P-04-158

Reflection seismics in the Forsmark area

Updated interpretation of Stage 1 (previous report R-02-43)

Christopher Juhlin

Uppsala University, Department of Earth Sciences

Updated estimate of bedrock topography (previous report P-04-99)

Björn Bergman

Uppsala University, Department of Earth Sciences

November 2004

Svensk Kärnbränslehantering AB
Swedish Nuclear Fuel
and Waste Management Co
Box 5864
SE-102 40 Stockholm Sweden
Tel 08-459 84 00
+46 8 459 84 00
Fax 08-661 57 19
+46 8 661 57 19

ISSN 1651-4416
SKB P-04-158

Reflection seismics in the Forsmark area

Updated interpretation of Stage 1 (previous report R-02-43)

Christopher Juhlin
Uppsala University, Department of Earth Sciences

Updated estimate of bedrock topography (previous report P-04-99)

Björn Bergman
Uppsala University, Department of Earth Sciences

November 2004

Foreword

A major reflection seismic survey was one of the earliest studies carried out within the scope of the Forsmark site investigation. The survey, which was conducted during the winter and early spring 2002, resulted in a comprehensive data set. The interpretation of the data was presented in the report R-02-43, "Reflection seismic studies in the Forsmark area – stage 1". Identified reflectors, possibly representing rock structures of different character, down to a depth of about 5,000 m, are presented in the report. The inferred three-dimensional extensions and intersections of the structures with the ground surface are also displayed. The results from the reflection seismic survey have served as an important guidance for elaborating strategies for the subsequent drilling and investigation programme at Forsmark. Several interpreted structures have been confirmed by these later investigations.

As indicated, the data material from the reflection seismic investigations is vast, and regarding details, there is scope for alternative interpretations and refinement of the interpretations suggested in R-02-43. Normally, such extended work would be performed in compliance with an activity plan, which is an internal SKB controlling document. In the present case, however, the author has re-evaluated the earlier interpretations independently of a specific governing document but, in general, in accordance with the principles stated in the original activity plan for the reflection seismic survey, AP PF 400-02-02.

As a separate activity, seismic tomography was applied to the reflection seismic data. This work was presented in the report P-04-99, "Estimate of bedrock topography using seismic tomography along reflection seismic profiles". Since the report was published, the tomography inversion method has been further developed to produce more reliable bedrock velocities. This allows for the refined interpretation of the overburden thickness documented in the present report. Also this update has been performed independently of a specific governing document but, in principle, in accordance with the original activity plan (in this case AP PF 400-03-84).

The revision of the data material is valuable from a quality assurance aspect. Furthermore, the refined interpretations will contribute to a better understanding of the geological setting within the investigated area. Finally, a complementary reflection seismic survey is currently being executed and the results now presented will contribute to the combined interpretation of the new and the previous data.

The new overburden thickness data have been inserted in the SICADA database, whereas the other updated information will be considered when the Stage 2 investigations are reported.

Lennart Ekman

Investigation leader – Forsmark site investigation.

Contents

Part 1

Updating and re-interpretation of results from reflection seismic studies – Stage 1

Seismic data were acquired in the Forsmark area in northeastern Uppland during the months of March, April and May in the year 2002 by Uppsala University under contract from SKB. Approximately 16 km of high-resolution (10 m shot and receiver spacing) reflection seismic data were acquired along 5 different profiles. Results were reported in R-02-43. The data have been further evaluated and an updated version of the previous interpretation has been made. The updated version is similar to the original with some modifications that may be important for the evaluation of the site. The new version is presented in this short communication.

Figures 1-1 to 1-3 show processed stacked sections from profiles 3 and 5 with the reflections marked as picked in R-02-43. Figures 1-4 to 1-6 show the same stacked sections with the reflections marked as picked in this update. The following differences may be observed:

1) Reflections are only marked where they are reasonably clearly observed in Figures 1-4 to 1-6. Earlier they were marked where they were expected to be observed based on the best fitting planes.
2) Reflection A2 does not extend onto profile 3, but is limited to profiles 2, 5 and possibly 4.
3) Reflection A7 has been added.
4) Reflection B6 has been added.
5) The orientations of reflections A3, B2, B3 and D3 have been slightly adjusted.
6) Reflection B4 does not extend to the surface, instead reflection B7 has been added.

These modifications result in a better fit of the picked reflections to the observed data (Figures 1-4 to 1-6).

Since all reflections have out-of-the-plane crossdip components, the stacked sections in R-02-43 were not migrated. However, set A reflections lie nearly within-the-plane of profile 3 and set B reflections lie nearly within-the-plane of the southeastern part of profile 5. Synthetic tests show that these reflections will nearly migrate to their correct spatial positions. Figures 1-7 to 1-9 show migrated sections of the stacked sections with results from KFM03A included. Strong high amplitude set A reflections fall nearly on the projected reflector depths along profile 3, while the same is true for set B reflections on profile 5. Good correspondence is seen between identified deformation zones and the picked reflections along profile 3. The correspondence is poorer along profile 5 since the set A reflections have a higher out-of-the-plane component and the borehole KFM03A is offset from profile 5. Note that reflection A2 projects into KFM03A at 900 m, but that it is not possible to trace it to the borehole on the seismic section (Figure 1-8). It may become too thin to be observed on the seismic section.

Figures 1-10 and 1-11 show the earlier projections to the surface and the ones from this update, respectively. In the updated version intersections with the surface are more conservatively plotted and only where reflections have been observed along the profiles.

Table 1-1 shows the orientations of the reflectors as presented in R-02-43 and, when applicable, the updated orientations. Tables 1-2 and 1-3 show the updated predictions for reflector intersection depths in KFM02A and KFM03A, respectively.

