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Oskarshamn site investigation

Reflection seismic studies performed in the Laxemar area during 2004

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September 2004

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Keywords: Reflection seismics, Reflectors, Mafic sheets, VIBSIST, Laxemar.

Abstract

Reflection seismic data were acquired in the Spring of 2004 in the Oskarshamn area, located about 300 km south of Stockholm, Sweden. The Oskarshamn area has been targeted by SKB as a possible storage site for high level radioactive waste. About 9.9 km of high resolution seismic data were acquired along three separate profiles, 3.9 km along N–S profile 3, 1.8 km along W–E running profile 4, and 4.2 km along N–S running profile 5. Nominal source and receiver spacing was 10 m with at least 160 active channels when recording data from a dynamite source (15–75 g). On part of profile 5, a mechanical VIBSIST source was tested for two days.

Results from the present survey show a similar reflectivity pattern to that observed on the Laxemar 1999 survey acquired further east. However, prominent reflections from the earlier survey appear to be limited towards the west on the present survey. The pronounced north dipping A reflector (penetrated by the KLX02 borehole at about 200 m) is not observed further west than km 1,548.5 E of the Swedish national grid on the present survey, indicating that it is not regional feature. In contrast, reflections with a south dipping component are present in the uppermost 0.2 s on the present survey. Zone ZSMEW002A (Mederhultszonen) is imaged as a steep (75°) south dipping reflector on all profiles. More gently (20–25°) south dipping reflections (set M) are also present on all profiles. This set does not appear to intersect the surface. The set M reflections are the only reliably oriented reflections that are expected to be penetrated by the KLX03 and KLX04 boreholes. Since the major reflections appear to strike mainly in the WE direction migrated sections of the N–S running profiles 3 and 5 show reasonable images of the general reflector geometry. On these images the set M reflectors appear to terminate in the north at the steeply dipping ZSMEW002A zone. Three other reflections observed in the upper 0.2 s can be correlated to topographic lows, suggesting they originate from fracture zones.

N–S running profiles 3 and 5 cross a major W–E striking topographic low at their southern ends. No reflections that can be correlated with this low can be observed. This suggests that the zone is either near-vertical or that the profiles were not extended far enough to the south to image south dipping reflections. Regardless, the zone does not appear to dip to the north into the survey area.

Gently north dipping deep reflections from below 1 s (3 km) are present on all three profiles. These have been observed on all previous data sets acquired (Ävrö 1996, Laxemar 1999, Ävrö 2003) in the area. These reflections project to the surface about 10 km south of the survey area and may represent a regional structure.

Processing of the VIBSIST data shows that comparable, and perhaps superior, images may be obtained using the mechanical VIBISIST source compared to the explosive source. Advantages of the VIBSIST system over dynamite are (i) lower cost, (ii) can be used where dynamite is prohibited, (iii) repeatable signal, and (iv) shorter startup times (no drilling of shot holes prior to acquisition). One disadvantage is that it is more difficult to use in the terrain, resulting in that profiles have to more closely follow roads.

Sammanfattning

Reflektionsseismiska data registrerades våren 2004 i Oskarshamnsområdet, ca 300 km söder om Stockholm. Oskarshamnsområdet är en ut av platserna SKB har valt för möjlig förvaring av hög aktivt kärnavfall. Ca 9,9 km av högupplösande reflektionsseismiska data samlades in längs tre separata profiler; 3,9 km längs N–S profil 3, 1,8 km längs O–V profil 4, och 4,2 km längs N–S profil 5. Nominella käll- och mottagaravstånd var 10 m med minst 160 aktiva kanaler. 15–75 g dynamit användes som källa. På en del av profil 5 testades en mekanisk VIBSIST källa under 2 dagar.

Resultatet från denna undersökning visar ett liknande mönster av reflektorer som det Laxemar undersökningen längre österut, som utfördes under 1999, gav. Men en del tydliga reflektorer från 1999 undersökningen tycks ha begränsad utsträckning västerut. Den tydliga mot norr stupande A reflektorn (genomborrad av KLX02 vid ca 200 m djup) observeras inte längre västerut än 1 548,5 km (RT90 koordinater) på de nya profilerna, vilket betyder att denna reflektorn inte är en regional struktur. Däremot finns det tydliga mot syd stupande reflektioner på de nya profilerna i de översta 0.2 s. Zonen ZSMEW002A (Mederhultszonen) syns som en brant (75°) mot syd stupande reflektor på alla profiler. Mer svagt lutande (20–25°) reflektioner (grupp M) finns också på alla profiler. Denna grupp av reflektorer tycks inte gå upp till ytan. Grupp M reflektionerna är de enda med säker orientering som borrhål KLX03 och KLX04 kommer att borra igenom. Eftersom huvudreflektorerna stryker främst i O–V, ger migrerade sektioner av NS profilerna 3 och 5 relativt bra bilder av reflektorgeometrin. På dessa bilder, ser det ut som om grupp M reflektorerna är begränsade i deras utsträckning norrut av den brant stupande zonen ZSMEW002A. Tre andra reflektorer i de översta 0.2 s kan korreleras med topografiska sänkor, vilket pekar på att de representerar sprickzoner.

N–S profilerna 3 och 5 korsar en större O–V topografisk sänka på deras södra ändar. Inga reflektioner som kan korreleras med denna sänka kan observeras. Detta innebär att zonen är subvertikal eller att profilerna inte gick tillräckligt långt söderut för att belysa mot syd stupande reflektorer från detta utgående. Oavsett orsaken, tycks det inte finnas några mot norr stupande reflektorer som kan knytas till sänkan.

Svagt mot norr stupande reflektioner finns på alla profiler djupare än 1 s (3 km). Dessa reflektioner har setts tidigare på alla undersökningar i Oskarshamnsområdet (Ävrö 1996, Laxemar 1999, Ävrö 2003). Reflektorerna kan projiceras till ytan ca 10 km söder om området och de kan representera en större regional struktur.

Databehandlade bilder av VIBSIST data visar bilder som är lika bra, eller möjligtvis bättre än bilderna erhållna från sprängning. Fördelarna med VIBSIST systemet över sprängning är (i) lägre kostnad, (ii) kan användas där dynamit inte tillåts, (iii) reproducerbar signal, och (iv) kortare mobiliseringstider (ingen borrning av skotthål behövs). En nackdel med systemet är att det är svårare att använda i terräng, vilket betyder att vägar och stigar måste följas i större utsträckning.

Contents

1 Introduction

This document reports the results gained by the reflection seismic studies performed in the Laxemar area during 2004, which is one of the activities performed within the site investigation at Oskarshamn. The work was carried out in accordance with activity plan AP PS 400-04-024 (SKB internal controlling document). In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

Table 1-1. Controlling documents for the performance of the activity (SKB internal controlling document).

Activity plan	Number	Version
Reflektionsseismik vid Laxemar, 2004	AP PS 400-04-024	1.0
Method descriptions	**Number**	**Version**
Metodbeskrivning för reflektionsseismik	SKB MD 241.004	1.0

Seismic data were acquired in the Oskarshamn area in southeastern Sweden (Figure 1-1) during late April to early June in the year 2004 by Uppsala University. Approximately 9.9 km of high resolution (10 m shot and receiver spacing) reflection seismic data were acquired with the SERCEL 408UL system along 3 different profiles (Figure 1-2) using about 740 shot points. In addition, a VIBSIST mechanical source was tested along part of profile 5 from shotpoint 5,145 to shotpoint 5,270.

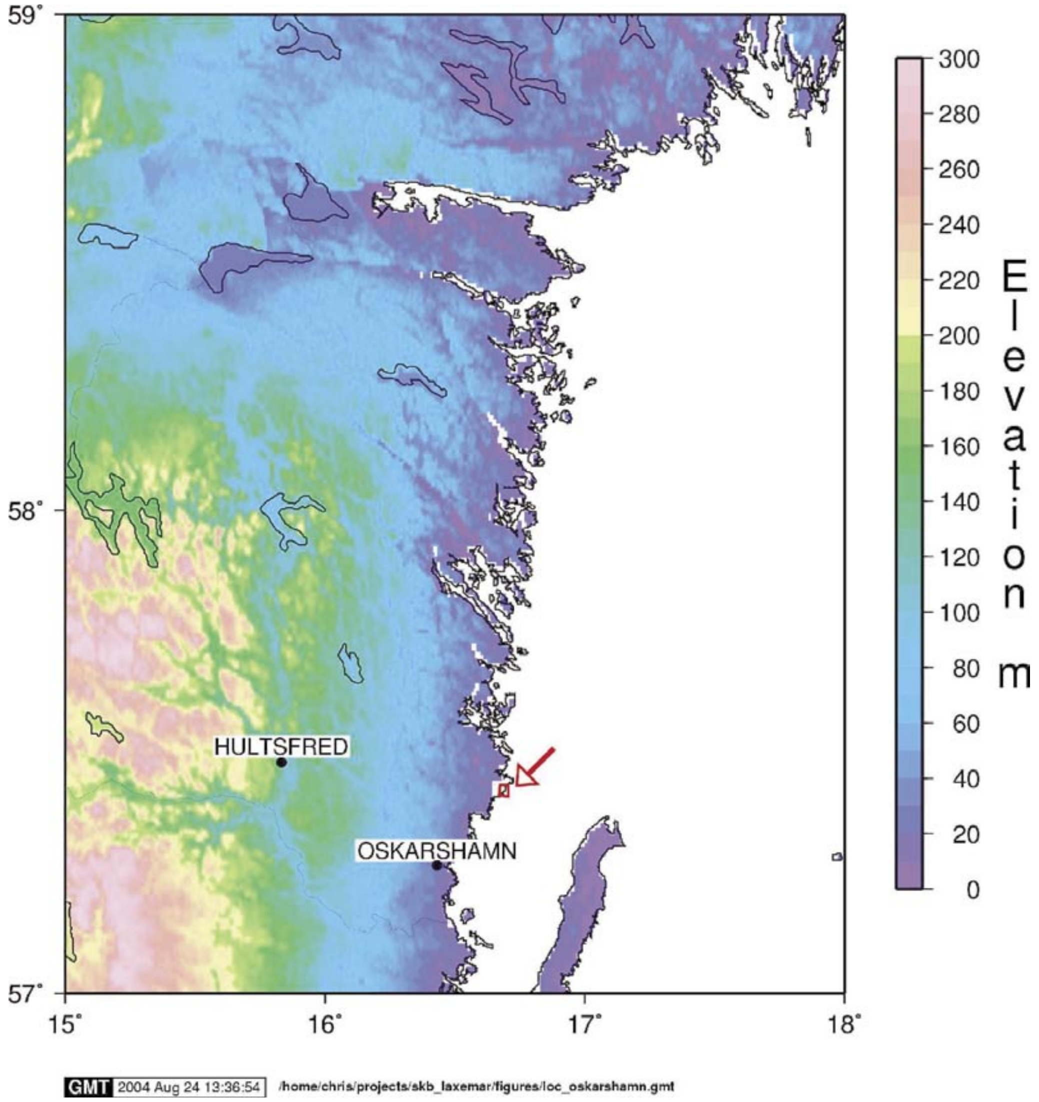

Figure 1-1. *Location of study area (red box marked by arrow).*

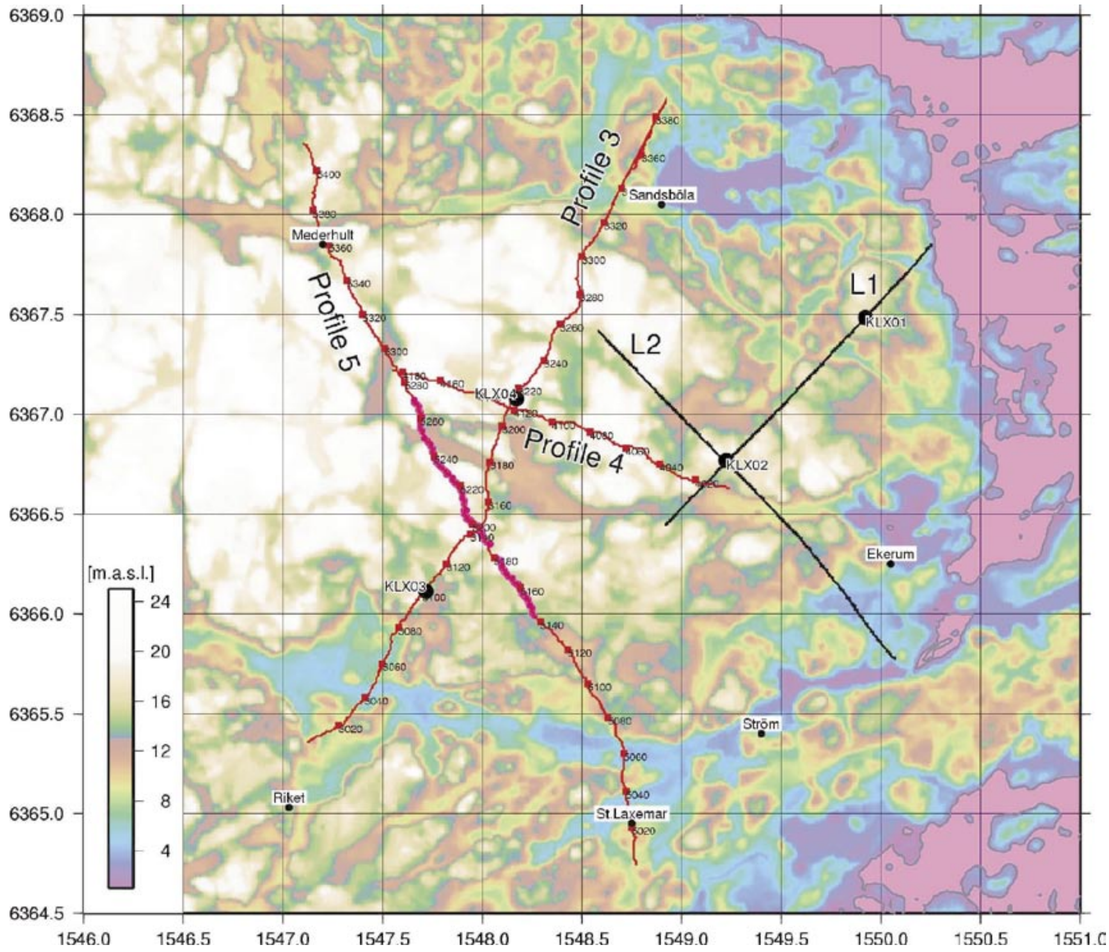

Figure 1-2. *Location of the seismic reflection profiles, profile 3 (LSM000704) profile 4 (LSM000705) and profile 5 (LSM000706) (red lines), and the VIBSIST test (purple dots). Also shown are the reflection seismic profiles acquired in 1999 (black lines) which have been reported on in /2, 3/.*

2 Objective and scope

The objectives with the reflection seismic method used here is to imagine the bedrock from the near surface (upper 100 metres) down to depths of several km. Reflectors obtained are due to changes in the elastic properties of the bedrock, i.e. lithological changes or possible fracture zones. Reflecting objects with a width greater than about a metre in thickness and dipping up to 60–70° can be imaged.

About 9.9 km of high resolution seismic data were acquired along three separate profiles, 3.9 km along N–S profile 3, 1.8 km along W–E running profile 4, and 4.2 km along N–S running profile 5. Nominal source and receiver spacing was 10 m with at least 160 active channels when recording data from a dynamite source (15–75 g). On part of profile 5, a mechanical VIBSIST source was tested for two days.

3 Execution

3.1 Data acquisition

The acquisition crew arrived in the field on April 26 and data acquisition began on April 29, 2004 along profile 3 using the acquisition parameters given in Table 3-1. Data acquisition finished on June 5, 2004 followed by 2 days of demobilization and clean-up. No data were acquired during the period 13–25 May due a scheduled break in the acquisition. VIBSIST data were acquired on 31 May and 1 June.

Shot points and geophones were located as much as possible on bedrock. Shot holes were drilled at the closest suitable location to a staked point where bedrock was present, but not further from the staked point than 30 cm parallel and 1 m perpendicular to the profile. 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 diameter shot holes were drilled to 90 cm depth with an electric drilling machine powered by a gasoline generator. Charges of 15 g were used in bedrock shot holes. In soil cover, 22 mm diameter shot holes were drilled to 150 cm depth with an air pressure drill. These holes were cased with a plastic casing with an inner diameter of 18 mm. Charges of 75 g were used in these holes. Bedrock shot holes were used on about 40% of the profiles. Geophones were placed in drilled bedrock holes wherever possible, otherwise they were placed directly in the soil cover. All shot holes and geophone locations were surveyed with high precision GPS instruments in combination with a total station. This combination gave a horizontal and vertical precision of better than 10 cm.

Table 3-1. Acquisition parameters for the reflection seismic profiles.

Parameter	Reflection
Spread type	Asymmetric split
Number of channels	Minimum 160 Maximum 276
Near offset	20 m
Geophone spacing	10 m
Geophone type	28 Hz single
Shot spacing	10 m
Charge size	15/75 gram
Nominal charge depth	0.9/1.5 m
Nominal fold	80
Recording instrument	SERCEL 408
Sample rate	0.5 ms
Field low cut	Out
Field high cut	500 Hz
Record length	3 seconds
Profile length / shots	3- 3,900 m / 298 4- 1,840 m / 148 5- 4,160 m / 285

3.2 Data processing

3.2.1 Reflection seismic processing

The reflection seismic data were acquired along crooked lines. CDP stacking lines were chosen that were piece-wise straight. The data were projected on to these lines prior to stacking (Figure 3-1). The stacks shown in this report refer to the CDP numbers along these lines.

