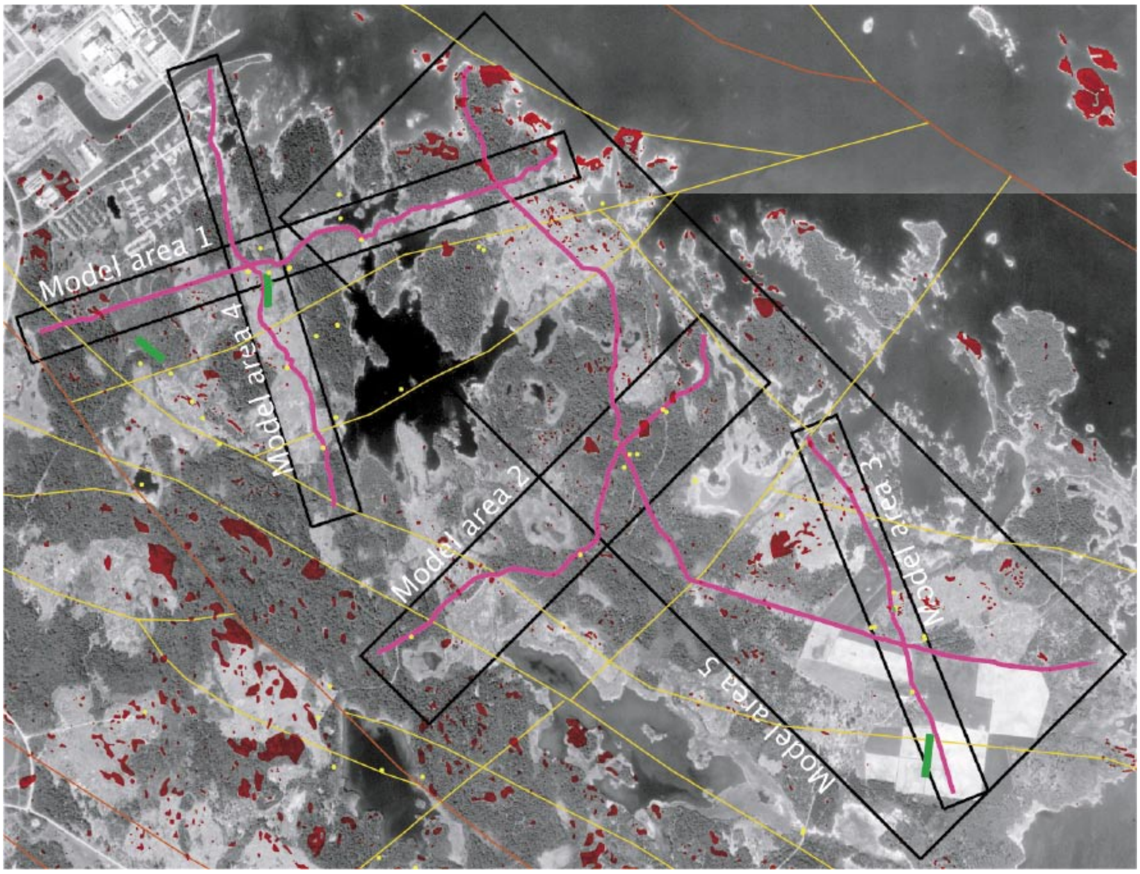

Figure 3-1. *Reflection seismic profiles (purple) and model areas (black frames). Yellow and orange lines show inferred fracture zones. Sites for refraction seismic (green short lines).*

4 Results

4.1 Refraction seismic

The refraction seismics performed revealed velocities and layer thickness according to Table 4-1 and Table 4-2. Refraction seismic data are shown in Figure 4-1 and Figure 4-2. From these data a time delay to velocity function was defined with a 90 cm thick layer with a velocity of 450 m/s, a second 2.5 m thick layer with a velocity of 1200 m/s and a bottom layer reaching down to bedrock and having a velocity of 3600 m/s.

Results from the forward direction come from shots point on the side with lower geophone location numbers. The reverse direction is from the side with higher geophone location numbers.

Table 4-1. Calculated refraction velocities.

Site–branch/	1		2		3	
Velocity (m/s)	Forward	Reverse	Forward	Reverse	Forward	Reverse
Layer 1	456	448	571	471	350	382
Layer 2	820	–	–	–	1133	1467
Layer 3	3215	–	3883	2913	2154	3710
Bedrock	6640	6220	6309	5872	5275	7885

Table 4-2. Calculated layer thickness.