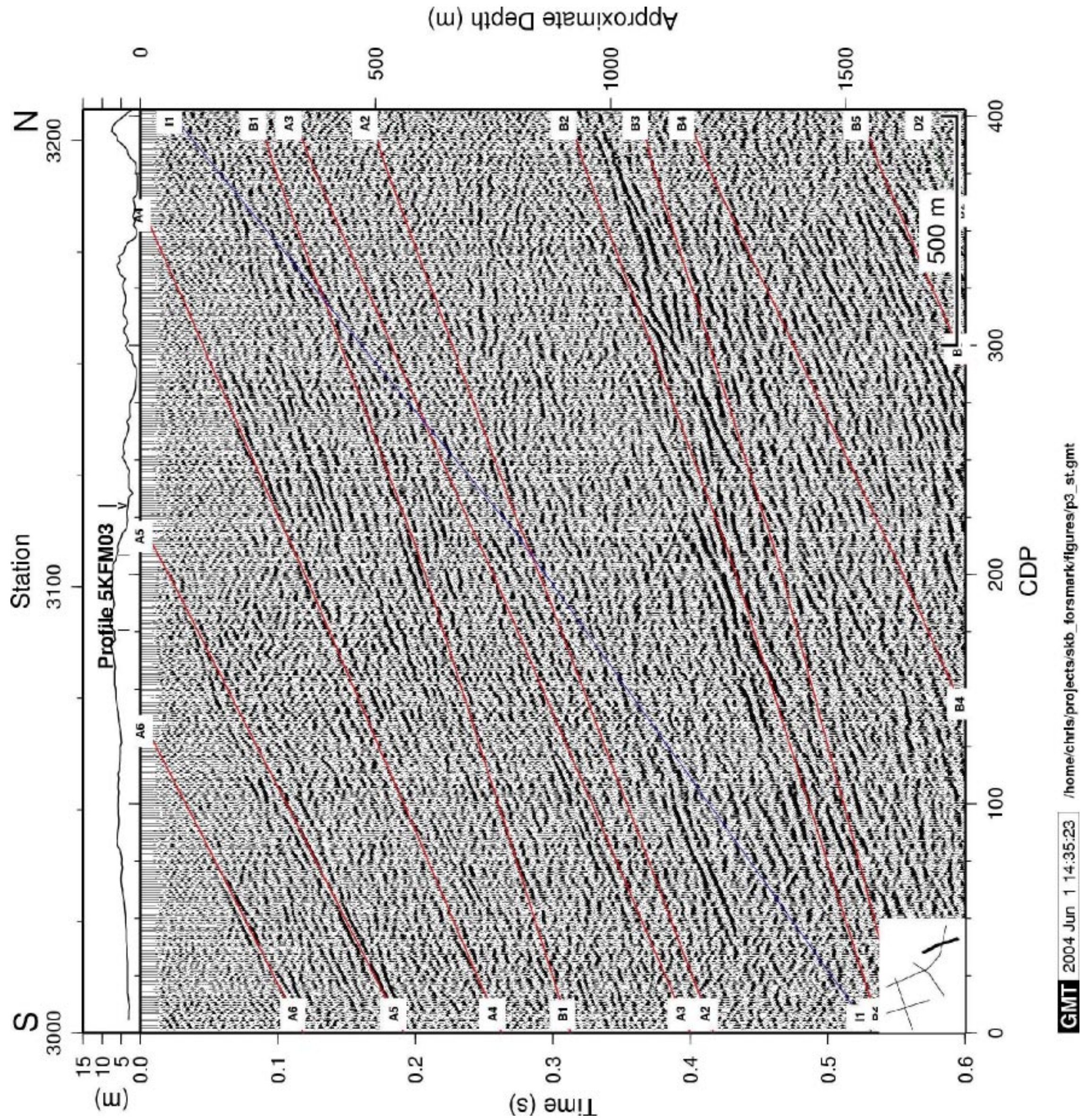

__Figure 1-1.__ Stacked section of profile 3 down to 0.6 seconds with reflections marked as picked in R-02-43 and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true subhorizontal reflections.

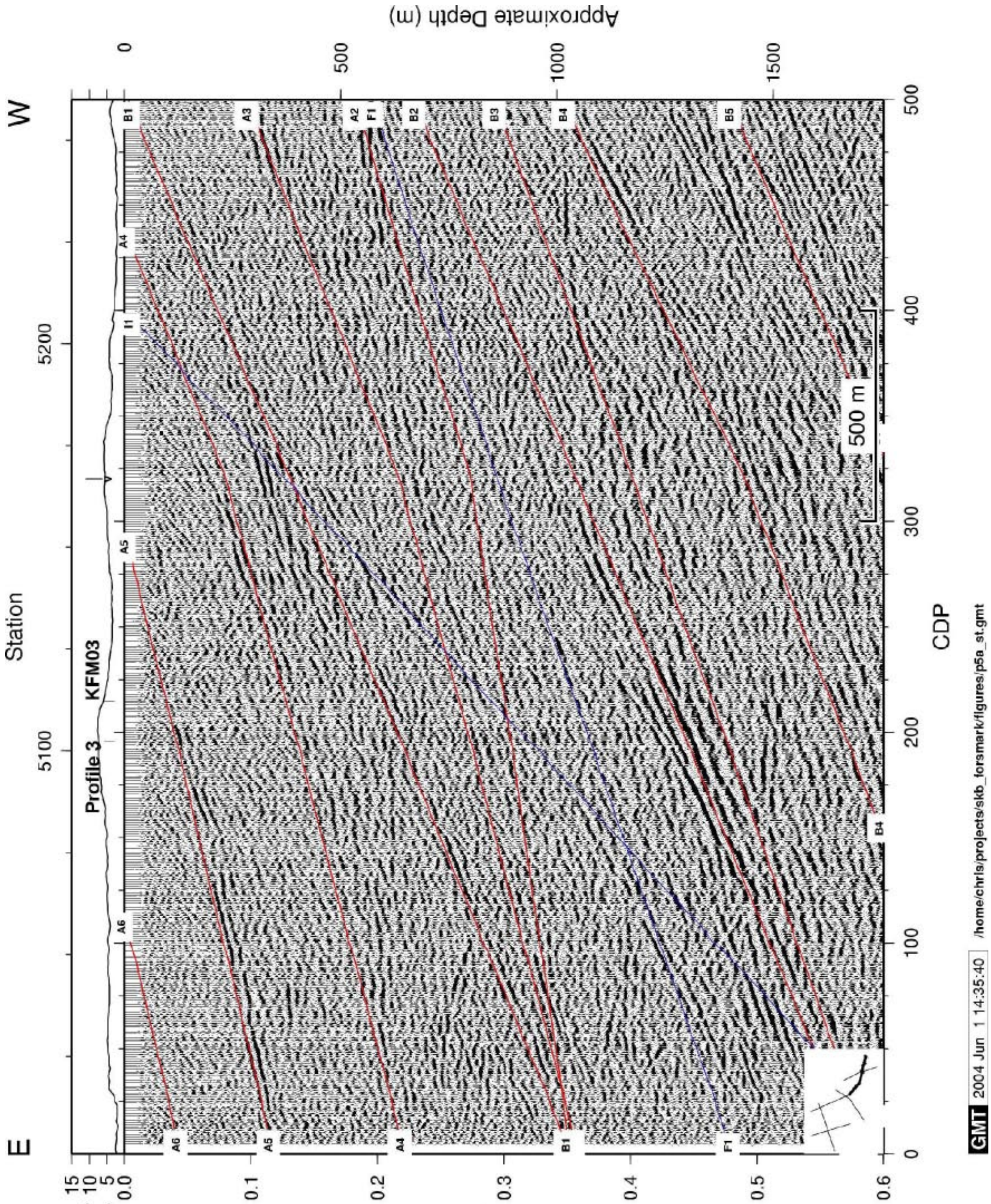

Figure 1-2. *Stacked section of southeastern half of profile 5 down to 0.6 seconds with reflections marked as picked in R-02-43 and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true sub-horizontal reflections.*