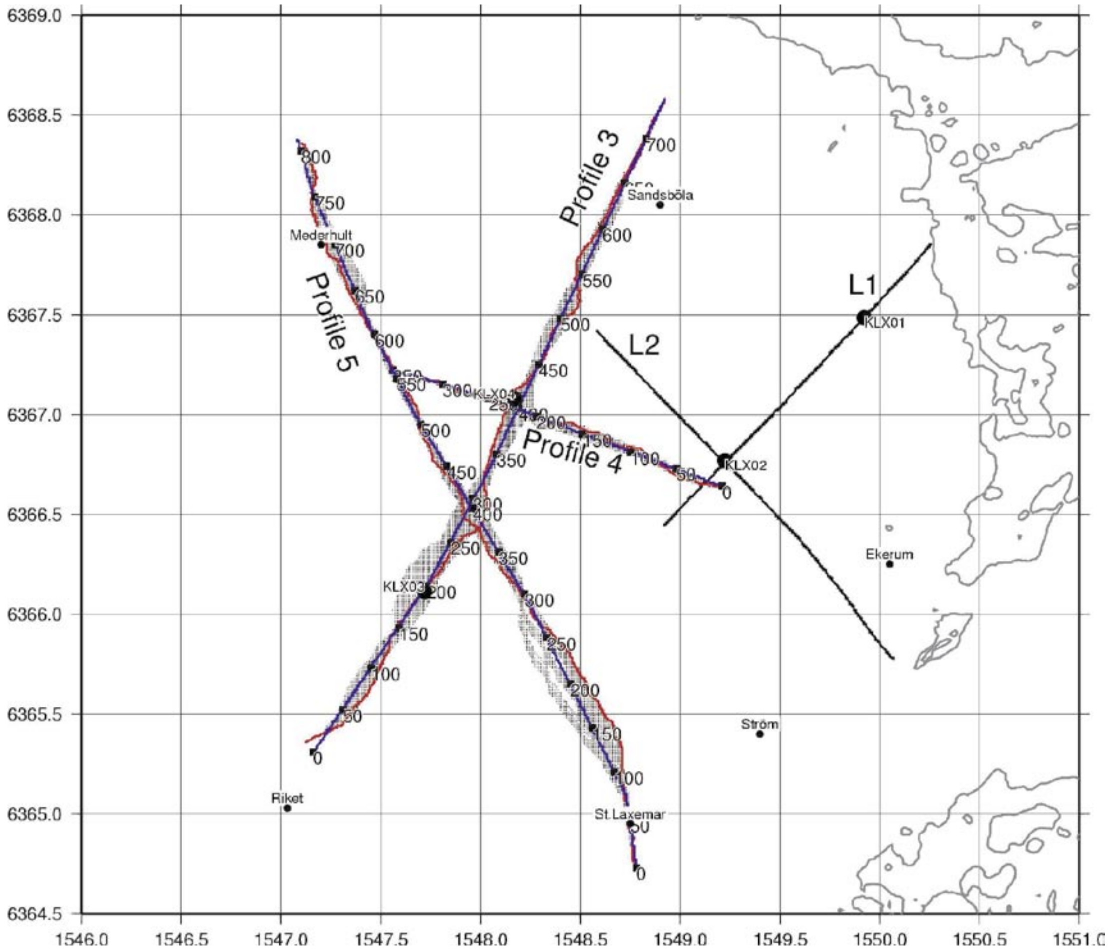

Figure 3-1. Midpoints between shots and receivers (black dots) used in the processing and the CDP lines that the data have been projected onto and stacked along (blue). Numbering refers to CDP position along the stacking line. Actual location of the seismic profiles (red) are also shown, profile 3 (LSM000704), profile 4 (LSM000705) and profile 5 (LSM000706).

The reflection seismic data were processed with the parameters given in Table 3-2. Important processing parameters were refraction statics along with deconvolution and filtering (Figure 3-2).

Table 3-2. Processing parameters for the seismic profiles.

Step	Process
1	Read SEGD data – 3,000 ms
2	Spike and noise edit
3	Pick first breaks
4	Scale by time
5	Surface consistent spiking deconvolution
	Design gate 0 m: 200–500 ms, 500 m: 350–600 ms, 1,800 m: 600–900 ms Operator 60 ms
	White noise added 1%
6	Bandpass filter
	70-140-300-450 Hz 0–100 ms 60-120-300-450 Hz 50–200 ms 40-80-240-360 Hz 150–500 ms 40-80-240-360 Hz 400–700 ms 35-70-180-240 Hz 600–2,000 ms
7	Refraction statics
8	Trace top mute: 5 + offset / 5.5 ms
9	Sort to CDP domain
10	Velocity analyses
11	Residual statics
12	Sort to common offset domain
13	AGC – 50 ms window
14	NMO (Normal moveout)
15	Common offset F–K DMO (Dip moveout) Average 1D NMO velocity after DMO
16	AGC – 50 ms window
17	Iterative DMO velocity analysis
18	Stack (mean)
19	Trace equalization 0–800 ms
20	FX Decon
21	Migration

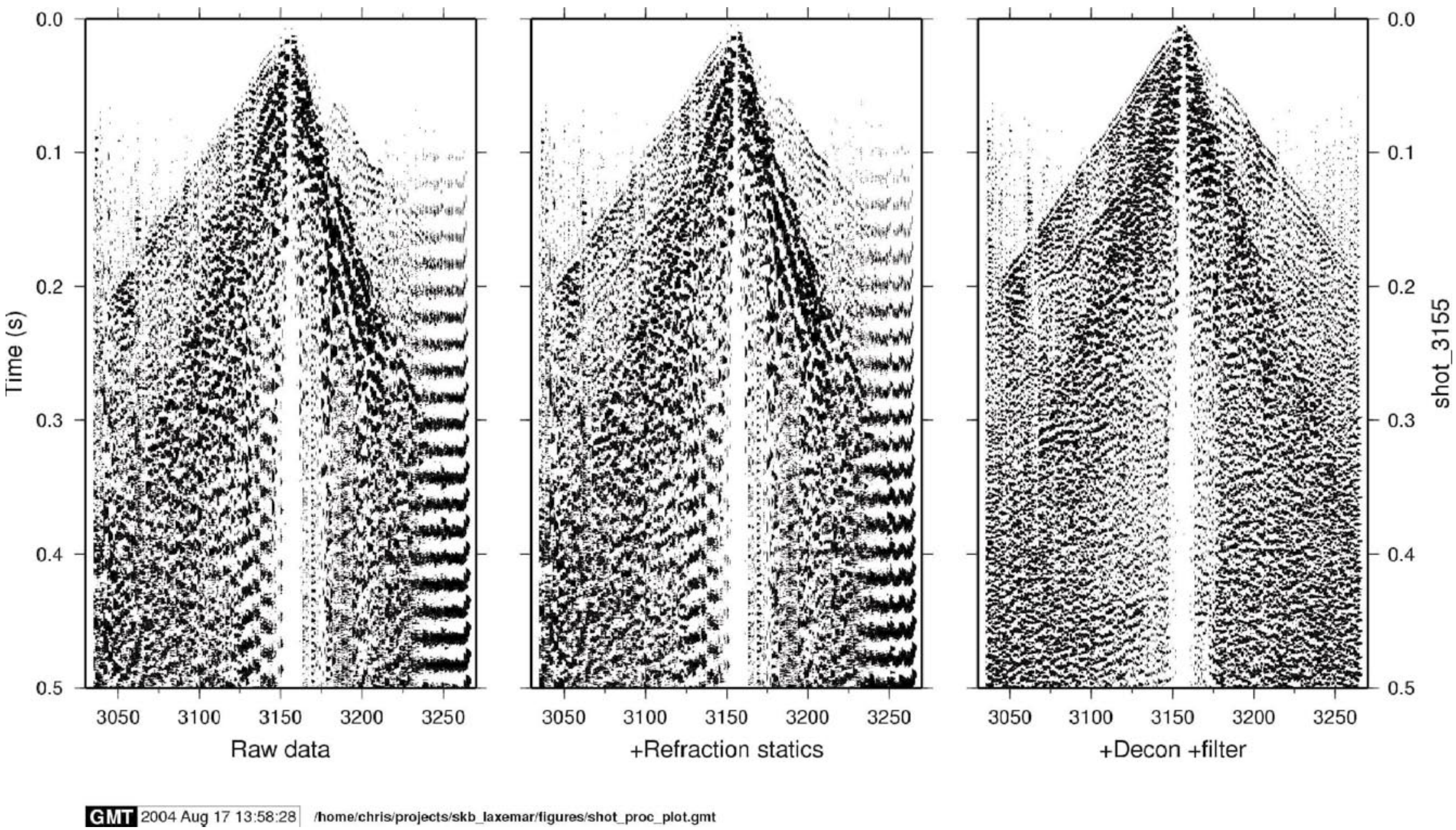

Figure 3-2. *Example of a shot gather from profile 3 (LSM000704) showing raw data scaled by time, with refraction statics added, and after deconvolution and filtering.*

3.3 Stacked and migrated sections

In the figures that follow (Figures 3-3 to 3-8) stacked sections down to 1.6 seconds are first shown followed by a more detailed image of the uppermost 0.8 s for each profile. In these figures the data have been processed to step 20 in Table 3-2.

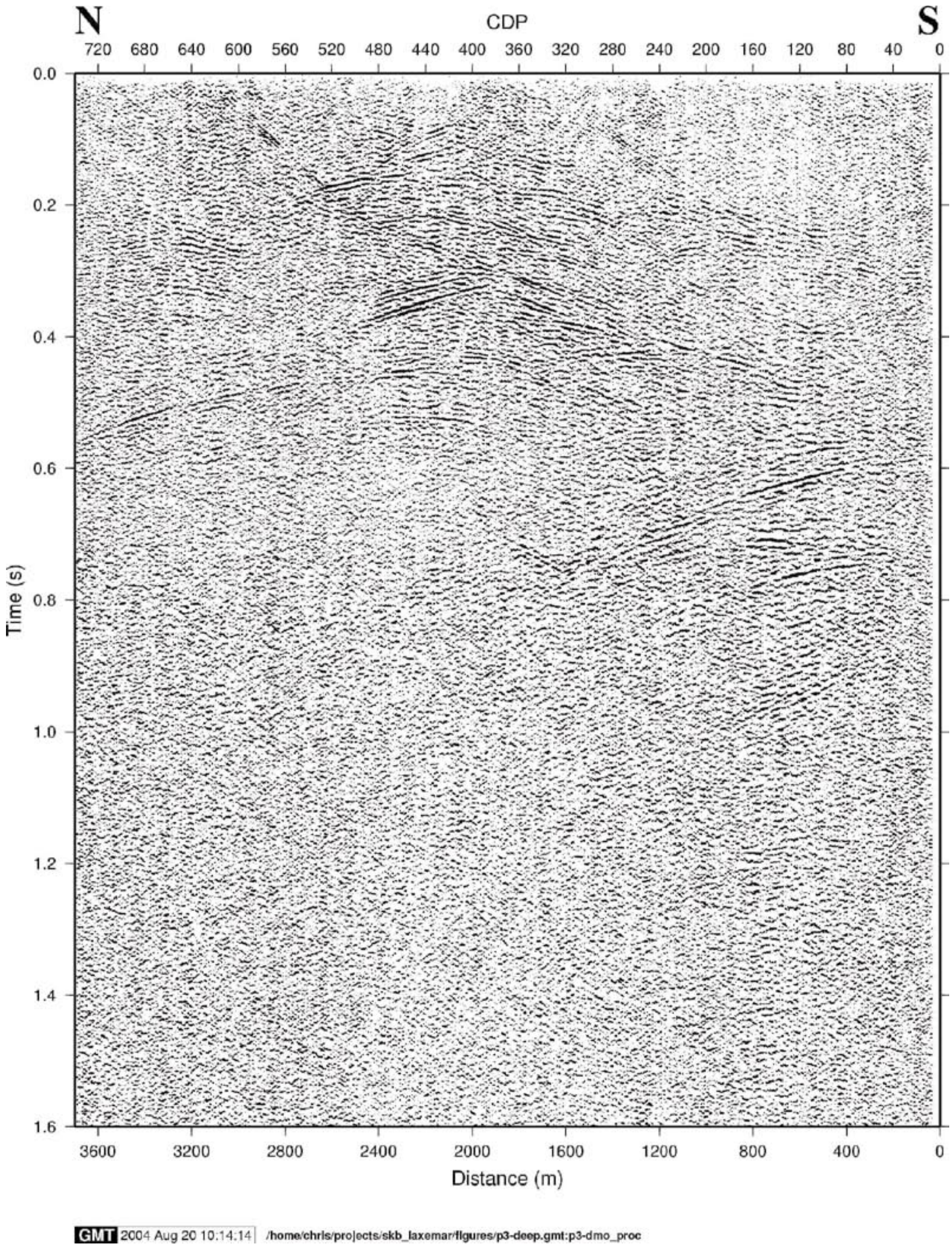

Figure 3-3. *Stacked section of profile 3 (LSM000704) down to 1.6 seconds.*

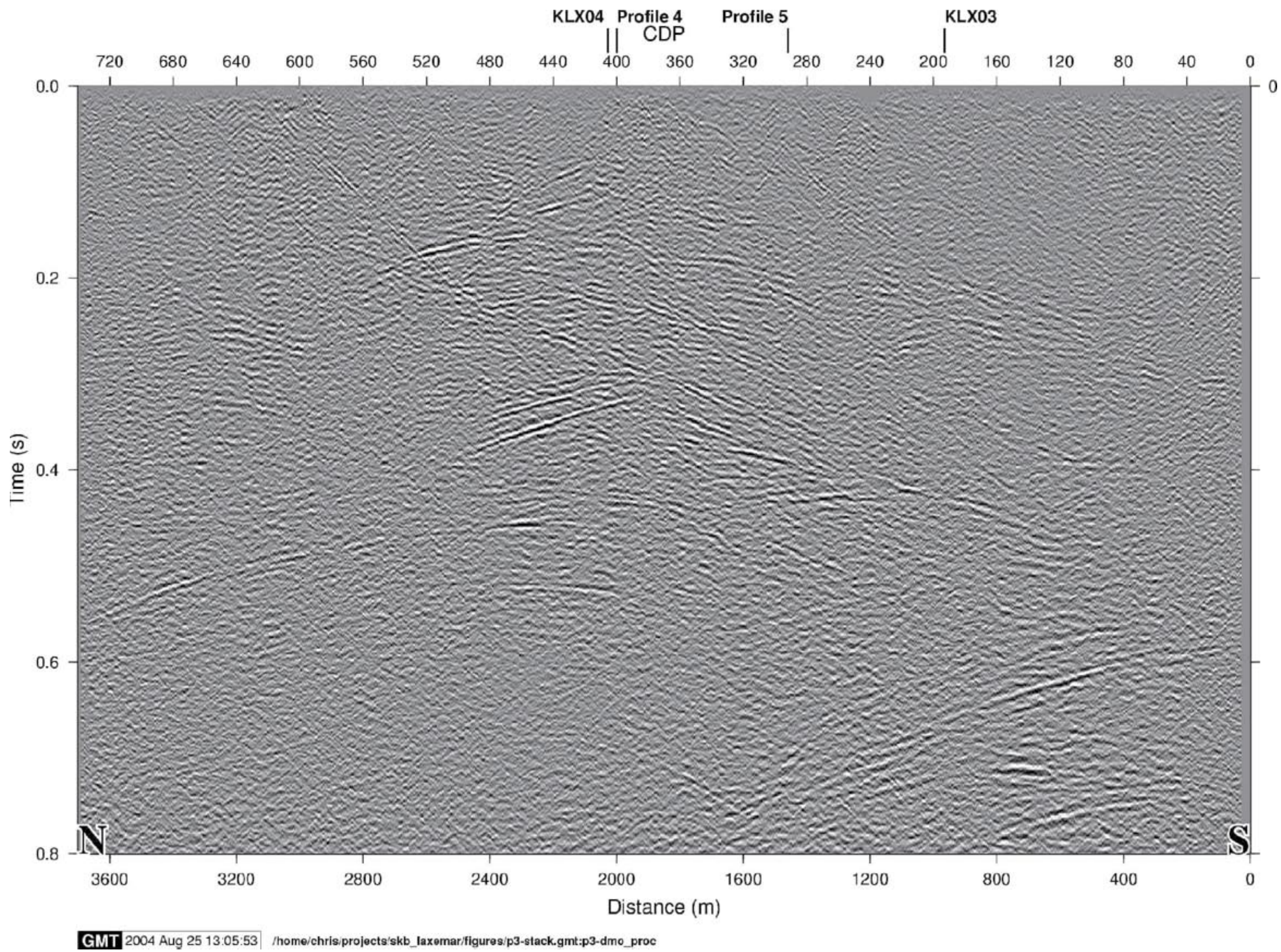

Figure 3-4. Stacked section of profile 3 (LSM000704) down to 0.8 seconds.