Site–branch/	1		2		3	
Layer thickness (m)	Forward	Reverse	Forward	Reverse	Forward	Reverse
Layer 1	0.4	5.4	1.6	1.2	0.9	0.9
Layer 2	2.4	–	9	9.2	1.6	5.6
Layer 3	8	–	–	–	12.7	48.6

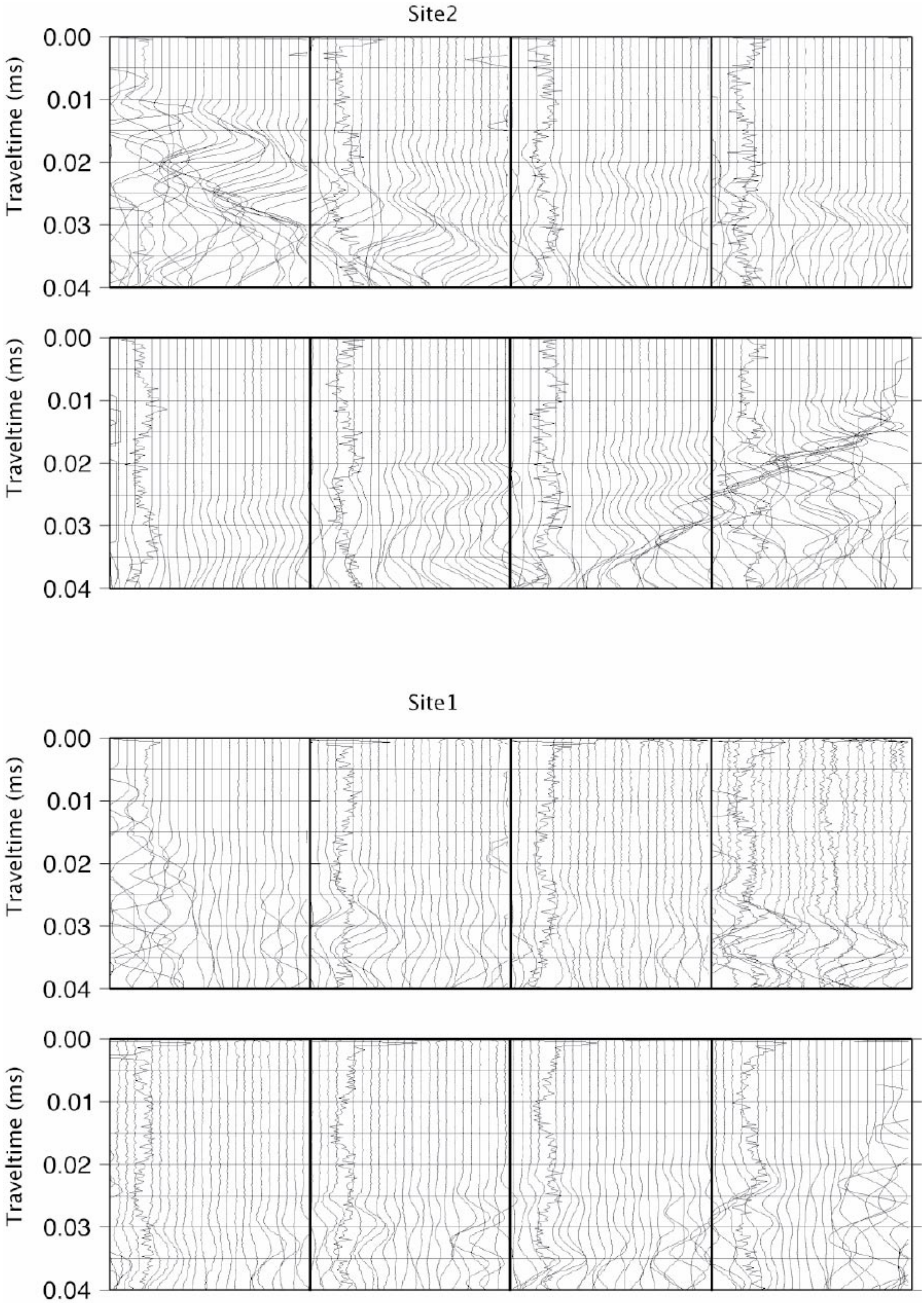

Figure 4-1. *Refraction seismic data, site 1 and 2.*

Figure 4-2. *Refraction seismic data, site 3.*

4.2 Tomography results

The tomography calculations gave time delays and estimated bedrock topography shown in Figures 4-3 to 4-7.

Each figure displays

Bottom: Time delays calibrated to yield 0 ms at locations with bedrock outcrop (red).

Middle: Surface topography along the geophones (black line). Estimated bedrock topography (red line). Geophone locations on bedrock outcrop (green circle). Position of what was assumed as bedrock while drilling the shot holes for the reflection seismic survey (black dots). Elevation of bedrock determined from boreholes (blue star). Boreholes are numbered in order of appearance (Table 5-2).