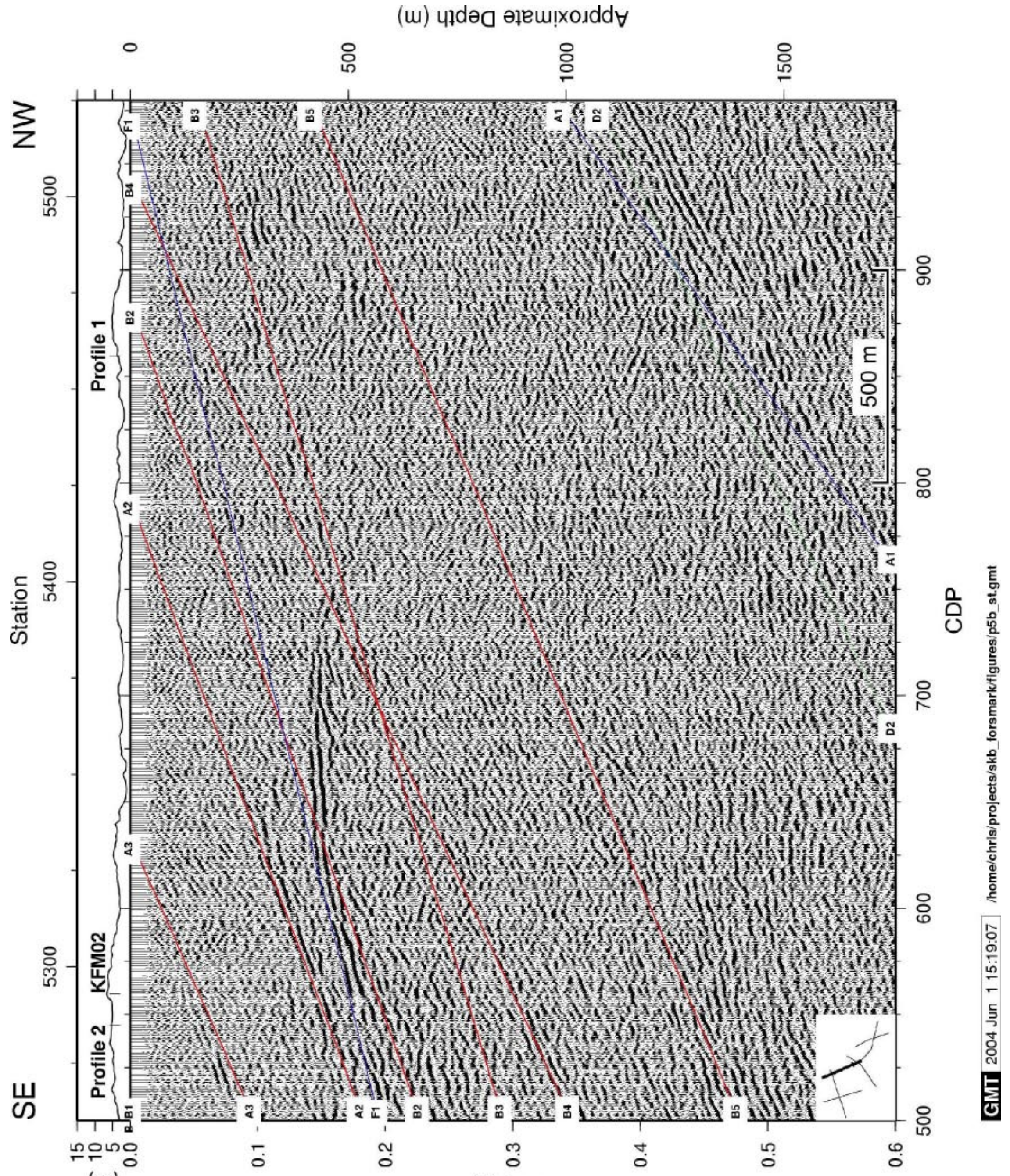

Figure 1-3. *Stacked section of northwestern half of profile 5 down to 0.6 seconds with reflections marked as picked in R-02-43 and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true sub-horizontal reflections.*

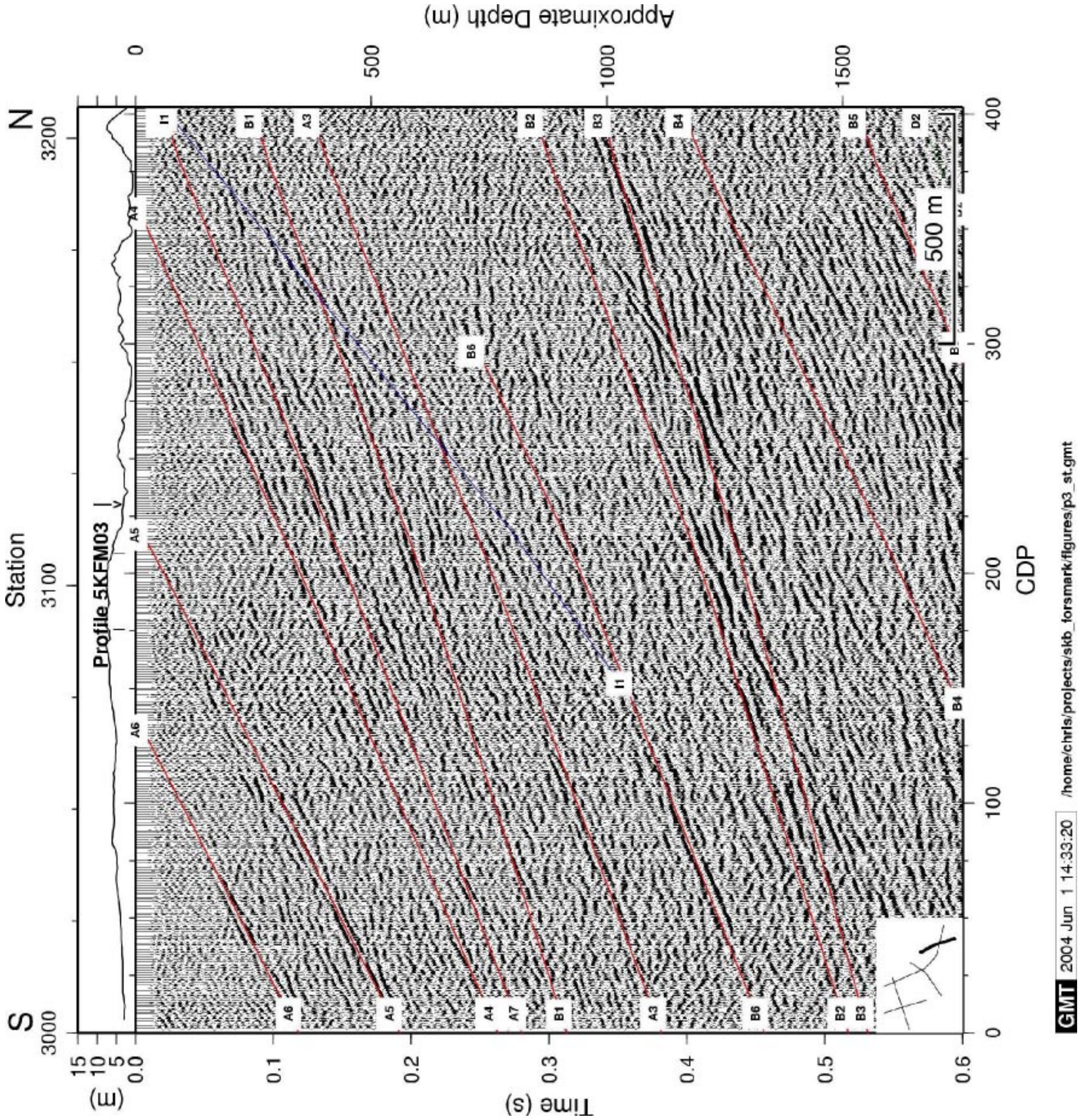

Figure 1-4. *Stacked section of profile 3 down to 0.6 seconds with reflections marked as in this update and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true sub-horizontal reflections.*