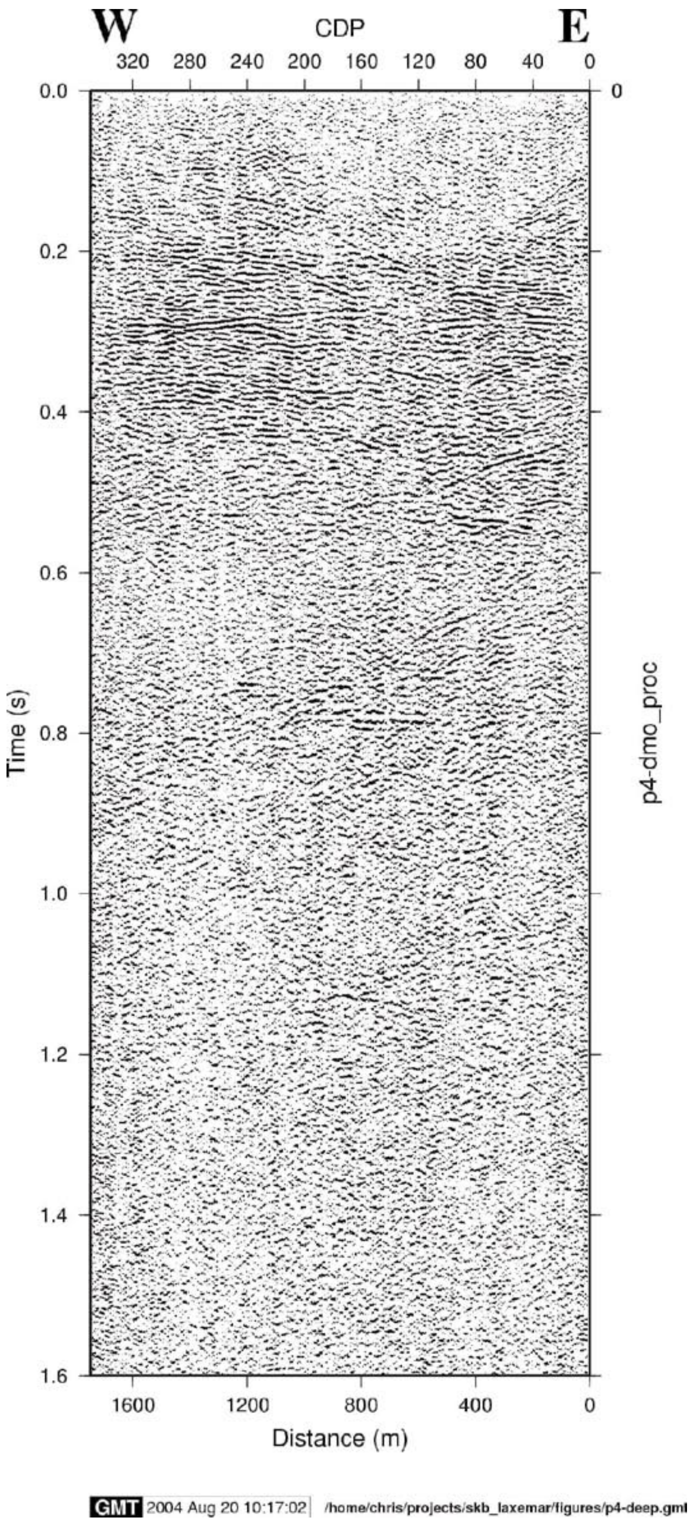

Figure 3-5. *Stacked section of profile 4 (LSM000705) down to 1.6 seconds.*

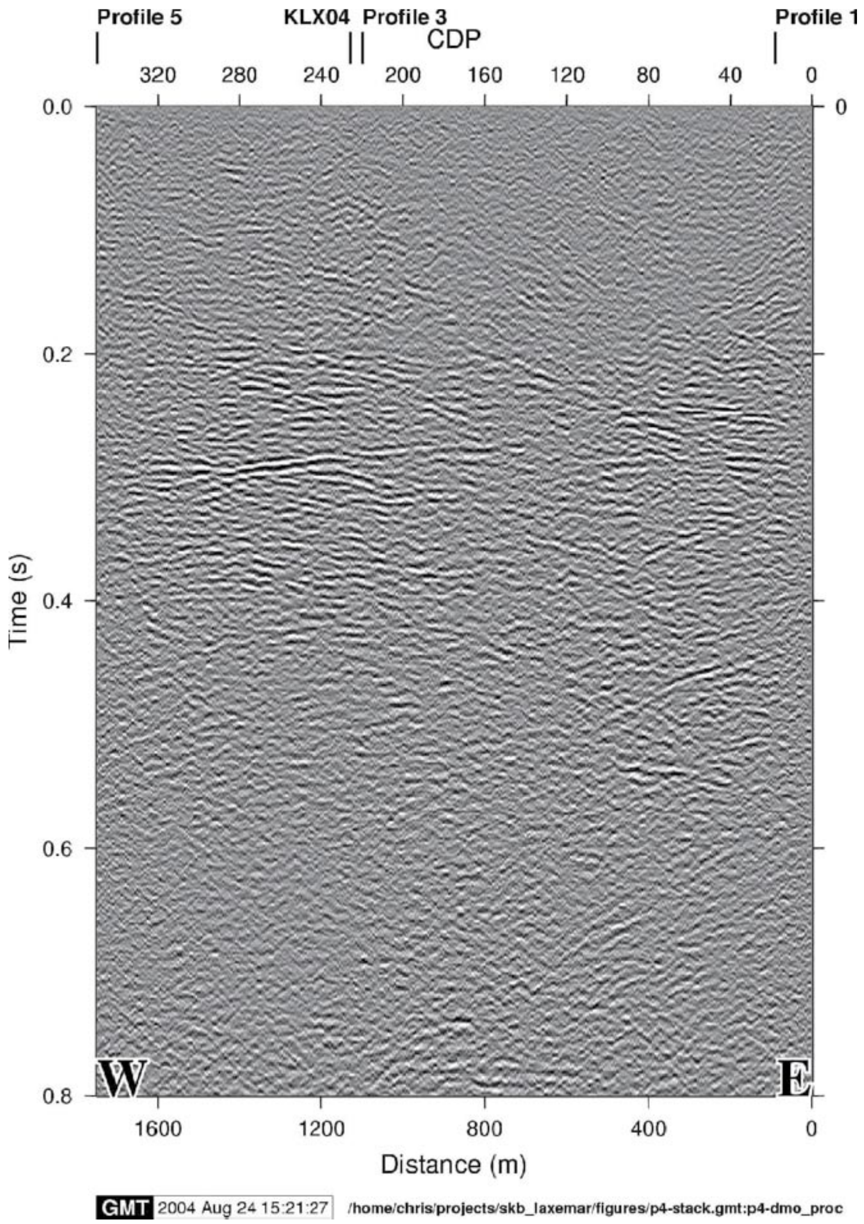

Figure 3-6. *Stacked section of profile 4 (LSM000705) down to 0.8 seconds.*

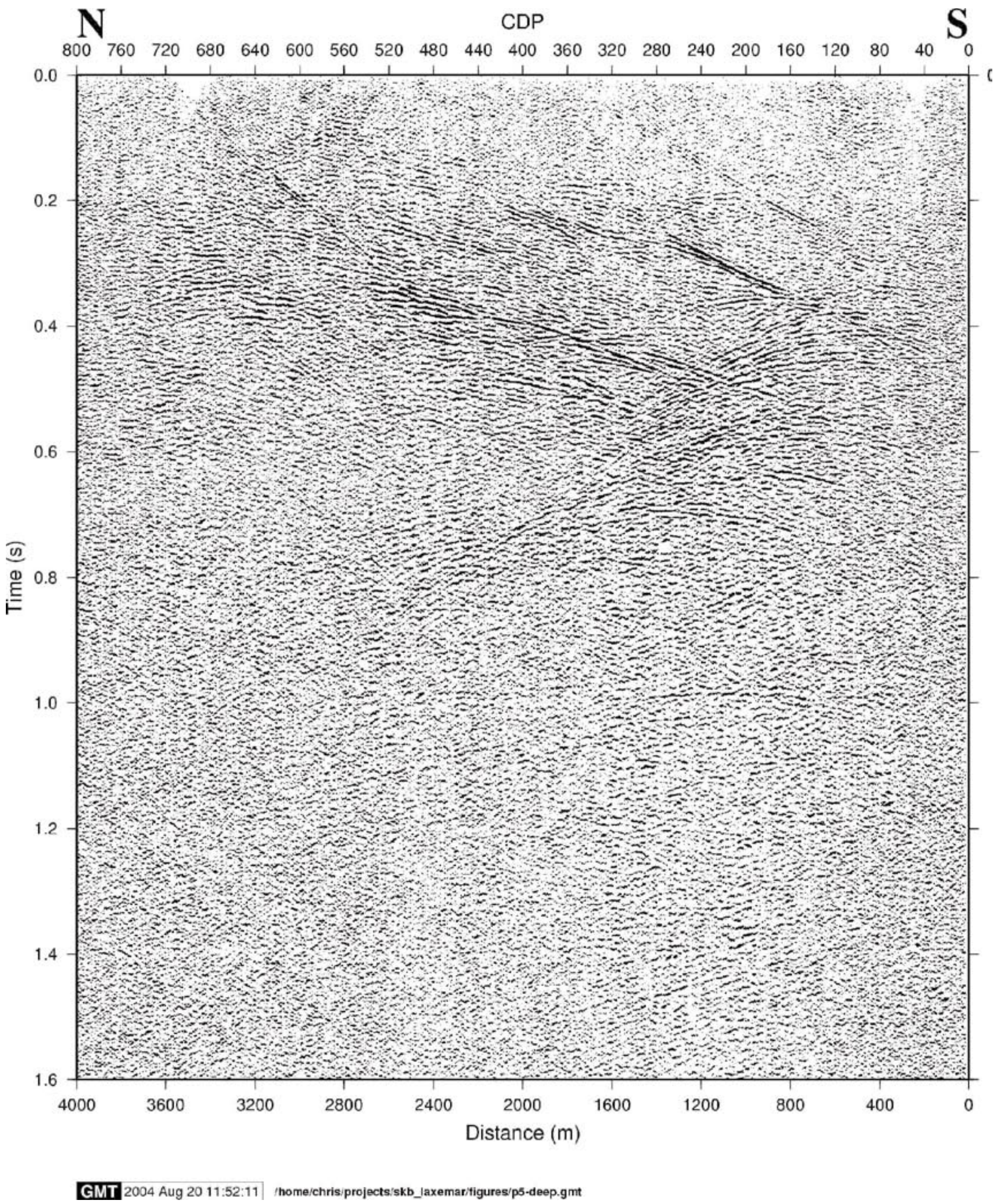

Figure 3-7. *Stacked section of profile 5 (LSM000706) down to 1.6 seconds.*

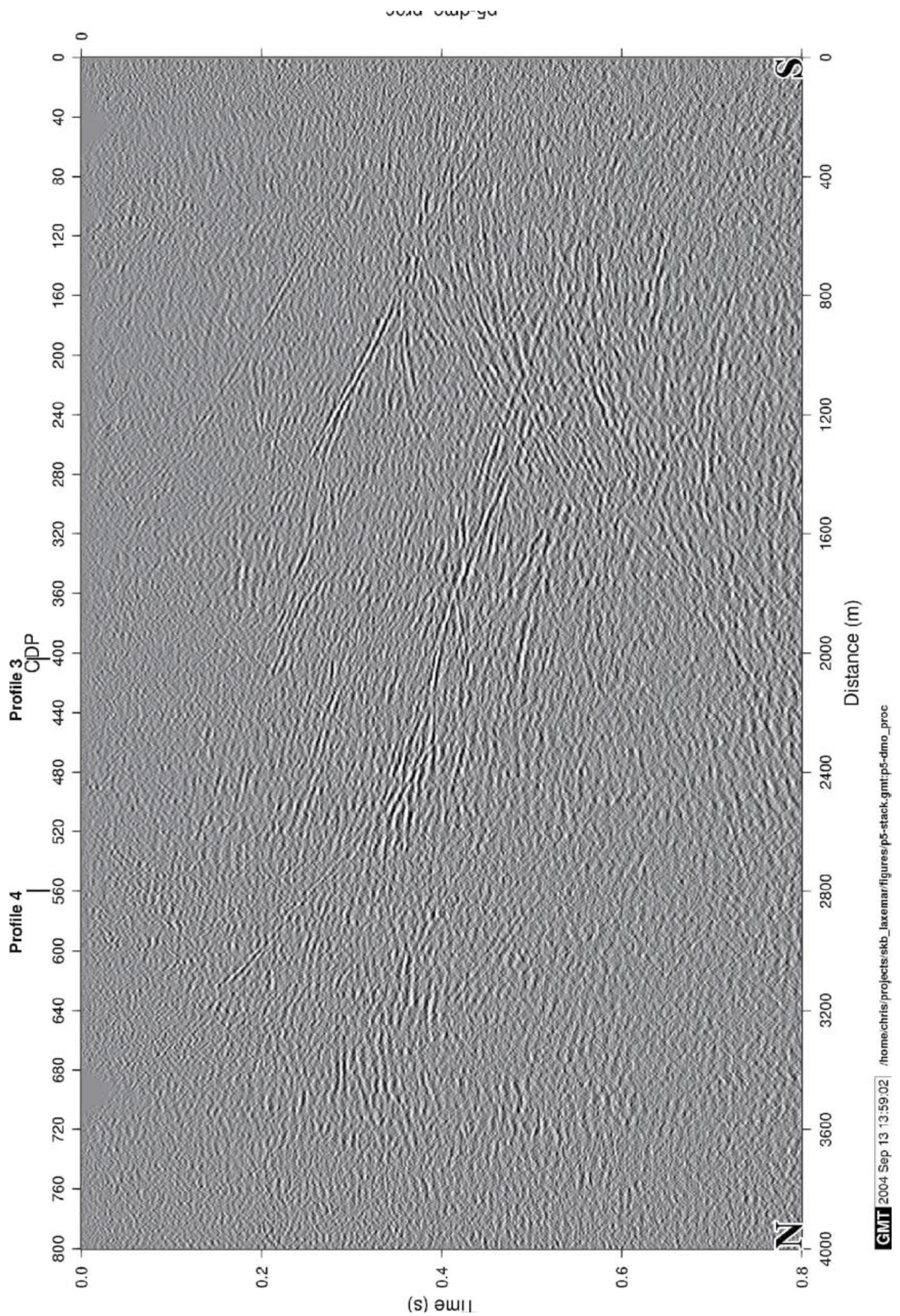

Figure 3-8. *Stacked section of profile 5 (LSM000706) down to 0.8 seconds.*

Profiles 3 and 5 have been migrated (Figures 3-9 and 3-10). The reader should keep in mind that many of the reflections are from out of the plane of the profile and, therefore, the migrated sections cannot be regarded as vertical slices below the profiles. Instead the depth scale should be regarded as distance from the surface to the reflector. The approximate depth scale shown in the figures is based on the average DMO velocity and is only valid for reflections striking perpendicular to the plane of the profile. Since many of the reflections appear to strike E–W (see chapter 4), the migrated images of profiles 3 (LSM000704) and profiles 5 (LSM000704) are reasonably realistic.

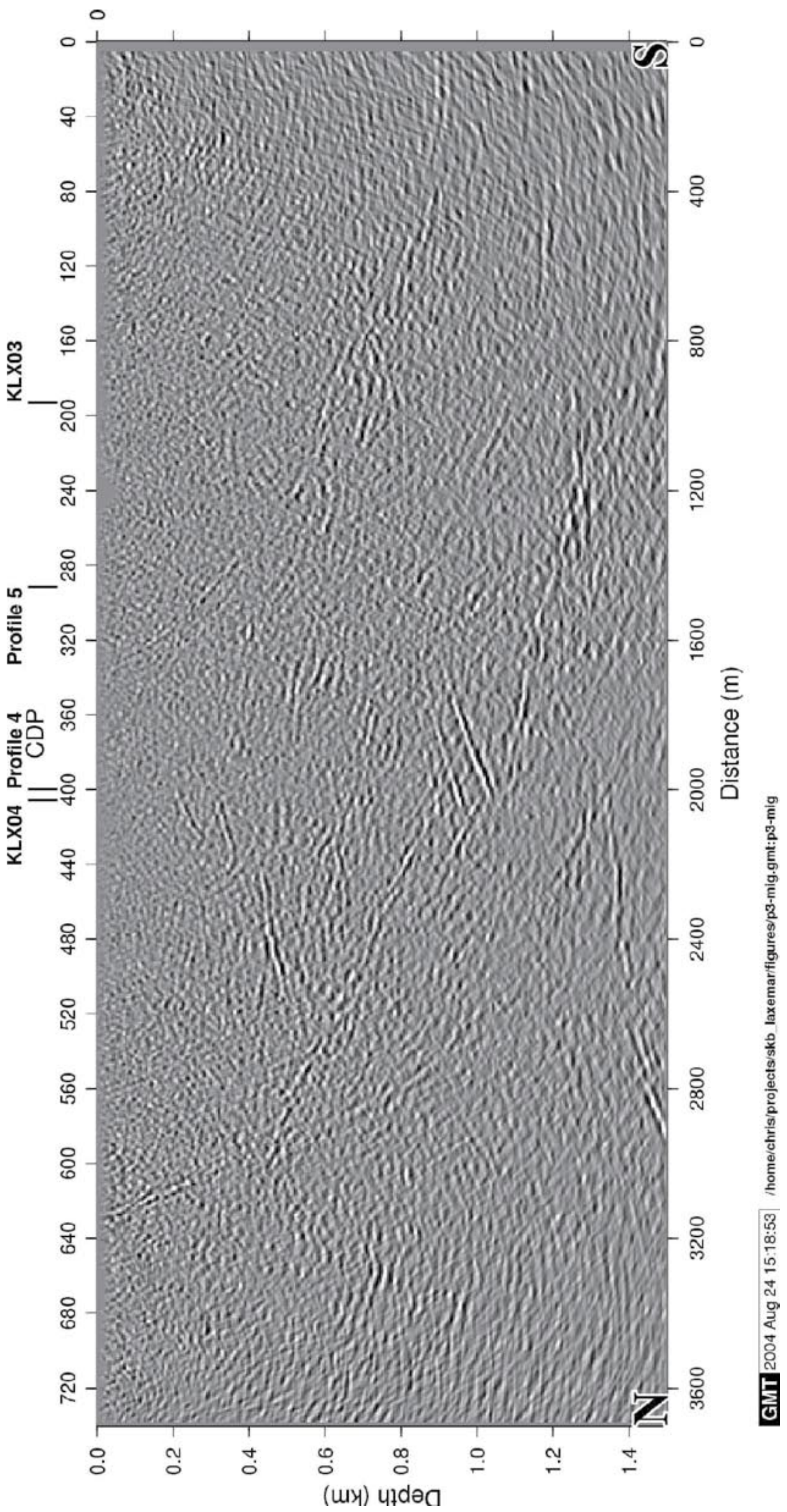

Figure 3-9. *Migrated section of profile 3 (LSM000704) down to 1,500 m. Depth scale only valid for true subhorizontal reflections.*