Top: Air photo of the model areas. Profile location (purple line), boreholes with bedrock elevation (yellow circle) and bedrock outcrop areas (red polygon). Yellow and orange lines show inferred fracture zones.

In every figure any crossing profile is marked with a label (e.g. P4) and a vertical bar.

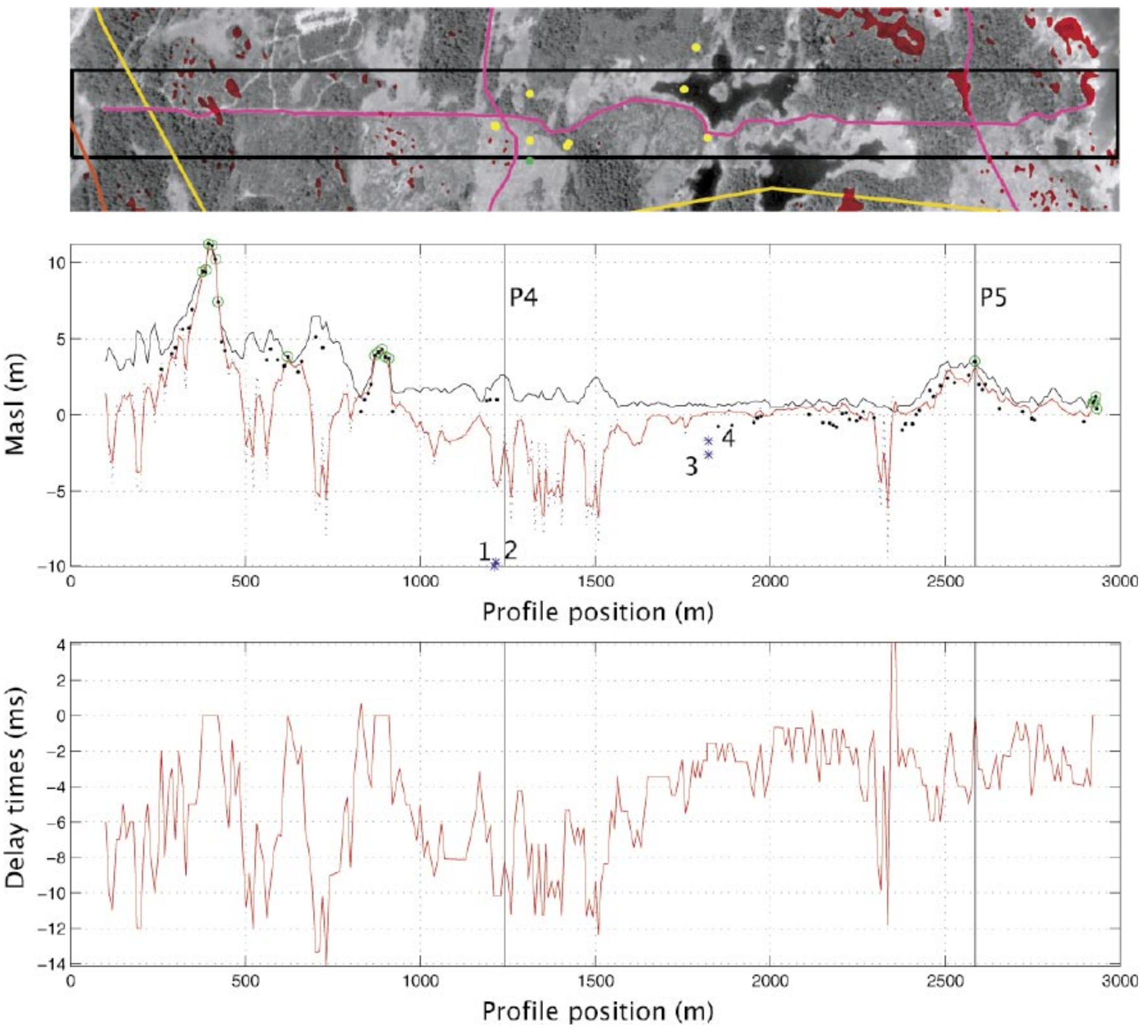

Figure 4-3. *Results for profile 1.*

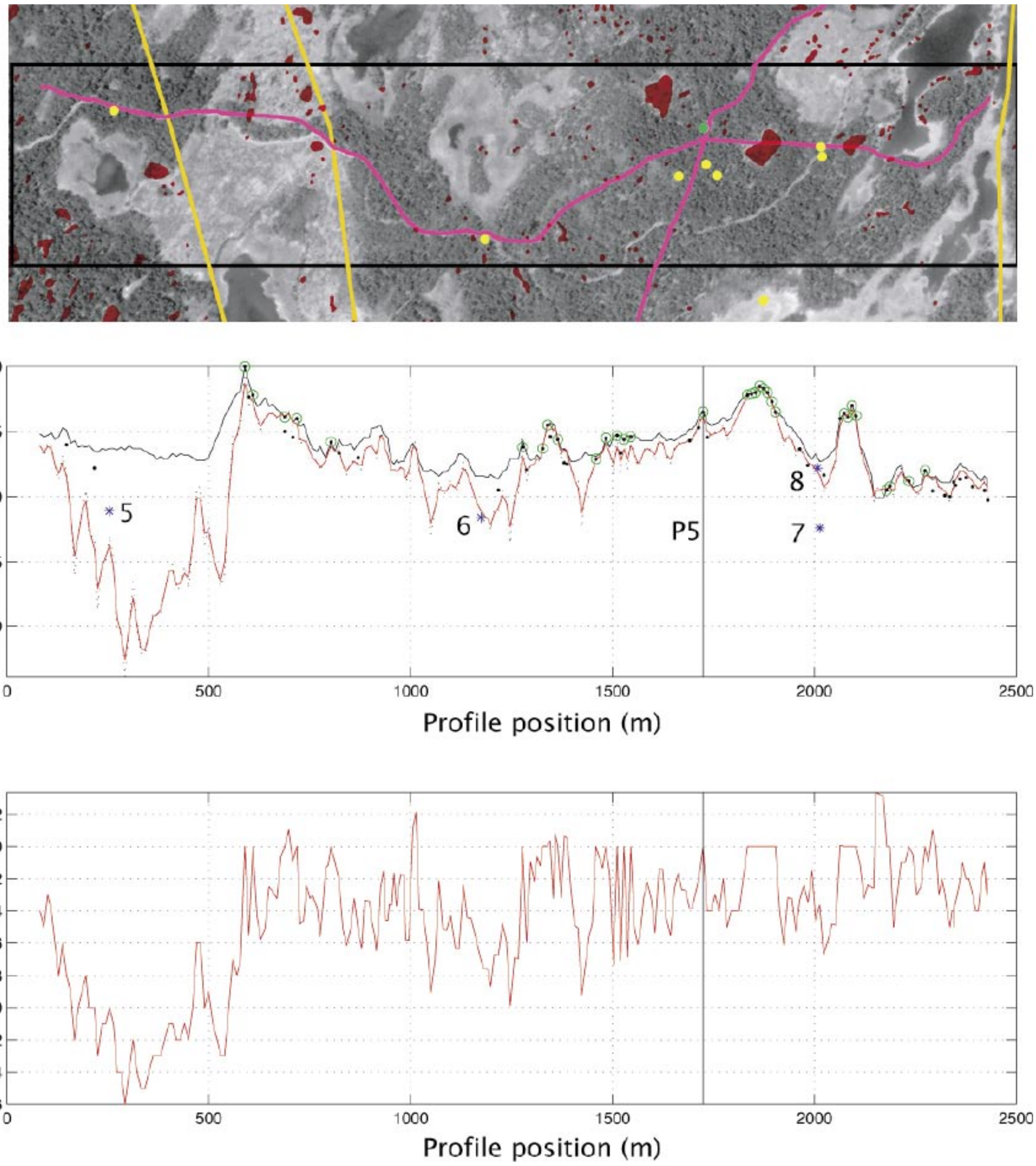

Figure 4-4. *Results for profile 2.*

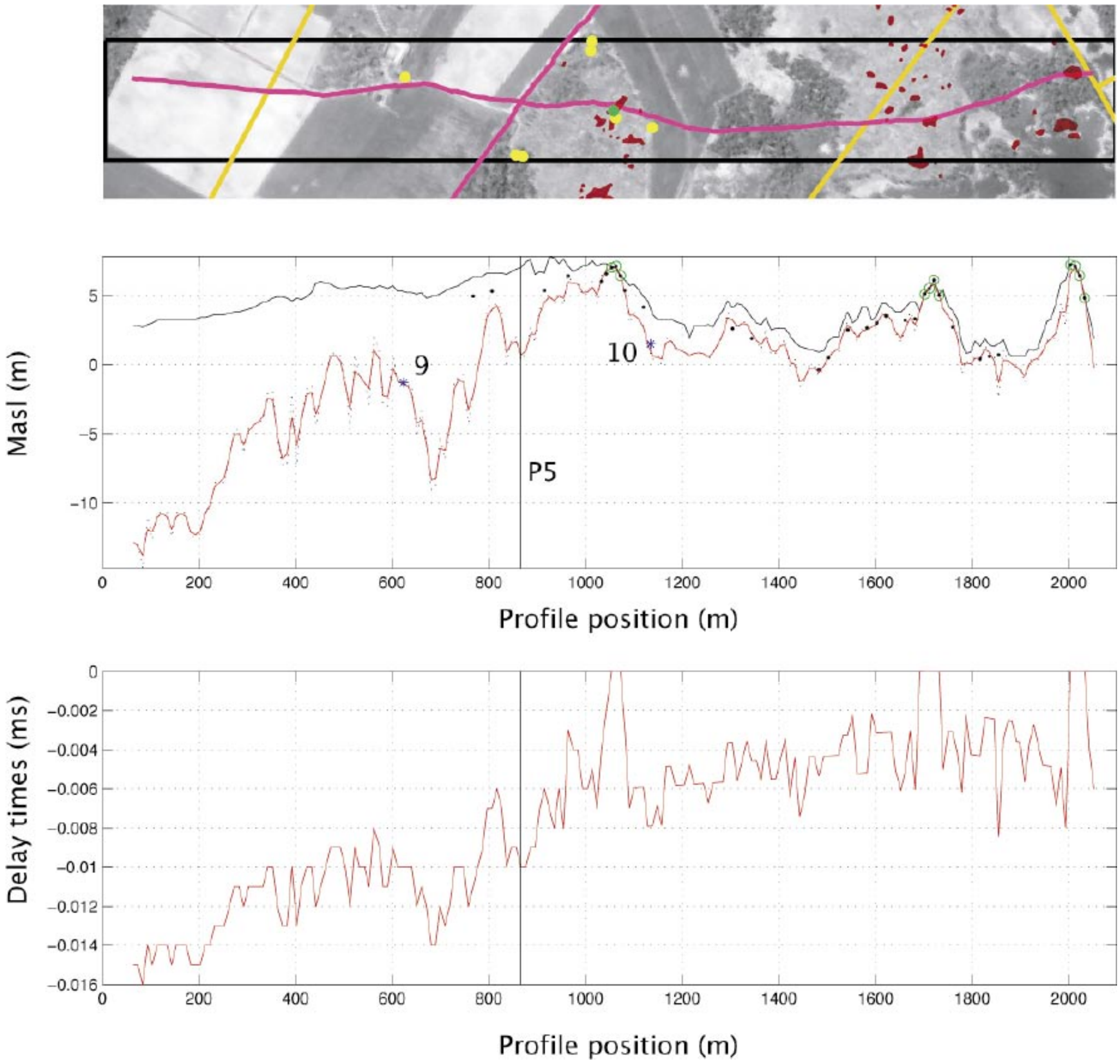

***Figure 4-5**. Results for profile 3.*

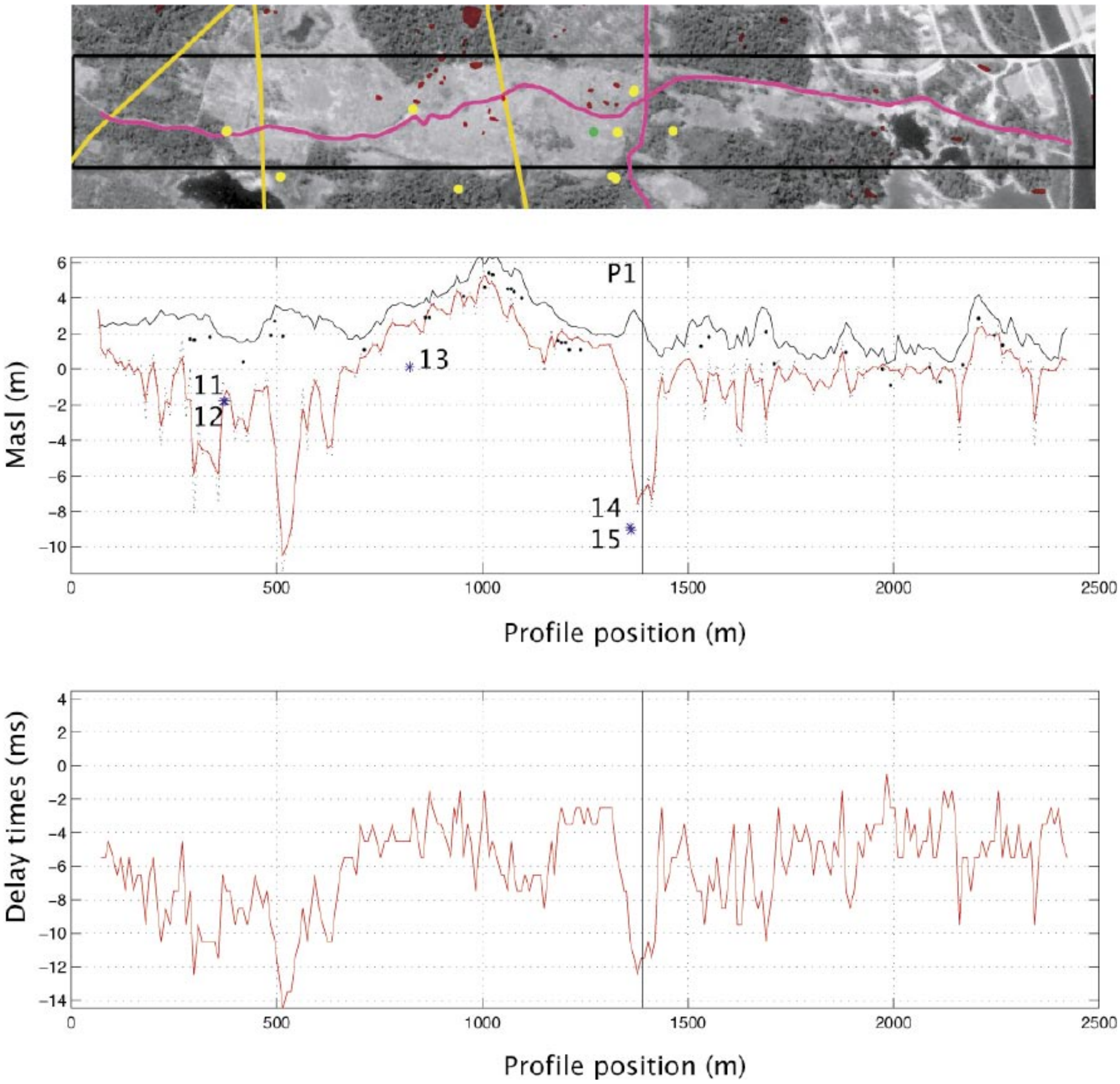

Figure 4-6. *Results for profile 4.*

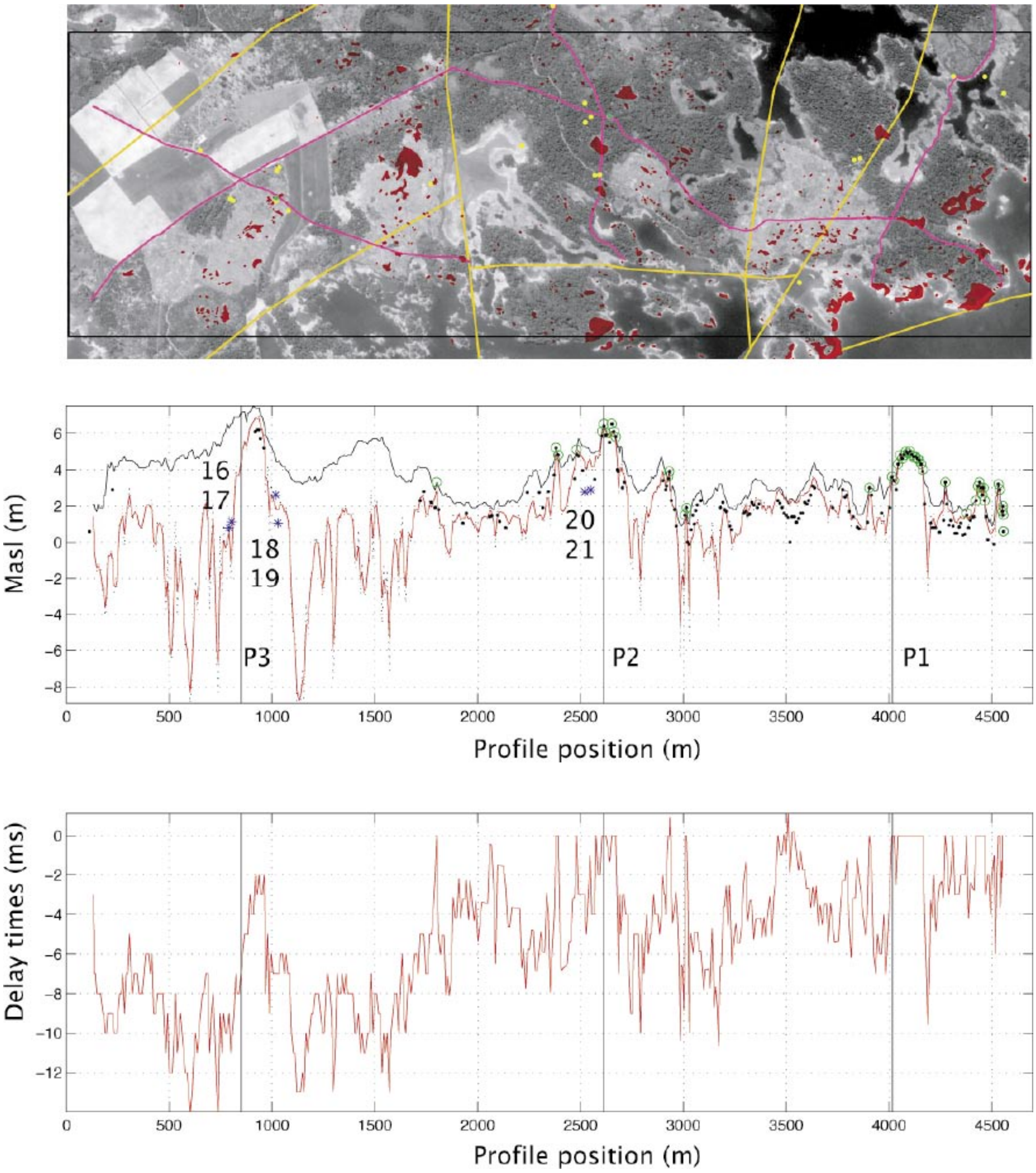

Figure 4-7. Results for profile 5.

5 Error estimation