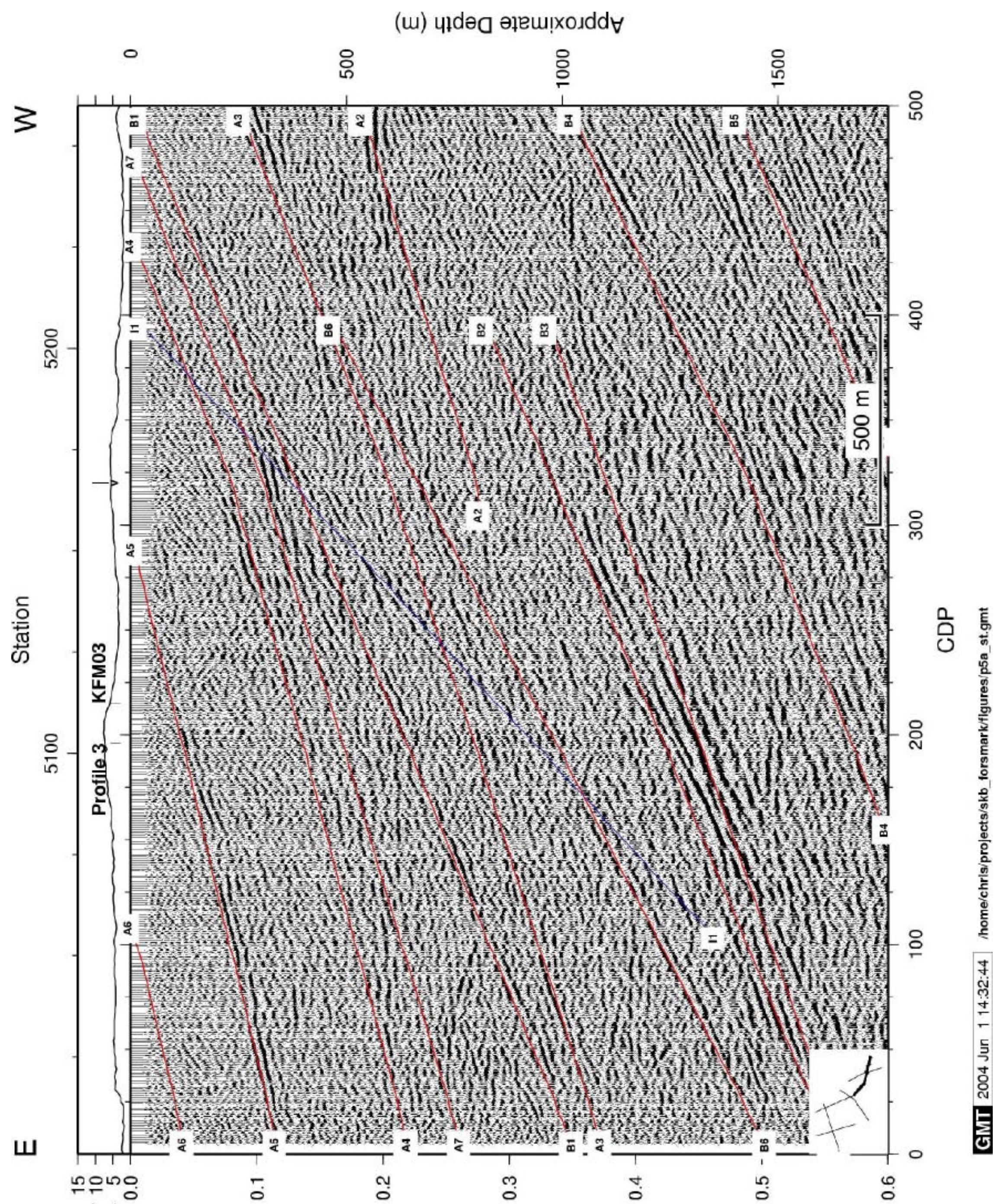

Figure 1-5. *Stacked section of southeastern half of profile 5 down to 0.6 seconds with reflections marked as in this update and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true sub-horizontal reflections.*

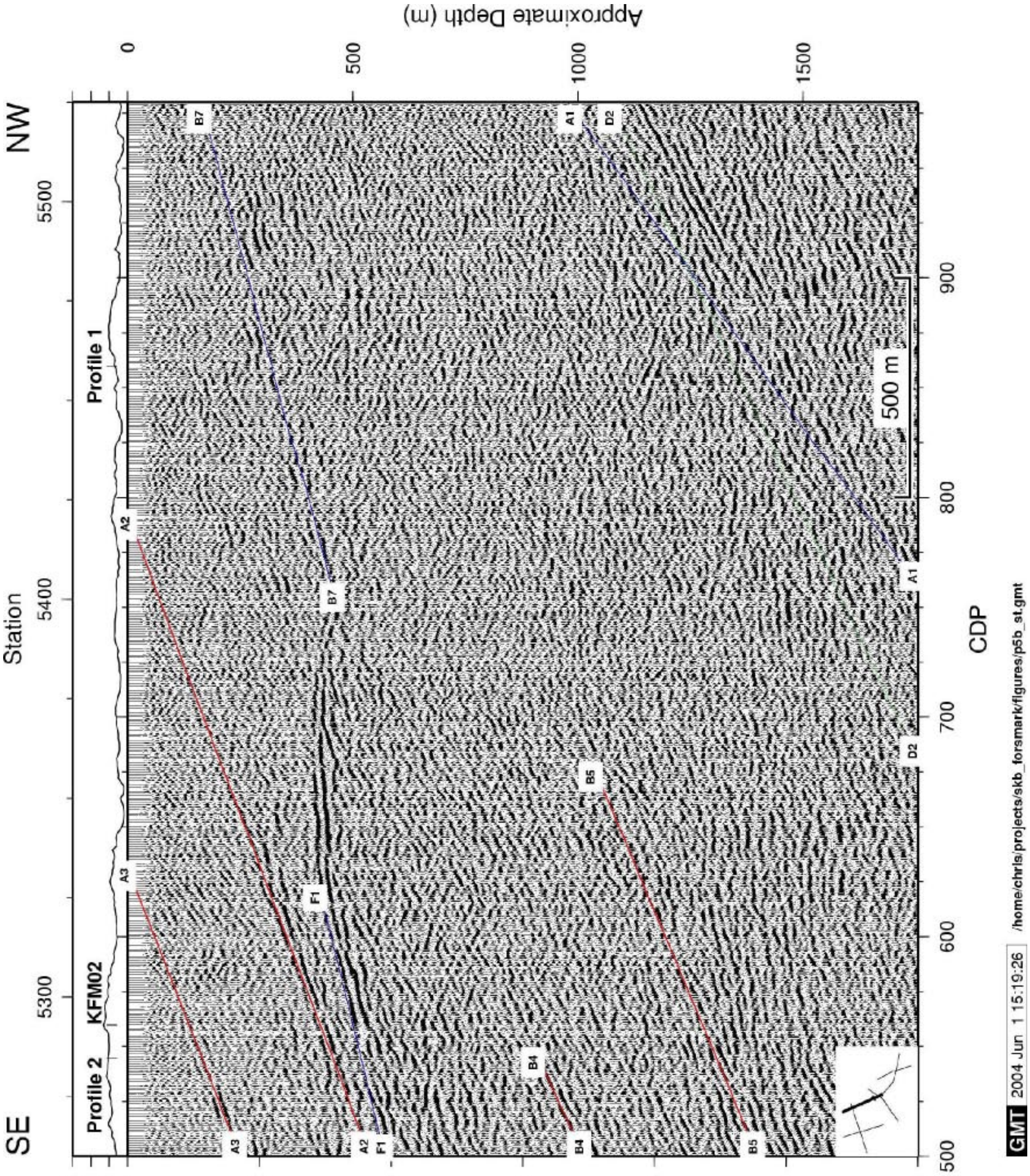

Figure 1-6. *Stacked section of northwestern half of profile 5 down to 0.6 seconds with reflections marked as picked in this update and given in Table 1-1. Location of section indicated in lower left corner. Depth scale only valid for true sub-horizontal reflections.*