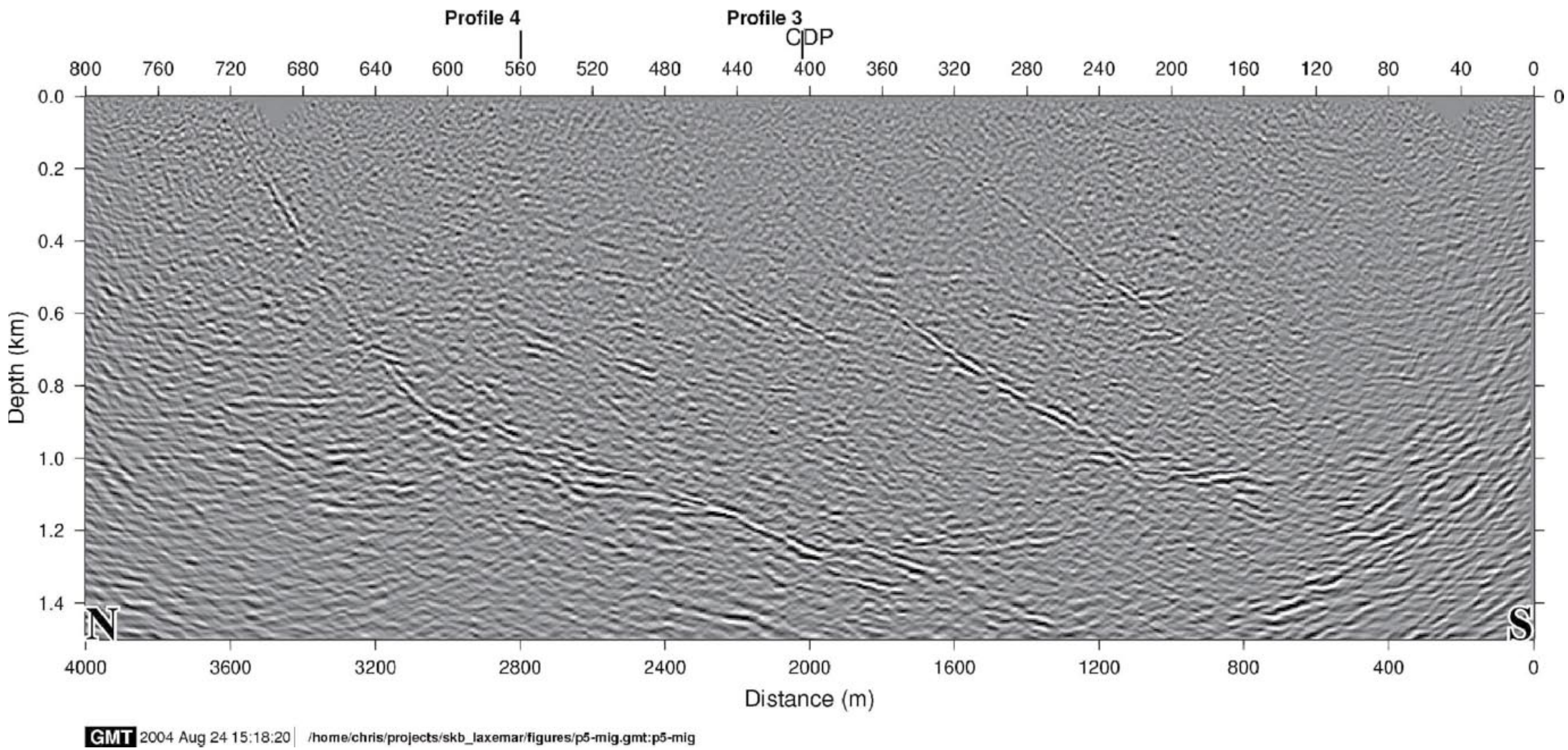

Figure 3-10. *Migrated section of profile 5 (LSM000706) down to 1,500 m. Depth scale only valid for true subhorizontal reflections.*

4 Results

4.1 Background

An important aspect of high-resolution seismic studies for nuclear waste disposal is the three dimensional imaging of reflectors and their correlation with borehole data. Fracture zone geometry is often complex and highly three dimensional /9/. Ideally, 3D data should be acquired, but this is a very expensive solution. When only 2D data are available, it is only in the vicinity of crossing lines that it is possible to calculate the true strike and dip of reflectors. Also, if reflections project to the surface on single-line data and can be correlated with a surface feature at the intersection point, then an estimate of the strike and dip can also be made.

Inspection of the stacked sections (Figures 3-3 to 3-8) shows zones of high reflectivity in the upper 0.5 s of crust in parts of the survey area. In general, reflections may be due to the presence of fracture zones, mafic sheets (sills or dikes), mylonite zones or lithological boundaries at depth. Experience has shown that mafic sheets, in particular, generate distinct high amplitude reflections. Reflections from fracture zones are generally weaker and less distinct. Lateral changes in the reflectivity along the profiles may be due to changes in the geology, but also to changes in acquisition conditions. Noise from the Oskarshamn power plant, crooked lines /10/ and changes in the near surface conditions where the shots were fired may result in poorer images of reflections along some portions of the stacked sections.

4.2 General observations

Reflectivity appears to be greatest between 0.2 s and 0.6 s on all three profiles. Fairly clear gently north dipping reflections are present below at 1.0 s on profiles 4 and 5 (Figures 3-3 and 3-7), but less on profile 3, suggesting that noise levels may have been greater during acquisition of this profile. These deep reflections were also observed on the Ävrö 1996 data /5/ the Ävrö 2003 data /7/ and below profiles 1 and 2 in the Laxemar area /2, 3/ and project to the surface about 10 km south of the surveyed area. Steeply dipping reflections project to the surface near CDP 640 on profile 3 (Figure 3-4) and CDP 720 on profile 5 (Figure 3-8). These reflections most likely originate from the zone ZSMEW002A (Mederhultszonen) and were also observed on the Laxemar 1999 data /2, 3/. No clear reflections can be correlated to the major W–E striking topographic low crossing profile 3 at CDP 50–100 and profile 5 at CDP 100–150 (Figures 1-2 and 3-1). Either the zone is near-vertical or the profiles were not extended far enough to the south to pick up south dipping reflections from it. In any case, the zone does not appear to have a northerly dip component.

4.3 Comparison with previous studies

It is useful to compare the present sections with those acquired earlier in the Laxemar area in 1999 /2, 3/. Reflection geometry along profile 3 (LSM000704) and profile 1 from 1999 show similar geometries (Figure 4-1), as do geometries along profile 5 (LSM000704) and profile 2 from 1999 (Figure 4-2). However, the signal to noise ratio is lower on the newly acquired data. At present it is not clear why this is so, but drier conditions, fewer geophones and shots in bedrock and more ambient noise on the new profiles may be factors.

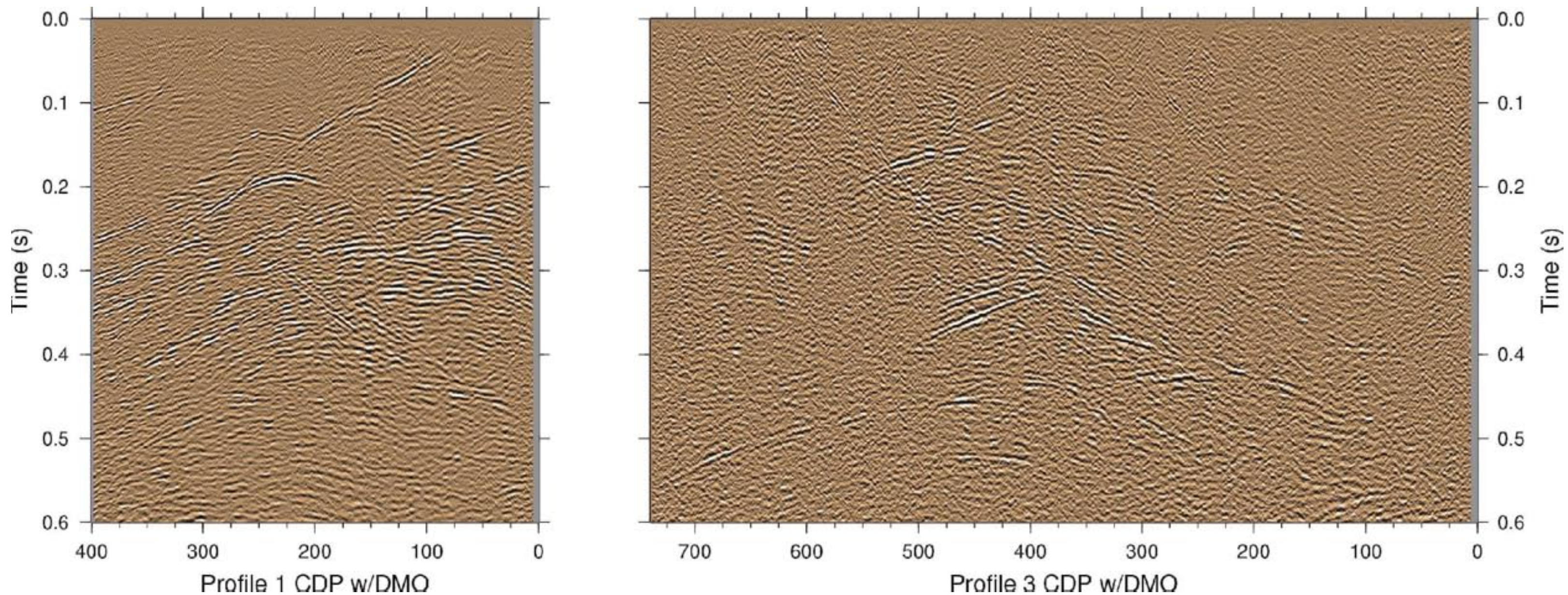

Figure 4-1. *Comparison of NE–SW running profile 1 from the Laxemar1999 survey with NNE–SSW running profile 3 (LSM000704) from the present experiment.*

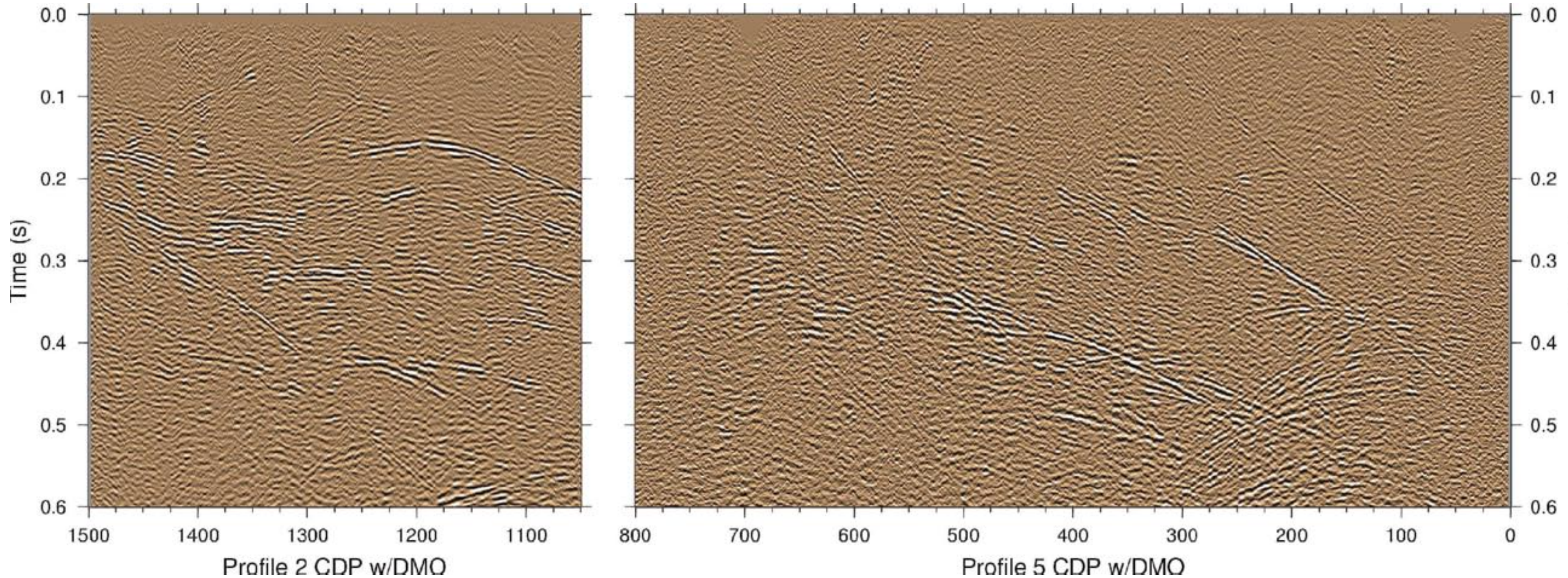

Figure 4-2. Comparison of NW–SE running profile 2 from the Laxemar 1999 survey with NNW–SSE running profile 5 (LSM000706) from the present experiment.

4.4 Orientation of reflections

In order to obtain 3D control in the upper 1.5 km where the profiles cross, a combination of correlation of reflections between the profiles (Figures 4-3 to 4-8) and seismic modelling /1/ has been used. In principle, a reflection observed on one profile should be observed on a crossing profile at the crossing point at the same traveltime. However, this is not always the case, especially for weaker reflections. Different reflections may have been enhanced in the processing on the different profiles. The crooked line acquisition geometry may also result in destructive stacking of certain reflections, especially those coming from out-of-the-plane of the profile. Also, since numerous reflections are present on some parts of the profiles it can be difficult to uniquely identify one and the same reflection on two crossing profiles due to interference effects.

Table 4-1 lists those reflections that have been oriented and these are ranked according to the likelihood that the reflector would be encountered in a drilling operation. As a check on the picking and the orientation, reflections from these interfaces have been modelled (Figures 4-4, 4-6 and 4-8), assuming that the interfaces are planes, and then compared with the observed data in order to obtain some idea of the lateral extent of the reflecting interfaces. When the reflection is not observed on the section or its position does not match that expected from the modelling, then the assumption of the reflector being a plane may have broken down. In Figures 4-4, 4-6 and 4-8 reflections are labelled as defined in Table 4-1 and colour coded according to their rank. Reflections that can be projected to the surface have been plotted on the topography (Figure 4-9).

Table 4-1. Orientation of reflectors as determined from the surface seismic and partly shown in Figure 4-9. Reflectors may either be defined by distance to a point on the surface (better for dipping reflectors) or by depth below this point (better for sub-horizontal reflectors). Distance refers to distance from the KLX02 borehole (6,366.768 km N, 1,549.224 km W) to the closest point on the surface to which the reflector projects. 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 the profiles that the reflection is observed on; 1 – definite, 2 – probable, 3 – possible.

Reflector	Strike	Dip	Distance (m)	Depth (m)	Rank	Profiles observed on
A	275	43	190		1	1, 2, 4
B	0	3		760	1	1, 2, 4
C1	90	70	1,330		1	1, 2, 3, 4
C2	85	70	1,330		1	4, 5
D	253	35	840		2	1, 2, 4
G	253	35	1,170		2	1, 2, 4
K	30	50	800		2	4?, 5
L	110	70	300		2	3, 5?
M1	95	20		350	1	3, 4, 5
M2	100	25		500	1	3, 4, 5
M3	100	25		750	1	3, 4, 5
M4	100	25		900	1	3, 4, 5
N	120	30		770	2	3, 4, 5
O	200	80	1,850		3	5
X1	295	15		400	3	3
X2	295	15		970	3	3
X3	295	15		1,070	3	3
Y1	295	27		300	3	3, 4?
Y2	295	15		350	3	3, 4?

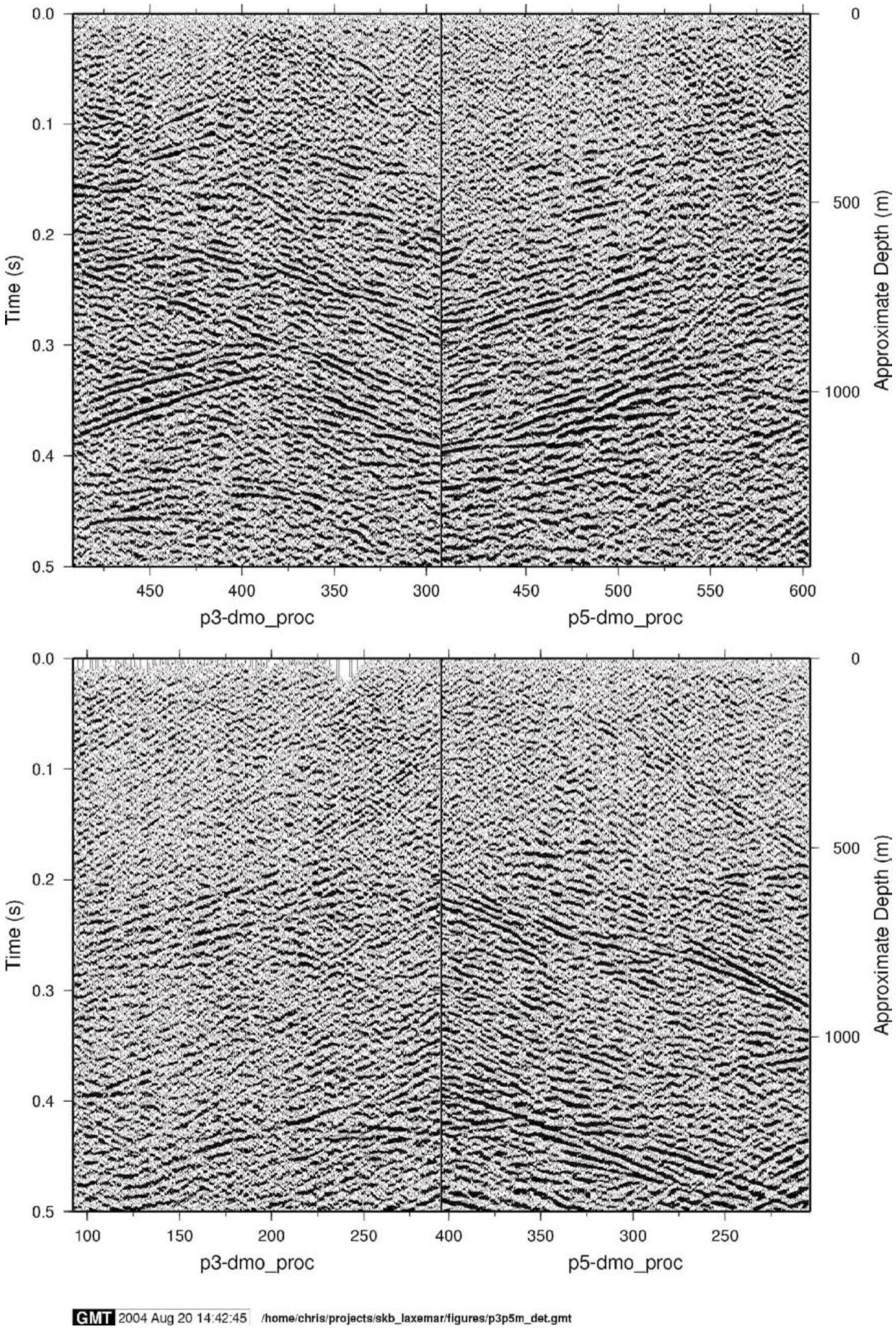

Figure 4-3. *Correlation of stacks from profiles 3 (LSM000704) and 5 (LSM000706) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP.*