There are no analytical methods to estimate the errors in the time delays. There are two available methods for evaluation of the results. One method is to check for differences in time delays (i.e. bedrock depths) where the profiles cross each other (Table 5-1). The other method is to compare the estimated bedrock depths to those found in borehole drillings (Table 5-2).

Table 5-1. Estimated cover thickness at profile intersections.

Crossing of profiles	Depth along first line	Depth along second line	Distance between measure positions
1–4	0.85	6.7	5.2
1–5	3.5	4.4	3.4
2–5	6.6	6.5	3.0
3–5	0.3	3.6	5.5

Table 5-2. Difference between estimated and measured depth for various borehole positions along the profiles.

Index	Borehole	Measured depth	Estimated depth	Difference in depths	Distance from profile
1	HFM0002	12.2	7.0	5.2	29.9
2	HFM0003	12.0	7.0	5.0	30.7
3	SFM0034	3.2	0.3	2.9	22.5
4	SFM0035	2.3	0.3	2.0	23.6
5	SFM0019	4.8	6.7	–1.9	12.1
6	SFM0020	3.2	2.4	0.8	16.3
7	HFM0004	5.1	0.8	4.3	26.1
8	SFM0004	0.8	1.2	–0.4	5.2
9	HFM0007	6.6	6.7	–0.1	19.8
10	SFM0008	2.5	3.2	–0.7	23.3
11	SFM0030	3.6	2.4	1.2	8.0
12	SFM0031	3.6	3.0	0.6	8.0
13	HFM0013	3.5	0.5	3.0	22.4
14	HFM0002	12.2	11.2	1.0	30.8
15	HFM0003	12	11.2	0.8	28.7
16	HFM0008	5.5	4.9	0.6	51.1
17	SFM0007	5.4	6.7	–1.3	64.2
18	HFM0005	3.4	2.7	0.7	39.5
19	SFM0006	2.0	2.1	–0.1	49.7
20	SFM0009	2.5	0.7	1.8	35.8
21	SFM0005	2.1	0.9	1.2	21.8

There are several parameters affecting the depth estimation.

- Sampling rate of the seismic signal and accuracy of used travel times for the recorded waves. With a typical velocity of 1000 m/s and the sampling rate of the data of 1 ms the wave front moves one meter for every sample of the data in the time series. Thus with an uncertainty of the determining the first onset of ground motion of 2 ms the uncertainty of the length of travel distance is 2 m for every ray. However since every geophone recorded several shots, i.e. rays, the precision of the distance travelled is enhanced in a statistical manner.
- Stiffness of the numerical model. Since the tomography problem is a mix of over- and under-determined model parameters, constraints have to be put on the velocity smoothness. This then affects the variation of travel times to the geophone from different shots and thereby makes the solution for the time delay terms, i.e. depth to bedrock, more uncertain.
- The bedrock cover thickness varies along the profiles as well as perpendicular to the profiles. Thus, if the borehole data used is offset from the profile then the depth recorded by drilling does not need to be the same as the depth at the position at the profile. As seen in Figure 5-1, a good correlation between estimated and measured depth is yielded for minor offsets. At greater offsets the differences are increasing. Finally, the nice fit for offsets greater then 30 m is not relevant for the error estimation.
- The time delay conversion to depth is done with a one dimensional model of the cover layer thickness and velocity, which only expect to yield a good match of recorded and estimated depth to bedrock where the simple model actually is the same as the true conditions.