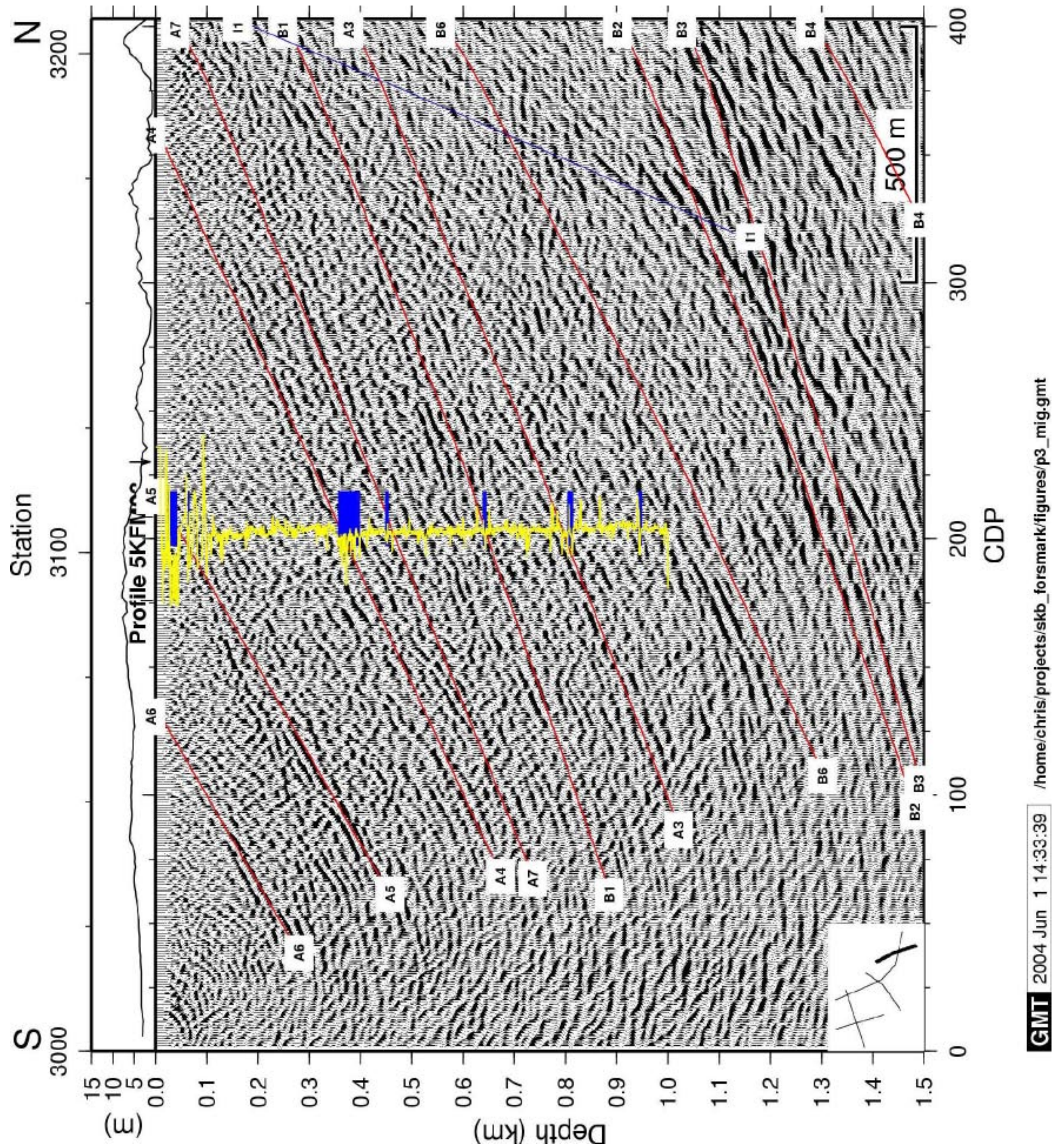

Figure 1-7. *Migrated section of profile 3 down to 1.5 km with reflections marked as picked in this update and given in Table 1-1. The location of the picked reflections takes into account out-of-the-plane crossdip, whereas the reflections are implicitly assumed to come from within-the-plane of the profile in the seismic section. Sonic log performed in borehole KFM03A in yellow, deformation zones in blue. Location of section indicated in lower left corner.*

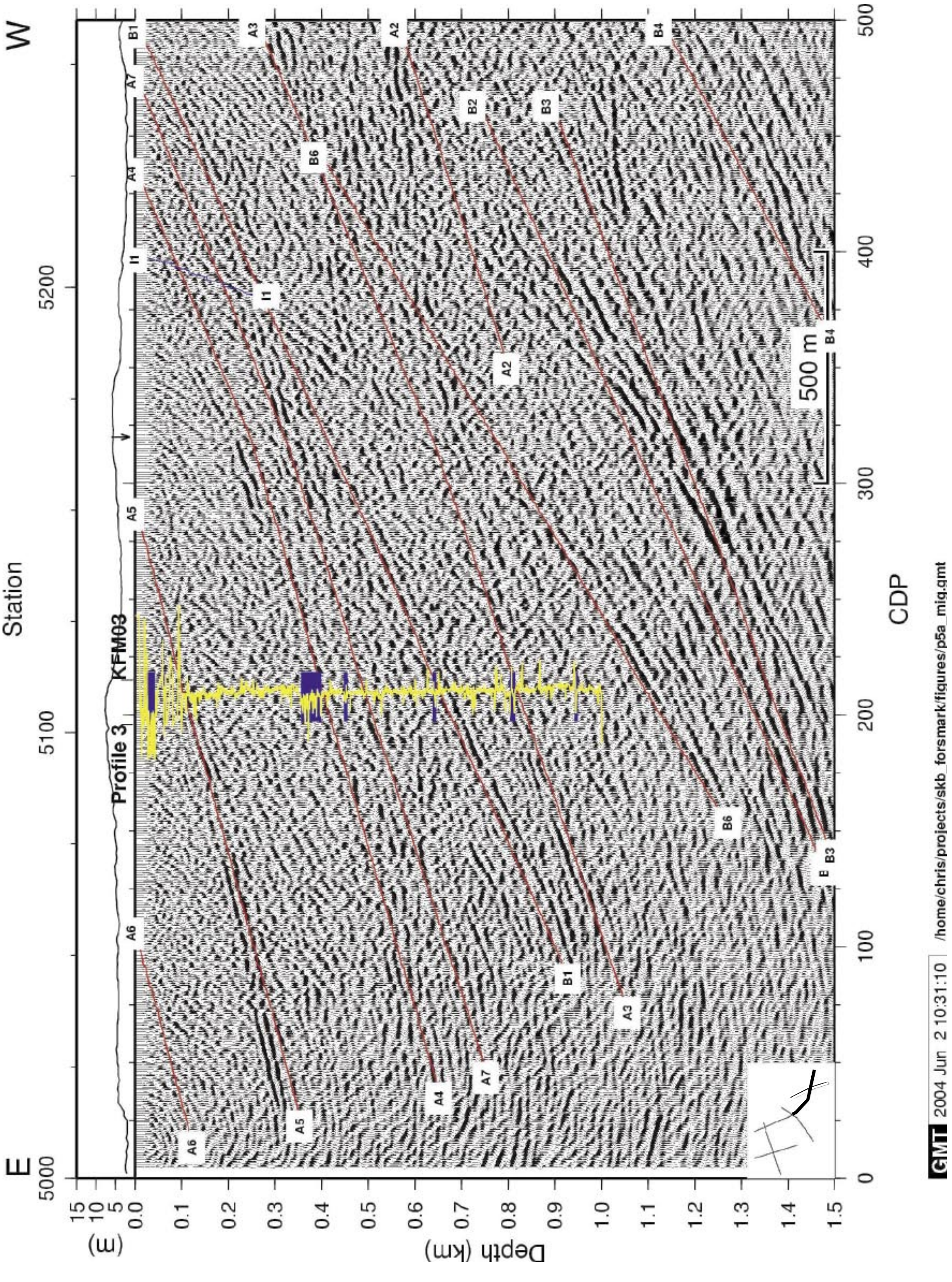

Figure 1-8. *Migrated section of southeastern half of profile 5 down to 1.5 km with reflections marked as picked in this update and given in Table 1-1. The location of the picked reflections takes into account out-of-the-plane crossdip, whereas the reflections are implicitly assumed to come from within-the-plane of the profile in the seismic section. Sonic log performed in borehole KFM03A in yellow, deformation zones in blue. Location of section indicated in lower left corner.*