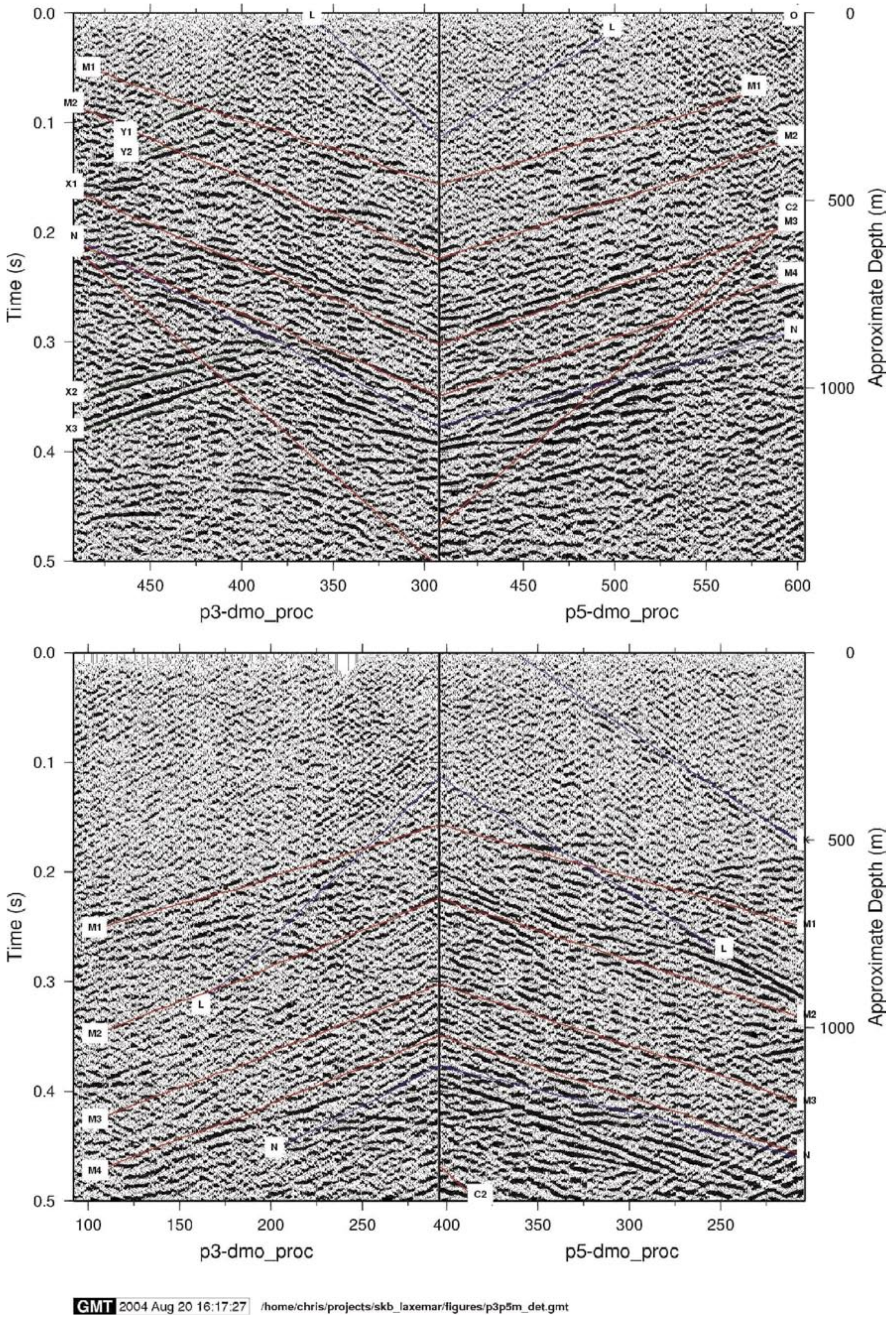

Figure 4-4. *Correlation of stacks from profiles 3 (LSM000704) and 5 (LSM000706) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP. Modeling of reflectors is coded as follows: red-rank 1, blue-rank 2, green-rank 3. Assumed strike and dips are given in Table 4-1.*

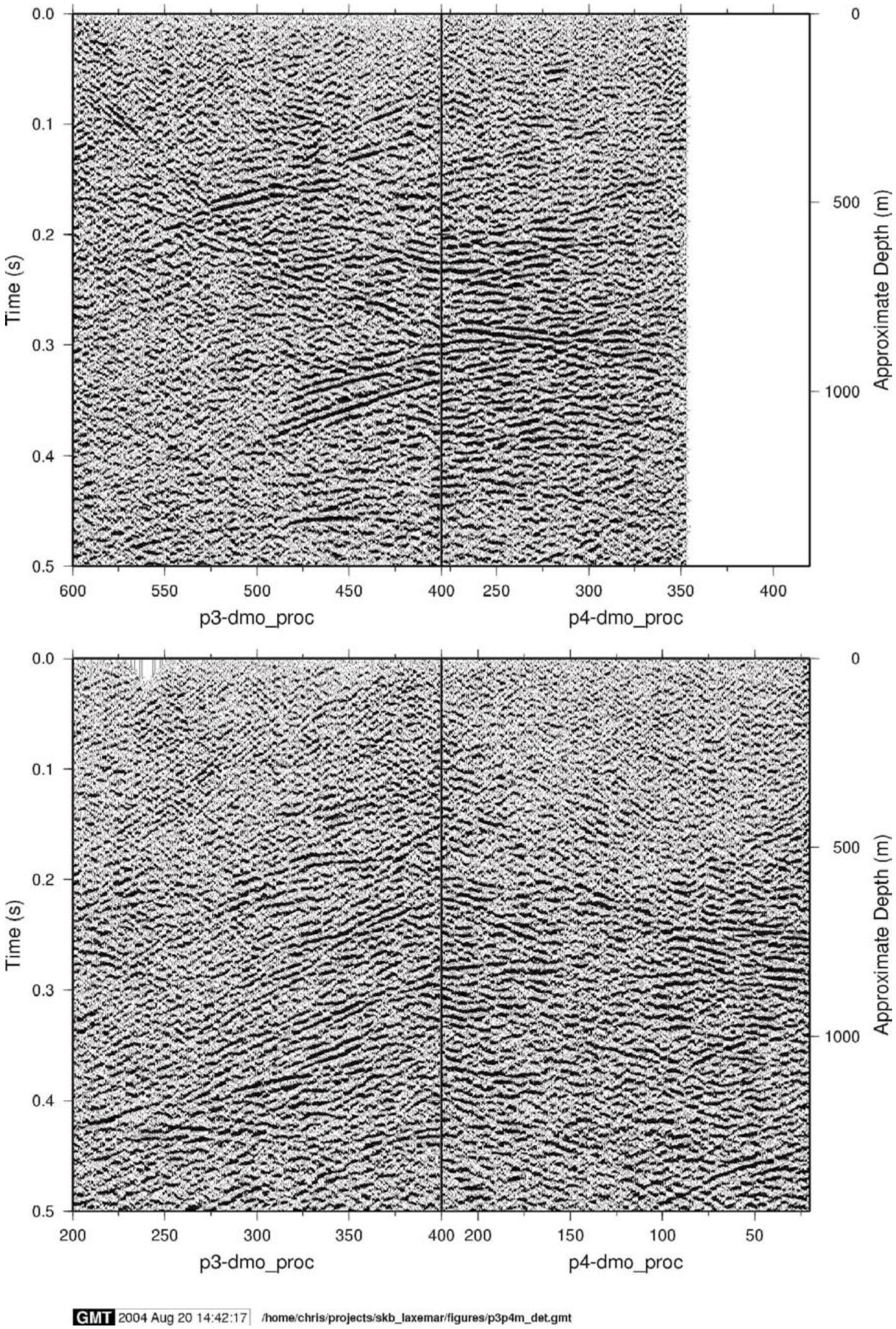

Figure 4-5. *Correlation of stacks from profiles 3 (LSM000704) and 4 (LSM000705) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP.*

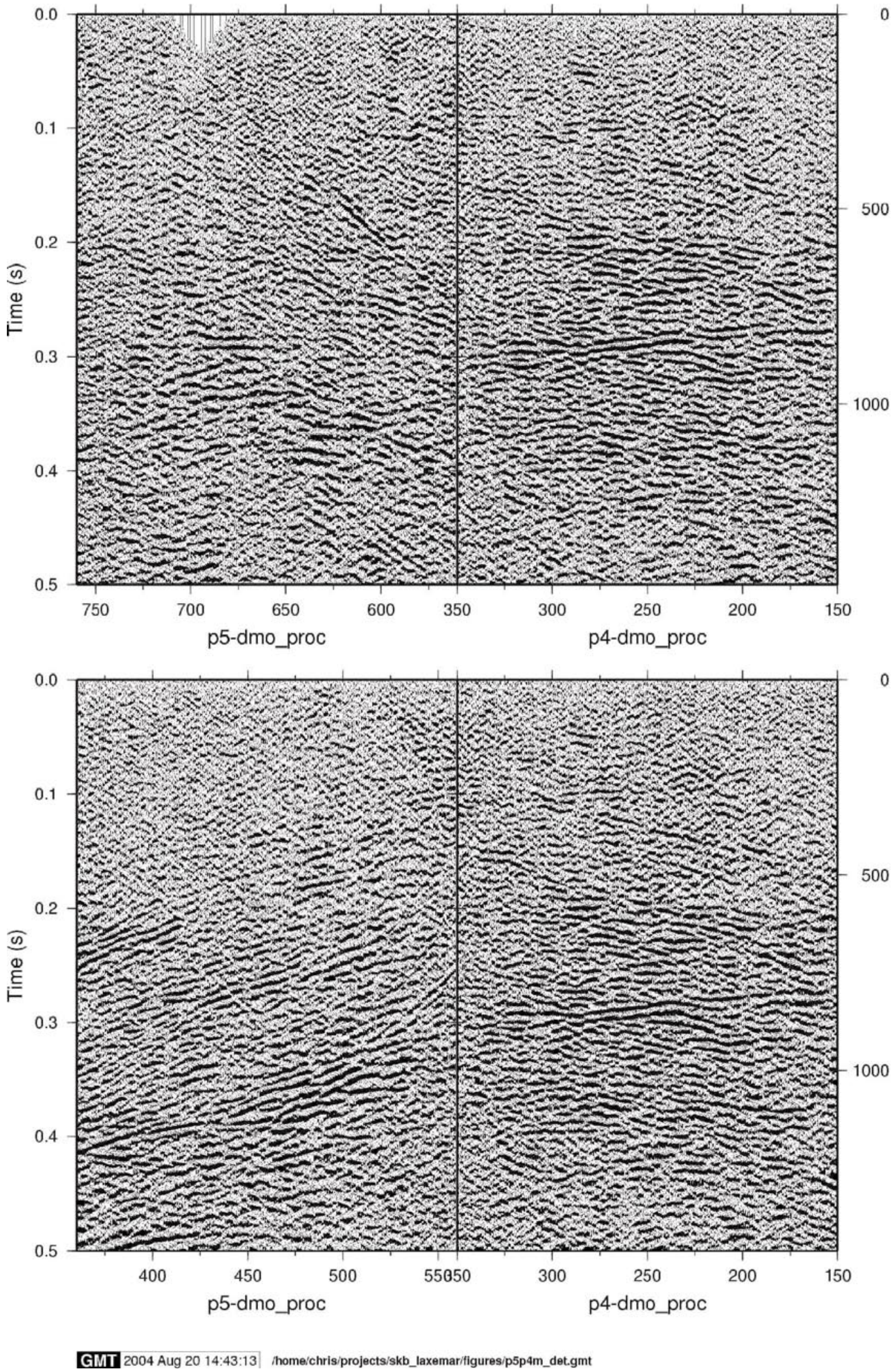

Figure 4-6. *Correlation of stacks from profiles 3 (LSM000704) and 4 (LSM000705) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP. Modeling of reflectors is coded as follows: red-rank 1, blue-rank 2, green-rank 3. Assumed strike and dips are given in Table 4-1.*

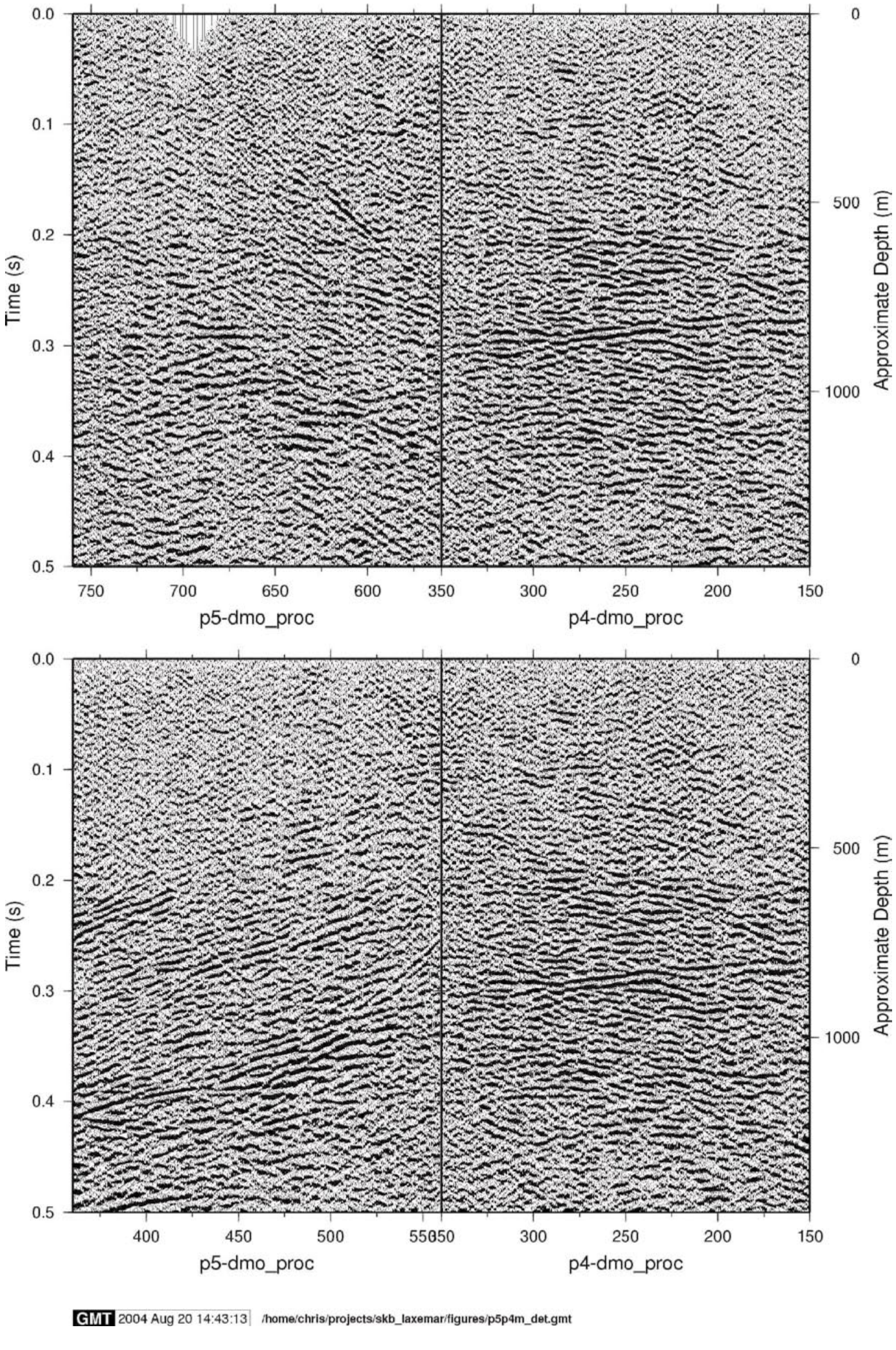

Figure 4-7. *Correlation of stacks from profiles 5 (LSM000706) and 4 (LSM000705) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP.*

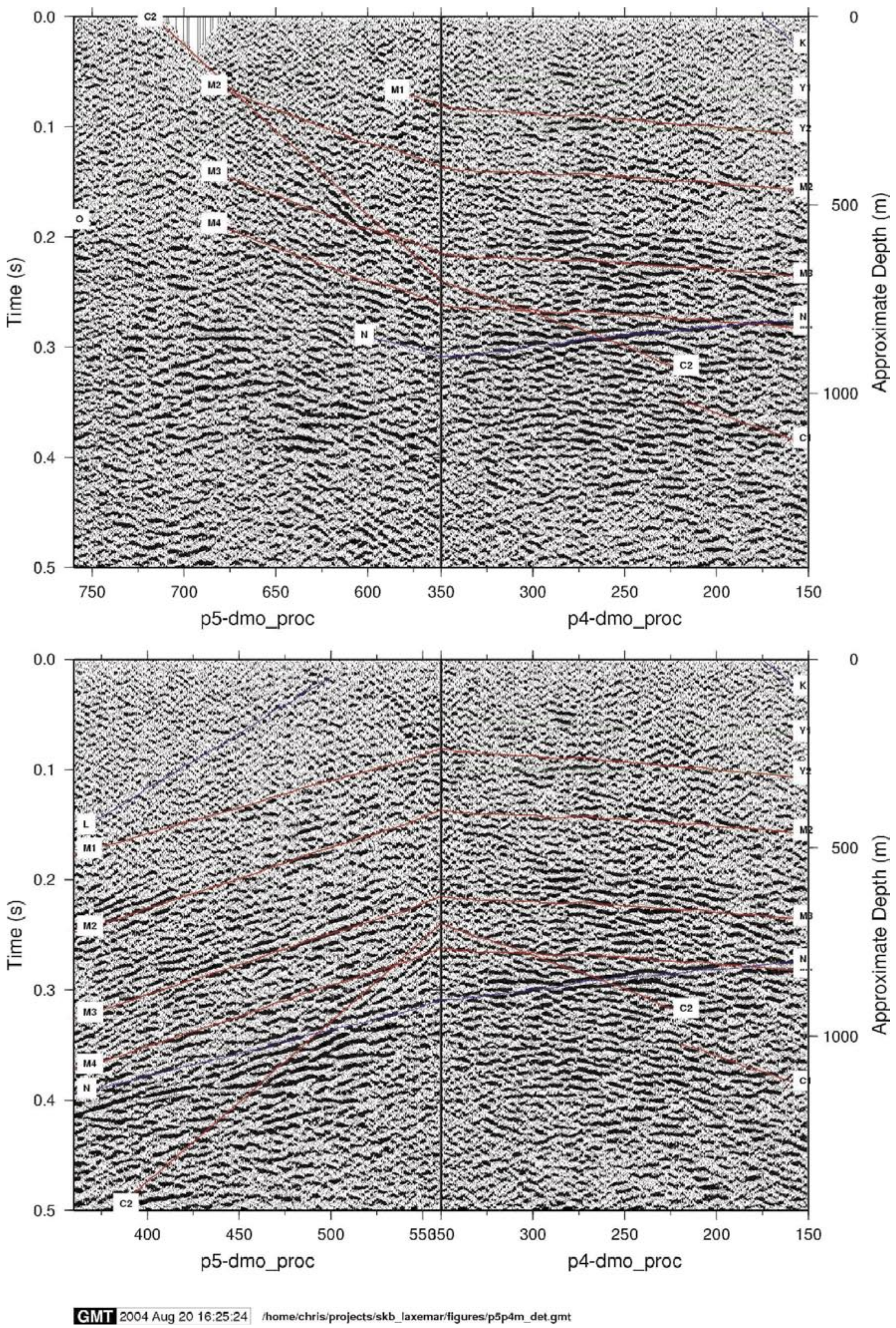

Figure 4-8. *Correlation of stacks from profiles 5 (LSM000706) and 4 (LSM000705) at their crossing point (Figure 3-1). Depth scale only valid for true sub-horizontal reflections. Horizontal numbering is CDP. Modeling of reflectors is coded as follows: red-rank 1, blue-rank 2, green-rank 3. Assumed strike and dips are given in Table 4-1.*