There is no possibility to judge how much the individual parameters mentioned in the list above and other less significant ones contribute to the final estimated depth.

The differences of estimated depth where the profiles cross is mainly from the process of calibrating the time delays to yield 0 ms at locations with bedrock outcrop. The uncalibrated time delays have a maximal error of 33%.

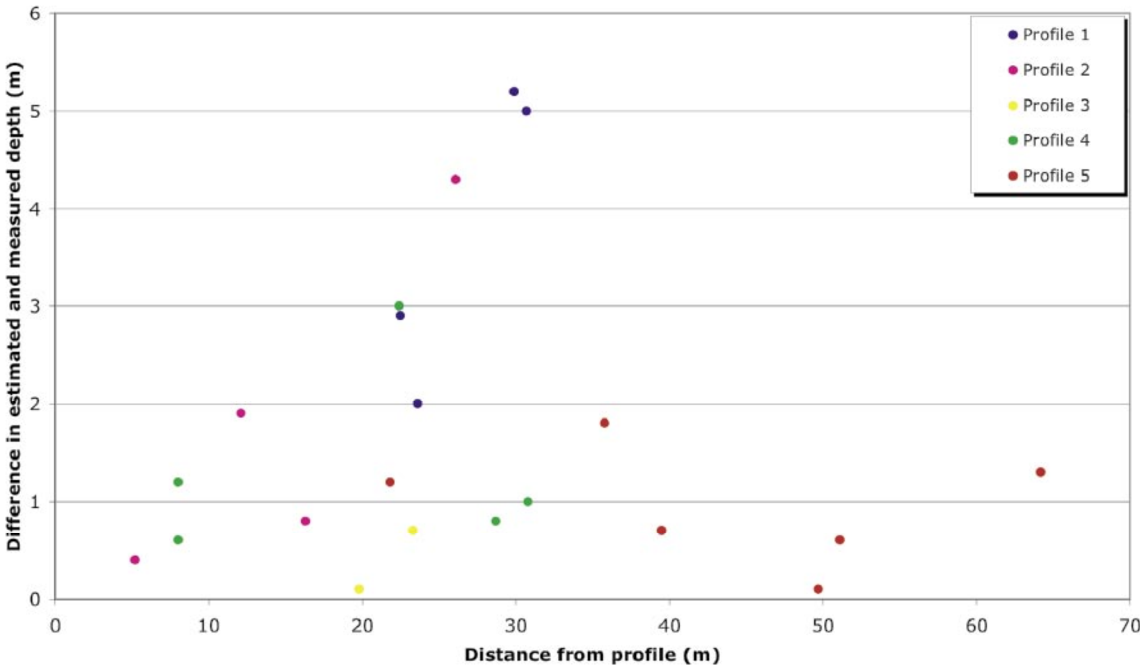

Figure 5-1. *The difference between estimated and measured depth as a function of distance from the profiles (m).*

6 Data delivery

Data delivered from the study consist of excel sheets with position of every used geophone, surface topography and estimated bedrock topography along the individual profiles.

The SICADA field note number is Forsmark no 351.

7 Conclusions and discussion

The estimated depths to bedrock from the calculated time delays correlate well with the measured depth from boreholes. The short wavelength variation in bedrock topography is most probably from variations in sediment velocities. The longer wavelength variation, however, appears to reveal the actual depth to bedrock. Still the actual depths will have to be considered uncertain since the simple one dimensional sediment model will not reflect the significant variations in sediment velocity that have to be expected in a study area of this size.

At present, time delays are only calculated at the receiver locations. The delay times calculated in this study is the sum of the delay times from both the receiver location and source location. From this it follows that the delay times will be up to twice what would be found from source or receiver time delays separately. For the time to thickness conversions the delay times consequently have been divided by two before assigning a thickness.

To calculate a less ambiguous model for the depth to bedrock the tomography software would need to be reprogrammed to find time delays for both the source and receiver positions. This is possible to do, but the estimated programming effort would be several weeks. Also a sediment model reflecting the change of sediment velocities along the profiles would need to be constructed. This could be achieved during the reflection seismic surveying if some chosen parts used an acquisition geometry with geophone separations in the order of one meter or less.

From the error estimates it is obvious that there is no perfect match between the estimated cover thickness and the measured depth to bedrock, since the correlation varies between good and bad. However, for a general estimate of the variation of the cover thickness these calculations are a useful new tool.

8 References

Bergman B, Tryggvason A, Juhlin C, 2004. High resolution seismic traveltime tomography incorporating static corrections applied to a till covered bedrock envirnment. In print for the July/August volume of Geophysics.

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