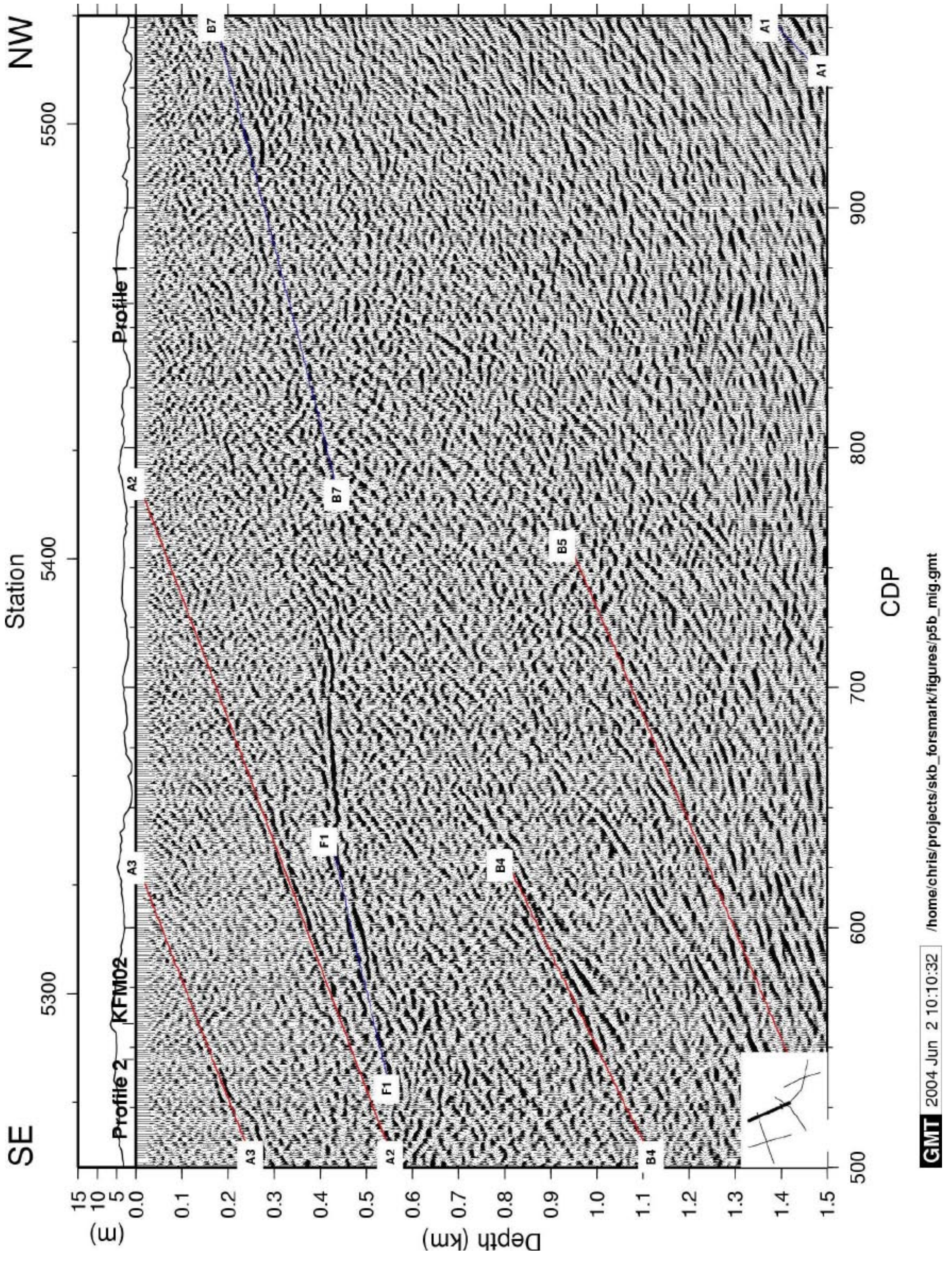

Figure 1-9. *Migrated section of nortwestern half of profile 5 down to 1.5 km with reflections marked as picked in this update and given in Table 1-1. The location of the picked reflections takes into account out-of-the-plane crossdip, whereas the reflections are implicitly assumed to come from within-the-plane of the profile in the seismic section. Location of section indicated in lower left corner.*

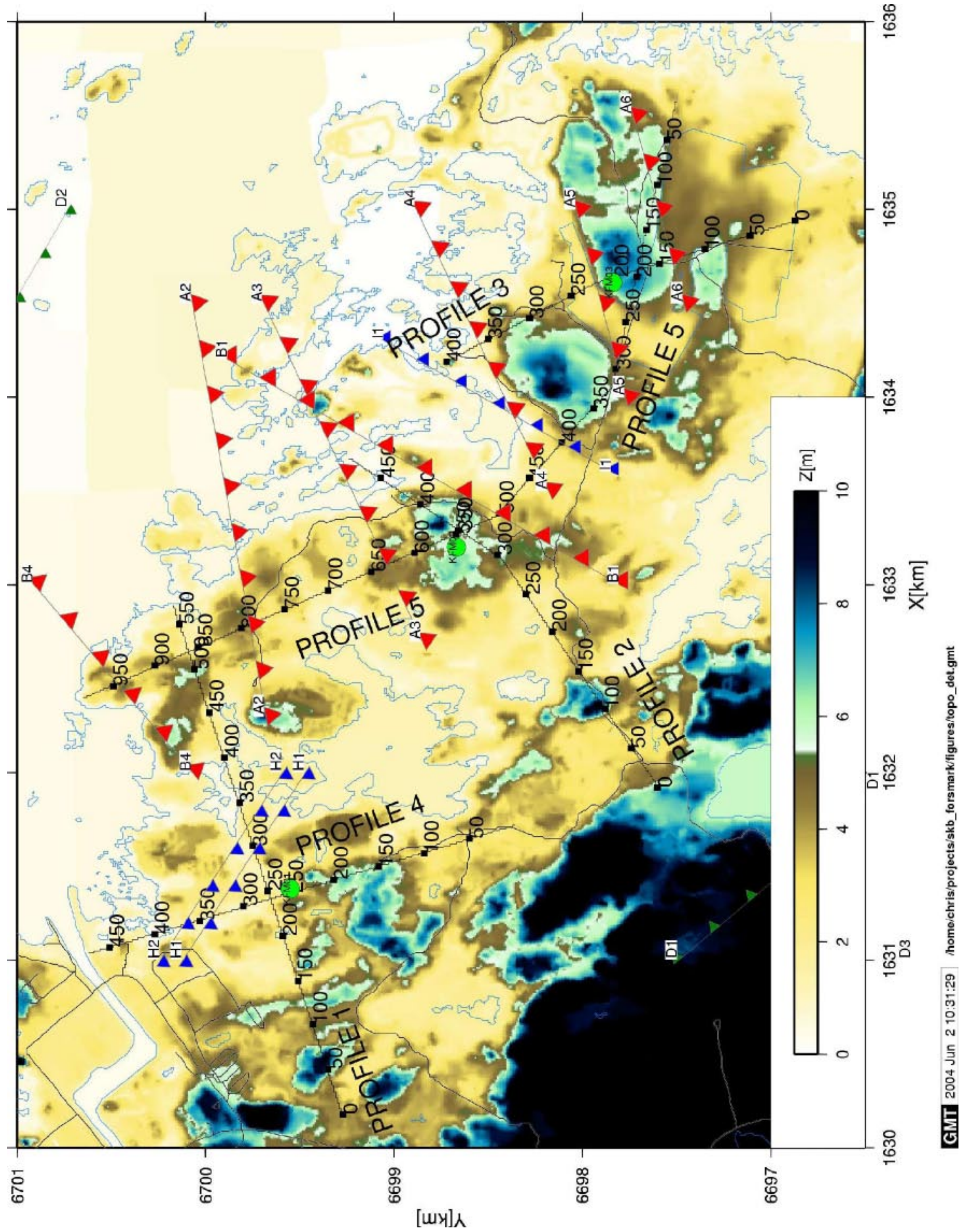

Figure 1-10. *Projected reflector intersections, as picked in R-02-43, with the surface plotted on the topographic map. Reflections from interfaces that clearly cannot be traced to the surface, such as F1 in Table 1-1, are not drawn. All indicated reflectors correspond to relatively thin zones (5–15 m thick). Reflectors are coded as follows: red = rank 1, blue = rank 2, green = rank 3.*