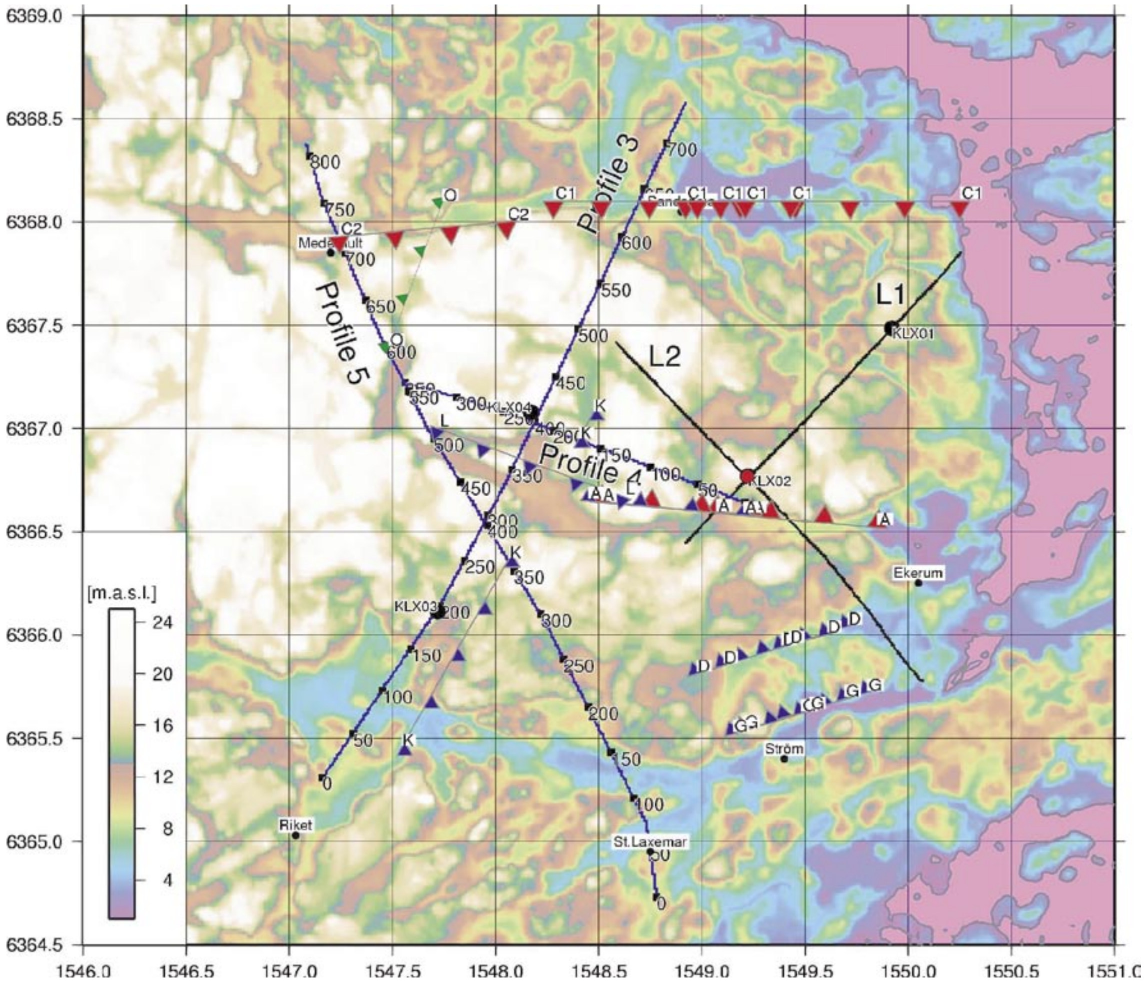

Figure 4-9. Projected reflector intersections with the surface plotted on topography for those reflectors which project up to the surface. Reflections from interfaces that clearly cannot be traced to the surface, such as N in Table 4-1, are not drawn. Picked reflectors correspond to the tops of the reflector. All indicated reflectors are interpreted to correspond to relatively thin zones (5–15 m thick). Reflectors are coded as follows: red-rank 1, blue-rank 2, green-rank 3.

Reflections A, B, C1, D and G are observed on profiles 1 and 2 of the Laxemar 1999 data /2, 3/ and should, therefore, be visible on profile 4 of the present data set. All of these reflections can be correlated onto profile 4 (Figure 4-6), but are limited in the lateral extent and rather weak, except for reflection C1. The pronounced reflection A in the 1999 data appears as a weak gently west dipping reflection in the upper 100 ms extending to at most CDP 160 on profile 4 (Figure 4-6). This suggests that the zone generating this reflection does not extend west of km 1,548.5 in the Swedish national coordinate grid (RT90). Reflections C1 and C2 corresponds to reflection C in /2, 3/ and are clearly observed on profiles 3 and 5 (Figure 4-4). It has been modelled as 2 separate reflections in this report since it appears to change orientation slightly on profile 5. In /2, 3/ it was modelled as dipping about 50° to the south, but the present data set shows a dip of 75° is more realistic.

Profiles 3 and 5 are characterized by clear gently south dipping reflections in the upper 0.5 s (Figure 4-3). The more distinct of these reflections have been modelled as the set M reflections. These extend over nearly the entire profile and do not appear to intersect the surface. Inspection of the migrated sections (Figures 3-9 and 3-10) indicate that they appear to be limited to the north by the steeply dipping set C reflector. The N reflection is also present on most of the profiles, but has a somewhat different orientation than the set M reflections (Figure 4-4).

Two more steeply dipping reflections are clearly imaged in the upper 0.2 s on profiles 3 (south dipping between CDP 200 and 360 in Figure 3-4, labelled L in Table 4-1) and profile 5 (south dipping between CDP 120 and 260 in Figure 3-8, labelled K in Table 4-1), but their orientation is not well determined. Reflection L should be observed on profile 5, but is not clearly imaged in the upper 0.2 s, although signs of south dipping reflections are found (Figure 4-4). Below 0.2 s a clear reflection with the orientation of the L reflector is observed on profile 5. Reflection K cannot be reliably oriented since there is no crossing profile to where it is observed on profile 5. Since it is not observed on profile 3, one can assume it dips to the SE and has been modelled as running parallel to a topographic low in the SSW–NNE direction (Figure 4-9). Signs of a reflection with this orientation are observed on profile 4 (Figure 4-8), but is not clear if this corresponds to the K reflector. A weak steeply dipping reflection is also found on the northern part of profile 5 and cannot be oriented (reflection O in Figure 4-8). It has been modelled as running parallel to the topographic low that it projects to at the surface (Figure 4-9).

Three distinct high amplitude reflections are present on profile 3 (LSM000704) (marked X1, X2 and X3 in Figure 4-4) that cannot be uniquely oriented. These reflections are sub-parallel and appear to dip in the opposite direction to the set M reflections. They have been assumed to lie in the plane of profile 3. The orientation of reflections Y1 and Y2 (Figure 4-4) is also uncertain, but these also appear to lie in the plane of profile 3.

4.5 Reflections which have been picked for input into RVS

Raw data from the measurements were delivered directly after the termination of the field activities. The delivered data have been inserted in the database (SICADA) of SKB. The SICADA reference to the present activity is field note no 364. Coordinates for the reflecting elements which have been picked for input into RVS are shown in Figures 4-10 to 4-12. These reflecting elements have been provided for input into SICADA.

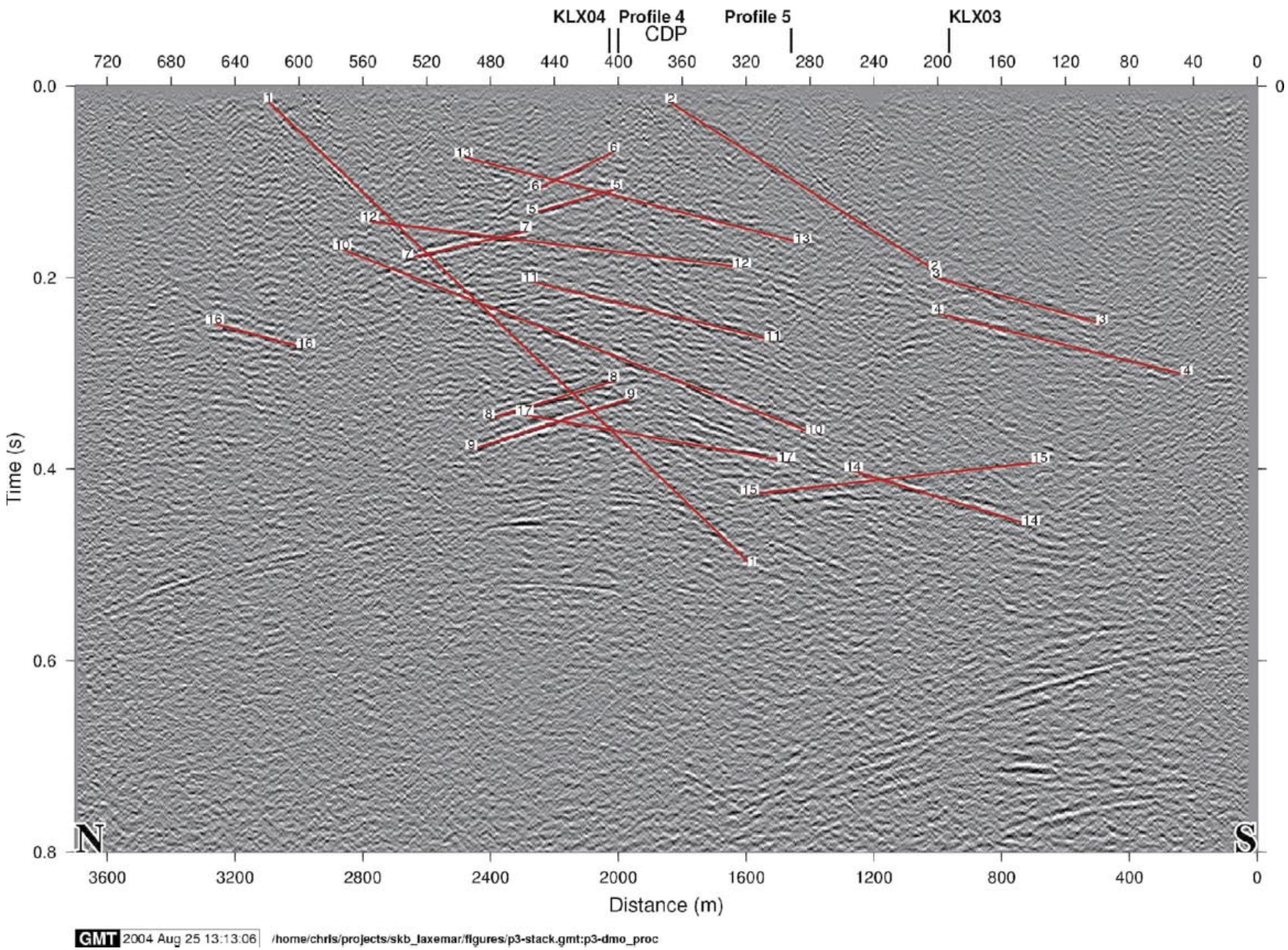

Figure 4-10. *Stacked section of profile 3 (LSM000704) down to 0.8 seconds with RVS picks.*

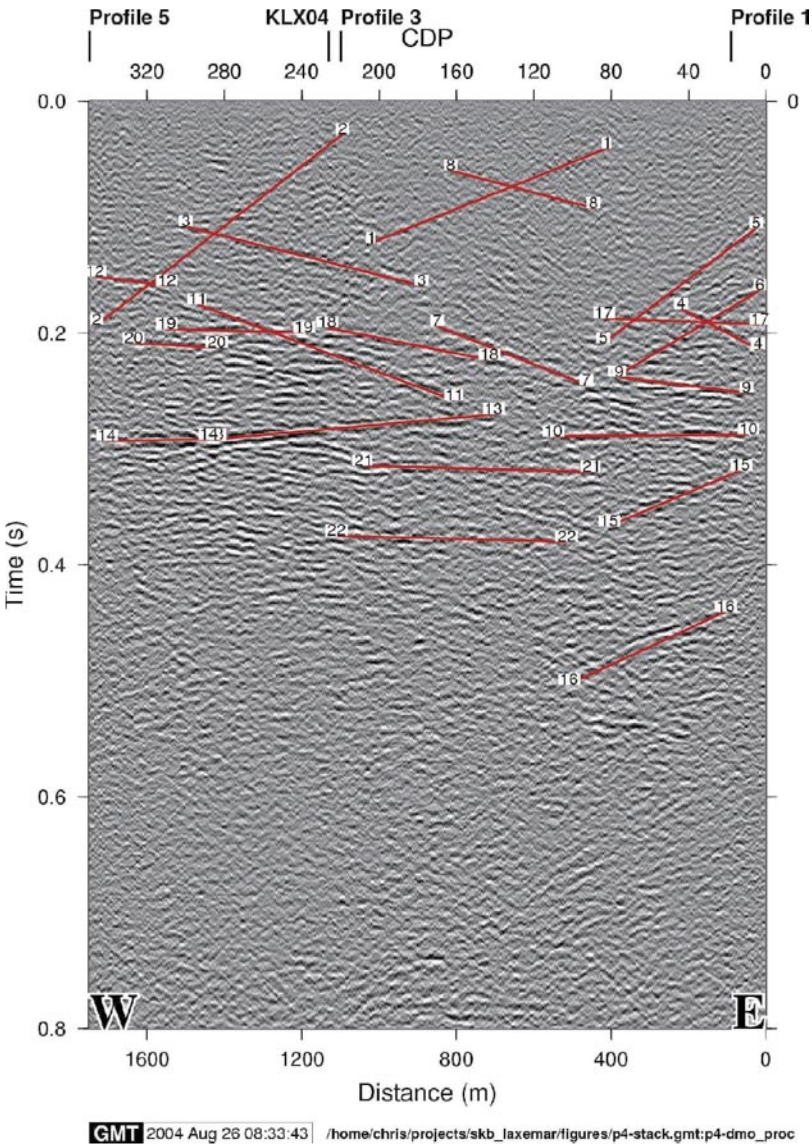

Figure 4-11. *Stacked section of profile 4 (LSM000705) down to 0.8 seconds with RVS picks.*

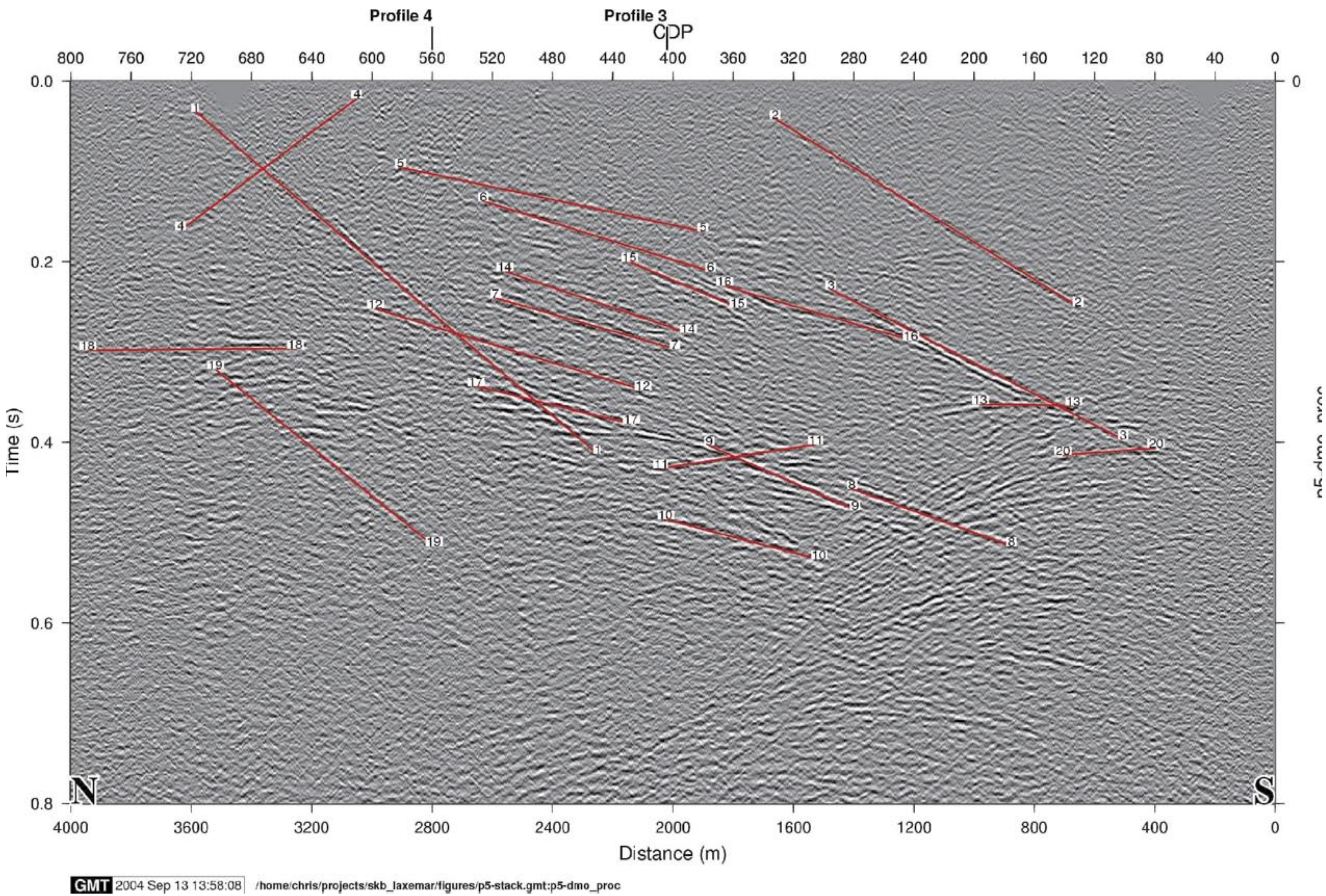

Figure 4-12. *Stacked section of profile 5 (LSM000706) down to 0.8 seconds with RVS picks.*

4.6 Predictions for deep borehole KLX03

Intersection points of the picked reflectors with the projection of borehole KLX03 (assumed to be vertical) downwards are given in Table 4-2. The only reflectors that are expected to be penetrated by the 1,000 m deep borehole are the south dipping set M reflections. Note that the depths are very approximate since these reflections are not very planar in nature.