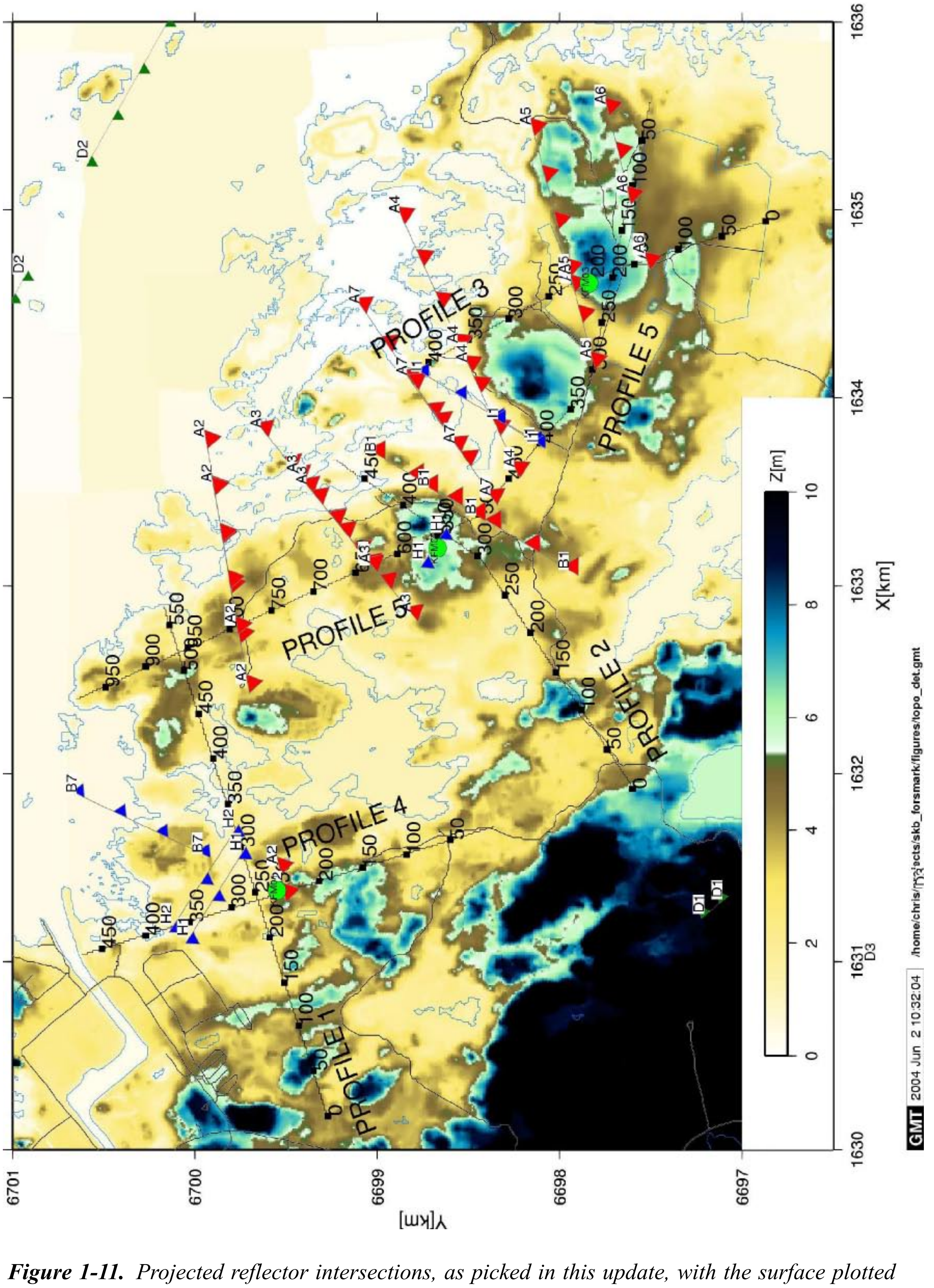

Figure 1-11. Projected reflector intersections, as picked in this update, with the surface plotted on the topographic map. Reflections from interfaces that clearly cannot be traced to the surface, such as F1 in Table 1-1, are not drawn. All indicated reflectors correspond to relatively thin zones (5–15 m thick). Reflectors are coded as follows: red = rank 1, blue = rank 2, green = rank 3.

Table 1-1. Orientation of reflectors as determined from the surface seismic in R-02-43 and new orientation in braces. Distance refers to distance from the arbitrary origin (6,699 km N, 1,633 km W) to the closest point on the reflector at the surface. Depth refers to depth below the surface at this origin. Strike is measured clockwise from north. Rank indicates how sure the observation of each reflection is on profiles that the reflection is observed on; 1 = definite, 2 = probable, 3 = possible.

Reflector	Strike	Dip	Distance (m)	Depth (m)	Rank	Profiles observed on
A1	75	45	3,200		1	1, 2?, 3?, 4, 5?
A2	80	22	790		1	2, 3, 4? 5
A3	65 (50)	25 (23)	–10 (–50)		1	2?, 3, 5
A4	65	25	–950		1	3, 5
A5	75	30	–1,450		1	3, 5
A6	75	30	–1,875		1	3, 5?
A7	(–55)	(23)	(–780)		1	3, 5
B1	30	25	–600		1	3, 5
B2	30	25	950 (800)		1	2?, 3, 5
B3	30	21	1,750 (1,550)		1	2?, 3, 4? 5
B4	50	28	1,460		1	2, 3, 4? 5
B5	50	25	2,600		1	3, 4? 5
B6	(30)	(32)	(–250)		1	3, 5
B7	(25)	(20)	(1,700)		2	1, 5
C1	15	20		3,300	1	1, 2, 3, 4, 5
C2	355	10		3,300	1	1, 2, 3, 4, 5
D1	320	65	2,500		3	2, 5?
D2	120	50	2,500		3	2, 5?
D3	320 (305)	65	3,200 (3,400)		3	2, 5?
E1	270	9		2,020	2	2, 5
F1	20	20		400	2	2, 5
G1	180	3		100	3	1, 4
G2	180	3		200	3	1, 4
G3	0	2		1,120	3	1, 4
G4	0	2		1,220	3	1, 4
H1	123	70	–150		2	1, 2?, 4
H2	123	70	–50		2	1, 2?, 4
I1	30	70	–1,100		2	3, 5

Table 1-2. Predicted intersection points of KFM02 with those reflectors that project into the borehole shallower than 1,500 m as reported in R-02-43 and in this update (in braces). Rank indicates how sure the observation of each reflection is on profiles that the reflection is observed on; 1 = definite, 2 = probable, 3 = possible.

Reflector	Intersection depth	Strike	Dip	Rank
A2	470	80	22	1
A3	180 (150)	65	25	1
B2	600 (–)	30	25	2
B3	800 (–)	30	21	2
B4	980	50	28	1
B5	1,390	50	25	2
F1	500	20	20	2
H1	50	123	70	3

Table 1-3. Predicted intersection points of KFM03 with those reflectors that project into the borehole shallower than 1,500 m as reported in R-02-43 and in this update (in braces). Rank indicates how sure the observation of each reflection is on profiles that the reflection is observed on; 1 = definite, 2 = probable, 3 = possible.

Reflector	Intersection depth	Strike	Dip	Rank
A2	900 (–)	80	22	1 (3)
A3	800 (810)	65 (50)	25 (23)	1
A4	370	65	25	1
A5	60	75	30	1
A7	(470)	(55)	(23)	1
B1	650	30	25	1
B6	(1,080)	30	32	1
B2	1,370 (1,300)	30	25	1
B3	1,430 (1,360)	30	21	1

Part 2

Updating of estimated bedrock topography

Introduction

Estimated bedrock topography data were presented in /Bergman et al. 2004, SKB P-04-99/, "Forsmark site investigation: Estimate of bedrock topography using seismic tomography along reflection seismic profiles". However, when the report was published, there was no method available to produce reliable bedrock velocities. Now such capabilities have been developed and the following should be added to the results of the study.

The new material in this update to the original report consists of:

- Bedrock velocities down to 10 m below the sea level.
- Update of bedrock topography estimates.
- Comparison of the bedrock velocities with the reflectivity of the stacked reflection seismic sections from /Juhlin et al. 2002, SKB R-02-43/.

The tomography inversion method used to estimate the bedrock velocity and topography has been further developed. The thickness of the unconsolidated sediment layer is much larger than the depth of the shotpoints in much of the data. Therefore, the size of the receiver corrections should not differ significantly from sources corrections calculated by tomography inversion with statics (TIS). This suggests an alternative iterative scheme:

- First, one initial TIS iteration to calculate receiver corrections is run but without updating the velocity field.
- Next, apply the calculated TIS corrections divided equally between the receiver and the sources. A small addition (2 ms/m i.e. 500 m/s medium velocity) of the static applied to the sources was used to account for the difference in vertical position from the geophones.
- Finally, update the velocity model by performing a tomographic inversion without simultaneous static calculations.

Using this suggested iterative scheme, reliable bedrock velocities are gained. Due to the change of iteration scheme and the somewhat stronger smoothing constraints that have to be used, the bedrock topography estimates become different then from those in /Bergman et al. 2004, SKB P-04-99/.

New and updated results

The new and updated results are presented in Figure 2-1. The differences between estimated and measured depths for various borehole positions along the profiles are presented in Table 2-1.

The most drastic change in the estimated bedrock topography is the much-reduced depths of the deepest valleys present in the earlier estimates. The valleys most changed are those at 500–750 m in profile 1, at 550 and 1,400 m in profile 4 and at 600, 700 and 1,150 m in profile 5. The estimated bedrock topography is generally smoother and troughs in the bedrock topography are to a less degree correlated with raises in surface topography. Still, the estimates of bedrock topography correlate well with the results from boreholes at a distance of up to about 25–30 m from the seismic profiles.

A clear correlation can be noted between the tomography velocity models and the reflectivity pattern in the stacked reflection seismic sections (Figure 2-1).

- The stacked sections of profile 1 and profile 2 reveal no distinct reflectivity near the surface. The more varying velocities in the tomographic velocity sections of profile 3, profile 4 and profile 5 coincide with clear reflectivity in the stacked sections.
- In profile 3, three reflectors may be projected up to the surface at 600, 1,200 and 1,850 m along the x-axis of the model. The clearest reflector, reaching the surface at 1,200 m, is seen as a low velocity in the tomography section. The same correlation holds for the other reflectors in profile 3.
- Profile 4 has no such clear reflectors as profile 3, but there are a number of weaker reflectors projecting up to the surface at 1,300 to 1,600 m into the profile correlating with the location of lower velocities.
- Profile 5 has the strongest reflectors on the stacked seismic sections and the most varying surface velocities. The strongest reflector reaches the surface at about 1,350 m along the x-axis, corresponding to a large decrease in the velocities of the tomography section. The reflector that projects up to the surface at 1,750 m is not matched by a low velocity part in the tomographic velocities. However, the reflectivity also seems to terminate before reaching the surface.

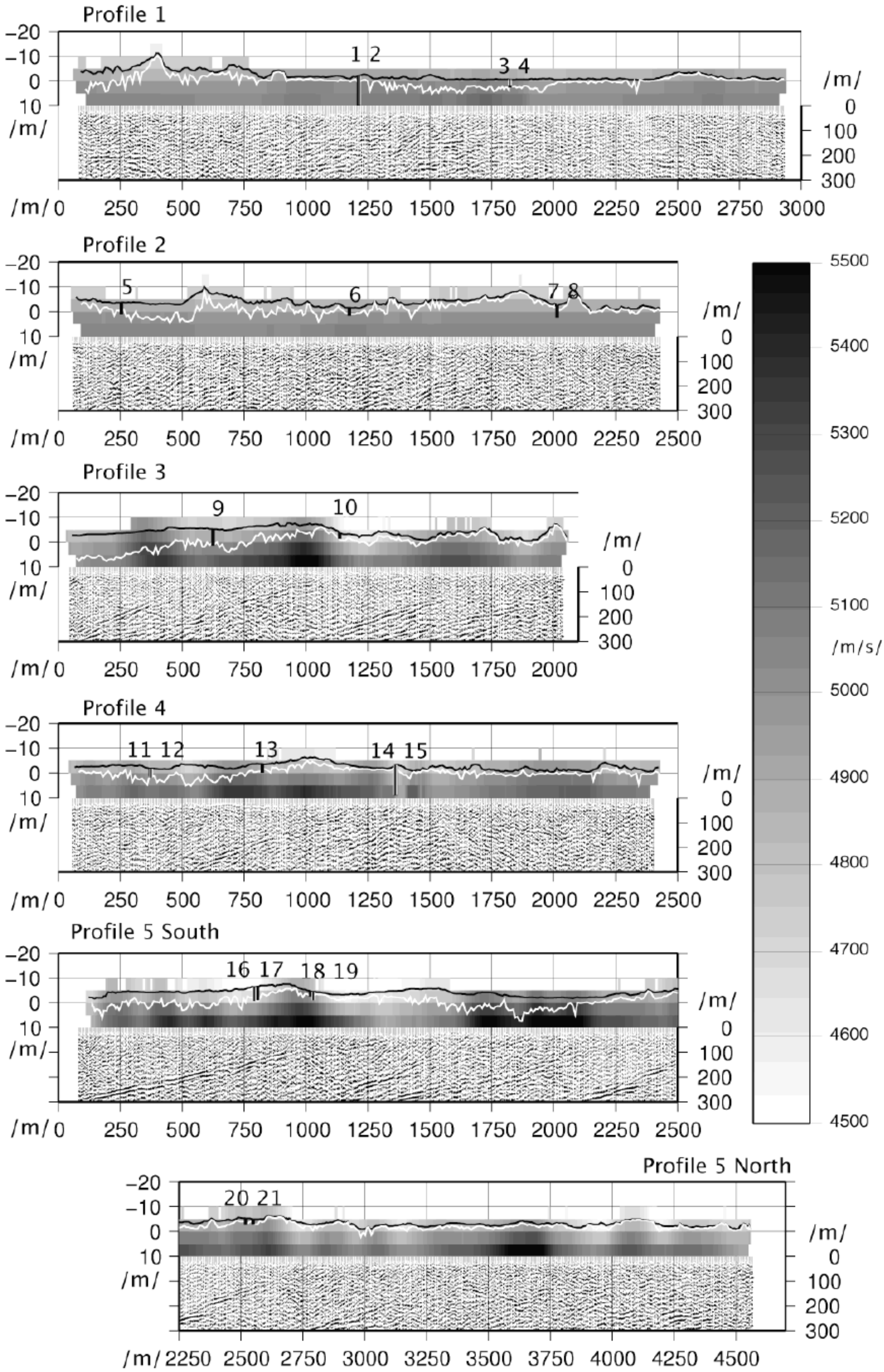

__Figure 2-1.__ Surface topography (black line) and estimated bedrock topography (white line). Boreholes (vertical black bar) are numbered as listed in Table 2-1. Stacked reflection seismic sections were depth converted with a constant velocity of 5,000 m/s.

Table 2-1. Difference between estimated and measurd depth for various borehole positions along the profiles for the update.

Index	Borehole	Measured depth (m)	Estimated depth (m)	Difference in depths (m)	Distance from profile (m)
1	HFM0002	12.2	2.6	9.6	29.9
2	HFM0003	12.0	2.5	9.5	30.7
3	SFM0034	3.2	3.1	0.1	22.5
4	SFM0035	2.3	3.1	–0.8	23.6
5	SFM0019	4.8	2.6	2.2	12.1
6	SFM0020	3.2	2.4	0.8	16.3
7	HFM0004	5.1	1.1	4.0	26.1
8	SFM0004	0.8	1.3	–0.5	5.2
9	HFM0007	6.6	5.6	0.9	19.8
10	SFM0008	2.5	2.8	–0.3	23.3
11	SFM0030	3.6	2.8	0.8	8.0
12	SFM0031	3.6	2.9	0.7	8.0
13	HFM0013	3.5	2.7	0.8	22.4
14	HFM0002	12.2	1.8	10.4	30.8
15	HFM0003	12	1.8	10.2	28.7
16	HFM0008	5.5	3.5	2.0	51.1
17	SFM0007	5.4	5.6	–0.2	64.2
18	HFM0005	3.4	1.4	2.0	39.5
19	SFM0006	2.0	1.6	0.4	49.7
20	SFM0009	2.5	1.4	1.1	35.8
21	SFM0005	2.1	1.1	1.0	21.8

Discussion and conclusions

The change of scheme for the tomography inversion has made it possible to produce a reliable velocity model for the bedrock. Still, the calculated velocities have to be regarded as approximate since there will always be an ambiguity between applied static corrections and the absolute tomographic velocities. The real information lays in the velocity variations. In the present velocity results there is a fine correlation between reflectivity and low velocities in the models. However, the effect of the low velocities in the fracture zones is spread out on a large region due to the smoothing. Thus, the low velocity zones cannot be used to resolve properties of the fractured bedrock.

The estimate of bedrock topography is different from those in the original report due to the use of a new scheme. The result is a more smooth bedrock topography estimate. The most distinctive valleys are much reduced in depths. Another effect is the less strong correlation between lows in the estimated bedrock topography with raises in the surface. Besides the stronger smoothing, this effect can be explained by the better (now existent) handling of the delay time contribution from the source positions. The new bedrock topography estimates are closer to those measured in boreholes than in the original report. A velocity model incorporating the distribution of the different types of unconsolidated sediments and their seismic velocities would yield better estimates of the bedrock topography than from a 1D-velocity model. This cannot be included in the tomographic inversion. The static corrections, calculated by the tomography inversion, are independent of the velocities in the different unconsolidated sediments. A more detailed map of the bedrock topography could possible be made using the calculated static corrections and knowledge of the Quaternary geology.

References

Bergman B, Juhlin C, 2004. Forsmark site investigation: Estimate of bedrock topography using seismic tomography along reflection seismic profiles. SKB P-04-99. Svensk Kärnbränslehantering AB.

Juhlin C, Bergman B, Palm H, 2002. Reflection seismic studies in the Forsmark area – stage 1. SKB R-02-43. Svensk Kärnbränslehantering AB.