Table 4-2. Predicted intersection points of KLX03 with those reflectors that project into the borehole shallower than 1,500 m. Rank indicates the quality of the prediction; 1 – highly likely, 2 – probable, 3 – possible. Note that these depths differ from those in Table 4-1 since the origin for the orientation (6,366.768 km N, 1,549.224 km W) is not coincident with the borehole. Depths to reflectors also differ from the approximate depths given in Figures 4-4, 4-6 and 4-8 since these are time sections and many of the reflections are dipping and from out-of-the plane of the profiles. Only sub-horizontal reflections will have correct approximate depths in Figures 4-4, 4-6 and 4-8.

Reflector	Intersection depth (m)	Strike	Dip	Rank
M1	650	95	20	1
M2	940	100	25	1
M3	1,190	100	25	1
M4	1,340	100	25	1

4.7 Predictions for deep borehole KLX04

Intersection points of the picked reflectors with the projection of borehole KLX04 (assumed to be vertical) downwards are given in Table 4-3. The set M rank 1 reflectors and the N rank 2 reflector are expected to be penetrated by the 1,000 m deep borehole. Note that the depths are very approximate since these reflections are not very planar in nature. Predictions for set X and set Y are very uncertain since their orientation is unconstrained.

Table 4-3. Predicted intersection points of KLX04 with those reflectors that project into the borehole shallower than 1,500 m. Rank indicates the quality of the prediction; 1 – highly likely, 2 – probable, 3 – possible. Note that these depths differ from those in Table 4-1 since the origin for the orientation (6,366.768 km N, 1,549.224 km W) is not coincident with the borehole. Depths to reflectors also differ from the approximate depths given in Figures 4-4, 4-6 and 4-8 since these are time sections and many of the reflections are dipping and from out-of-the plane of the profiles. Only sub-horizontal reflections will have correct approximate depths in Figures 4-4, 4-6 and 4-8.

Reflector	Intersection depth (m)	Strike	Dip	Rank
M1	290	95	20	1
M2	460	100	25	1
M3	710	100	25	1
M4	860	100	25	1
N	940	120	30	2
X2	950	295	15	3
X3	1,050	295	15	3
Y1	240	295	27	3
Y2	330	295	15	3

5 VIBSIST test

In order to test the potential of using a mechanical source for surface reflection seismic studies at SKB sites a test of the VIBSIST source was performed along part of profile 5.

Seismic signals were produced by a VIBSIST /4, 6, 8/ mechanical source mounted on a tractor (Figure 5-1). The tractor with the hydraulic arm and rock-breaking head was rented locally (Bo Hultgren). The test was performed with a Rammer ER-64 model with a “nominal” energy output of 2,300 J/impact. The computer-controlled flow regulator, command equipment and software were supplied by Vibrometric Oy.

Data were recorded from station 5,150 to station 5,270 along profile 5 (LSM000706) into a variable spread of 180–240 geophones (Figure 5-2). The geophone closest to the VIBSIST source was used as the pilot signal for later decoding of the data. An average of 5 sweeps were recorded at each source point and later stacked. The majority of the data were recorded at a 1 ms sampling rate for 26 seconds using 15 second sweeps. Some tests were also done with recording at 0.5 ms for 16 seconds.

Figure 5-1. *Hydraulic hammer and tractor used for the VIBSIST test.*

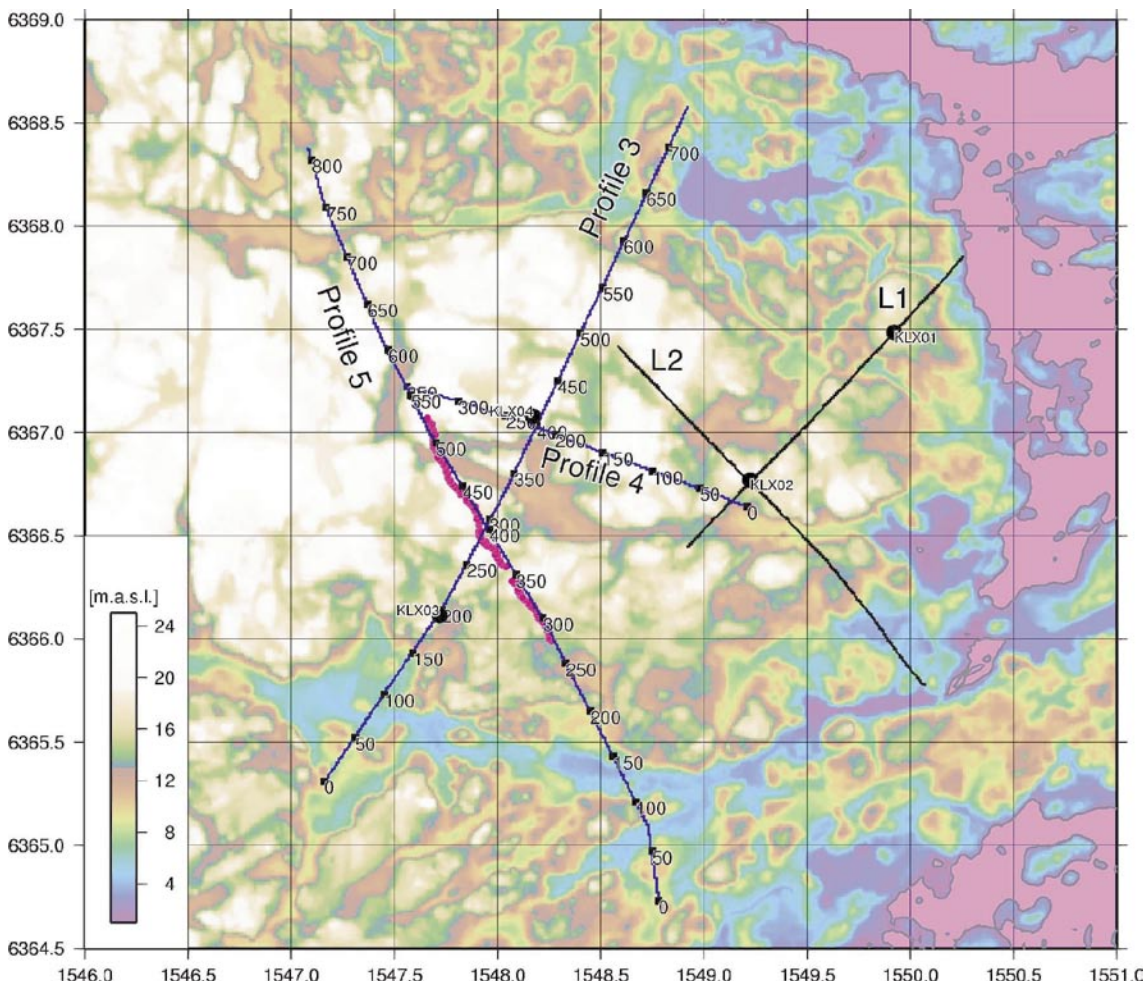

__Figure 5-2.__ Location of the VIBSIST sources (purple dots) relative to explosive source along profile 5 (LSM000706). Stacked sections from where the sources overlap are shown in Figure 5-9.

Required pre-processing of the VIBSIST records is described elsewhere /4, 6/. After shifting and stacking of the raw data records shot sections are produced that are of comparable or better quality than the explosive source data recorded from the same source points (Figures 5-4 to 5-8). Figure 5-4 shows a comparison of the two sources from station 5,204 where 75 grams of explosives were fired in a 150 cm deep shot hole. Here, the explosive source data are of higher quality, but this is an exception. After highpass filtering, several clear reflections can be observed in both shot gathers at 300–400 ms (Figure 5-3). Generally, the VIBSIST data are of higher quality, even when the explosive source is fired in bedrock (Figures 5-5 and 5-6). At a number of locations the explosive source data are of poor quality while the VIBSIST data are still of fairly good quality (Figure 5-7). For example, at source point 5,193, clear reflections are observed on the VIBSIST gather after highpass filtering, whereas the explosive source data show only noise.

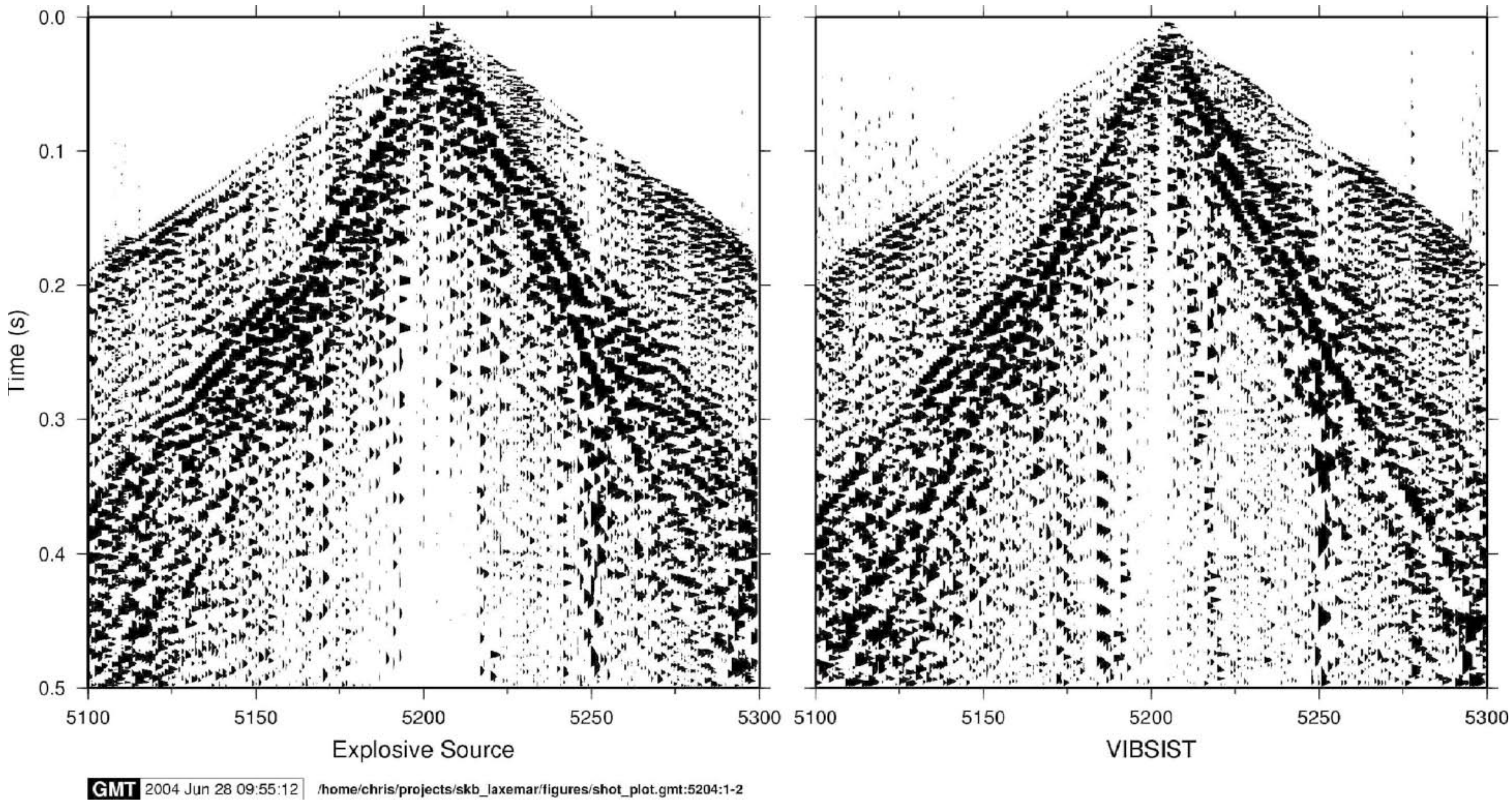

Figure 5-3. *Comparison of explosive source and VIBSIST at source point 5,204 which is located on sediment.*

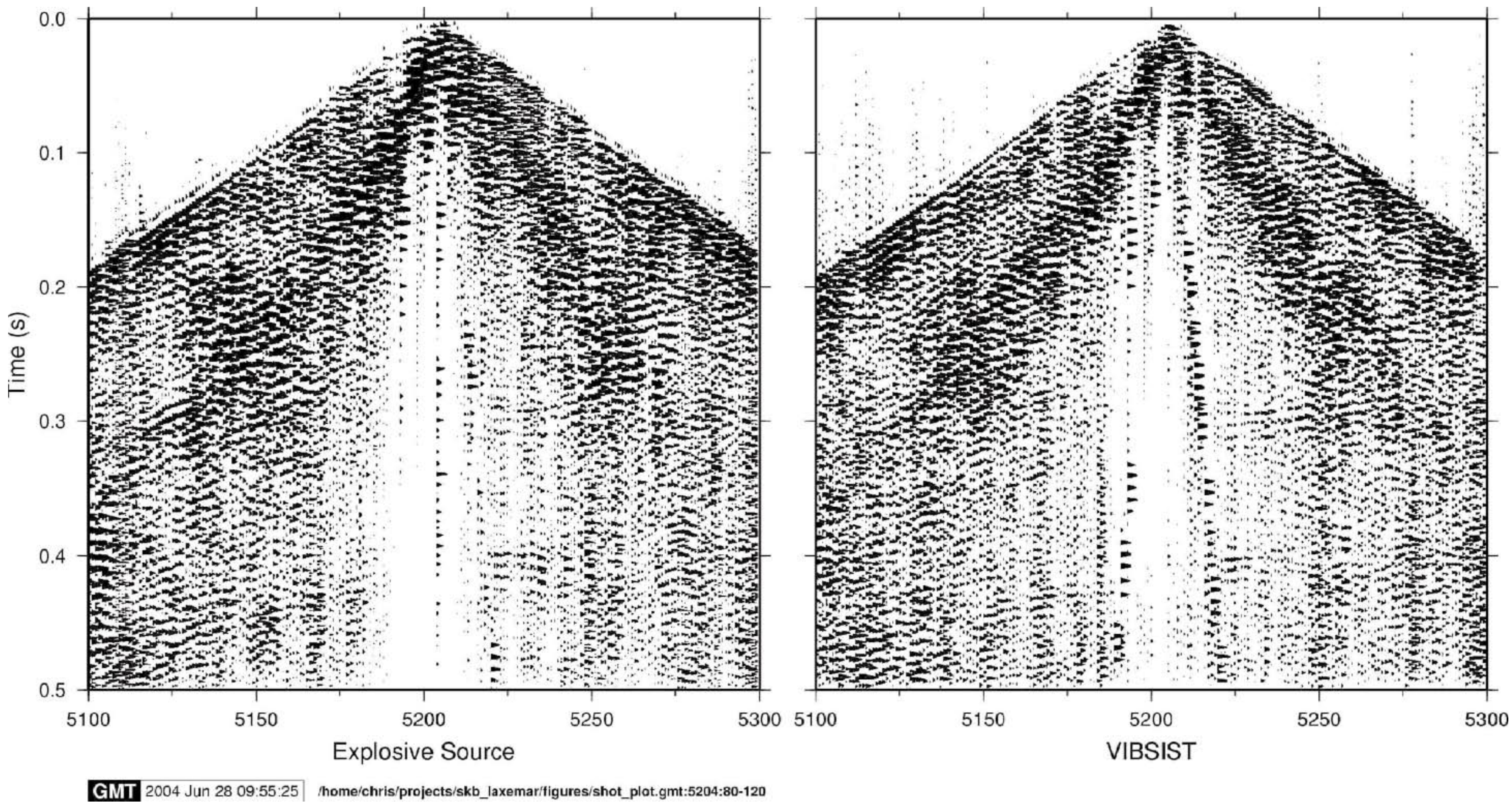

Figure 5-4. *Comparison of explosive source and VIBSIST at source point 5,204 which is located on sediment. Data is highpass filtered at 120 Hz.*

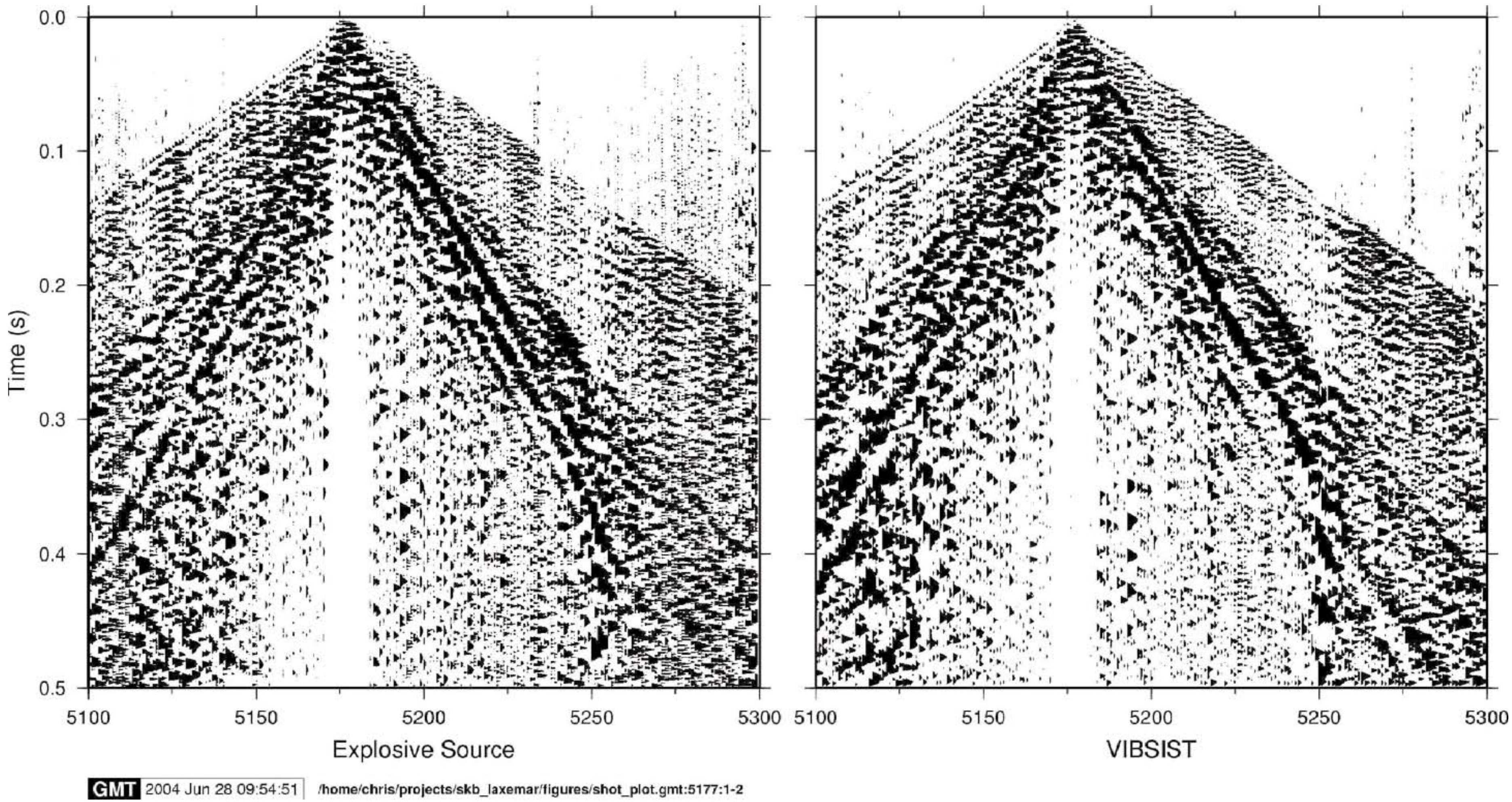

Figure 5-5. *Comparison of explosive source and VIBSIST at source point 5,177 which is located on bedrock.*

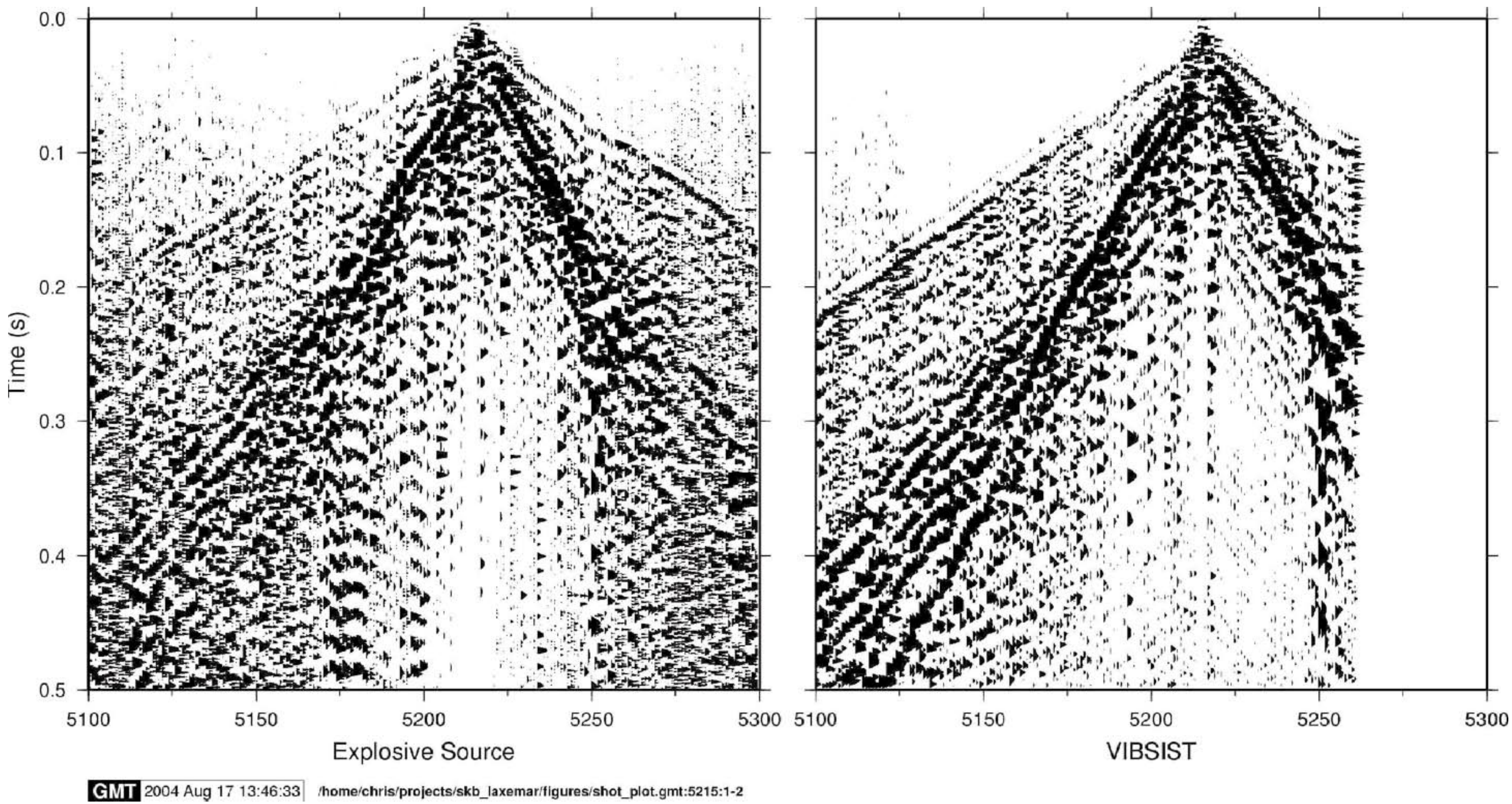

Figure 5-6. *Comparison of explosive source and VIBSIST at source point 5,215 which is located on bedrock.*

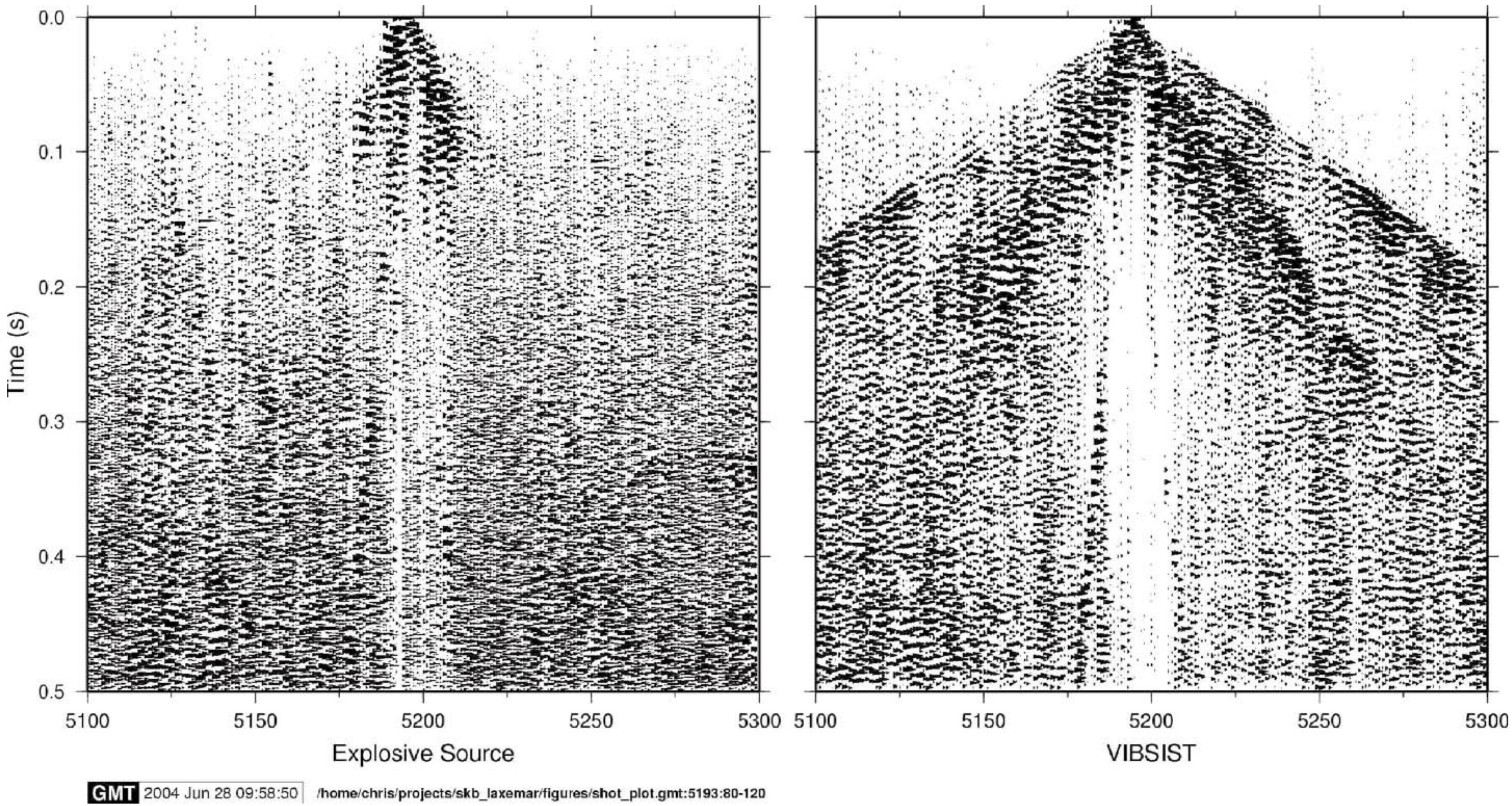

Figure 5-7. *Comparison of explosive source and VIBSIST at source point 5,193 which is located on sediment.*

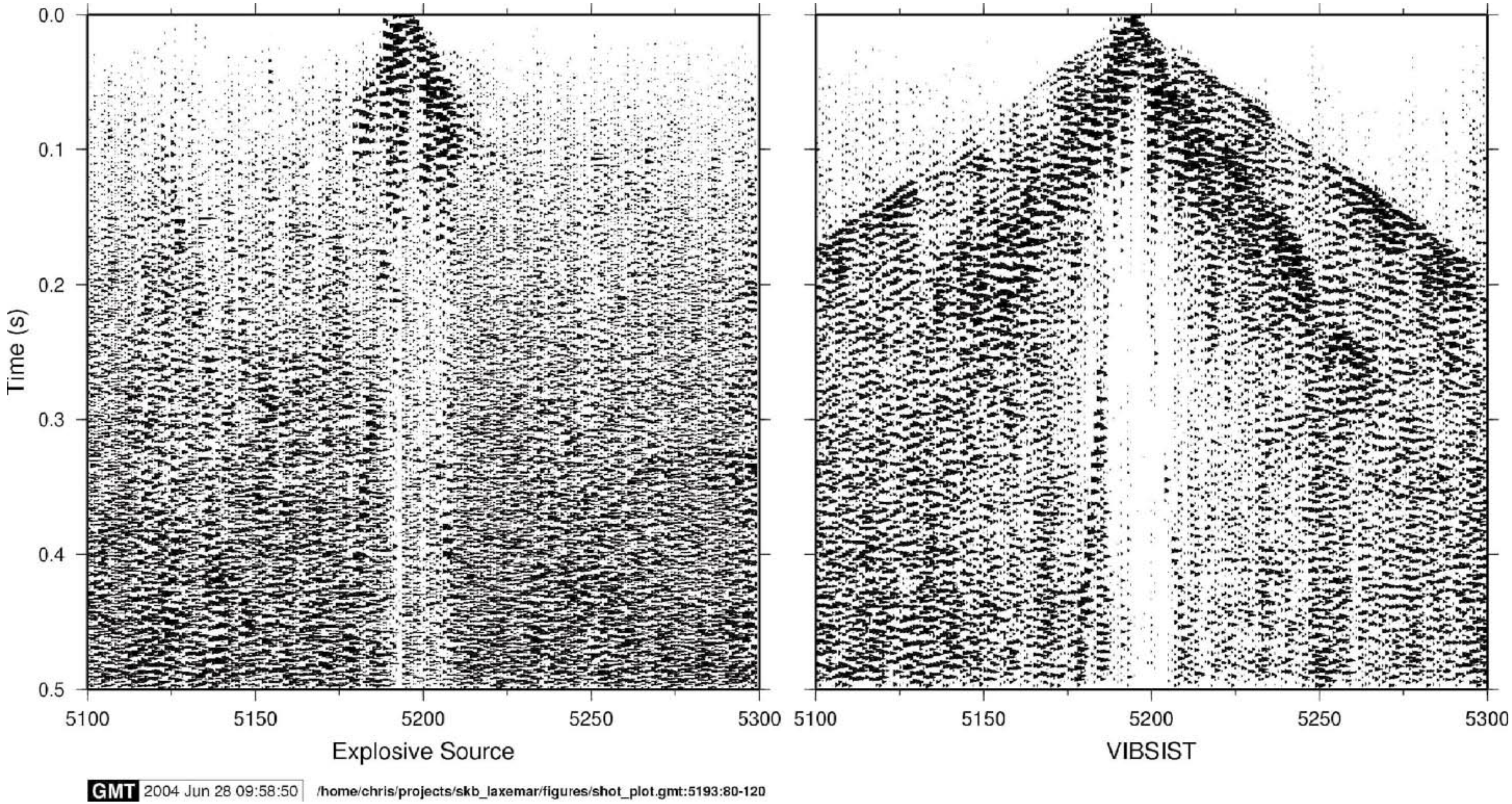

Figure 5-8. *Comparison of explosive source and VIBSIST at source point 5,193 which is located on sediment. Data are highpass filtered at 120 Hz.*

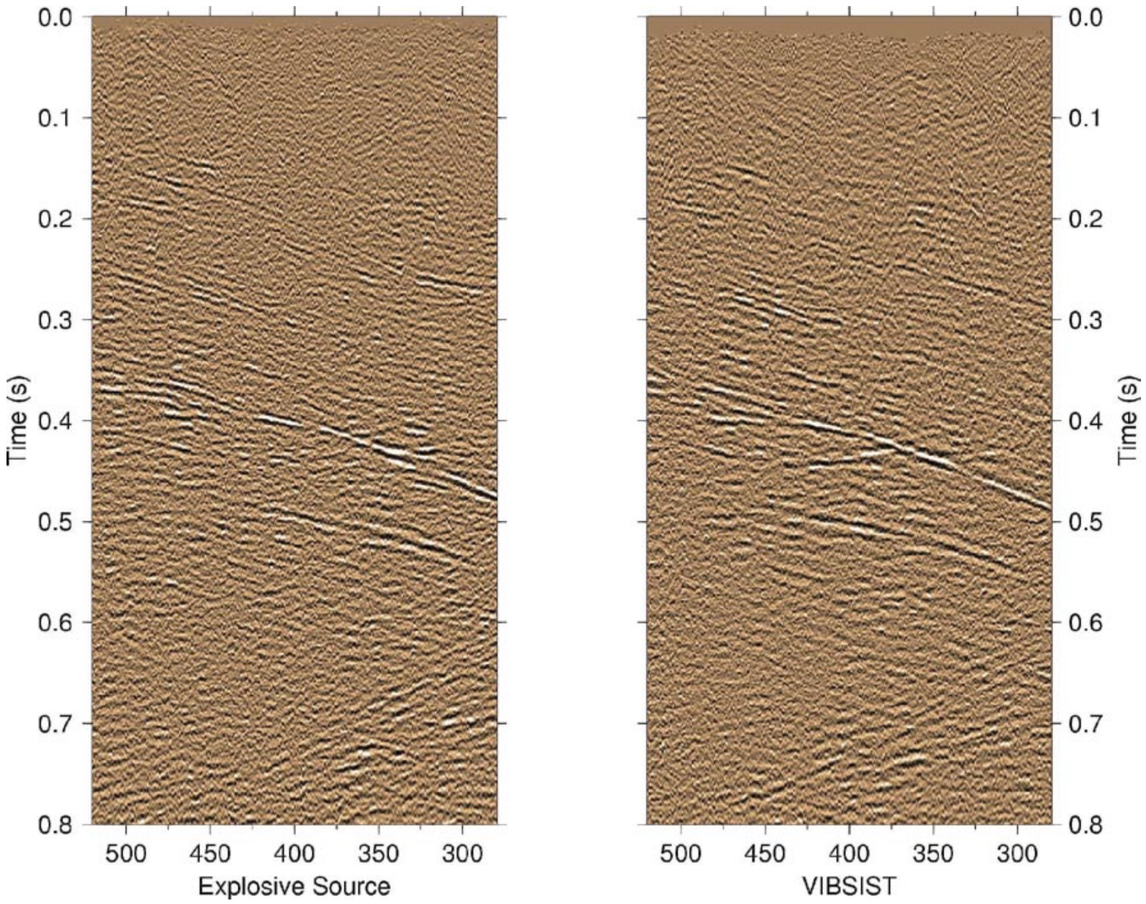

Figure 5-9. *Comparison of explosive source and VIBSIST stacked sections along profile 5. Data are only shown for where the VIBSIST section is full fold.*

Shot records from the VIBSIST source were processed in a similar manner to the explosive source data (up to step 14 in Table 3-2 and then stacked) to produce a stacked section (Figure 5-9). The two sections are quite similar, differing only in detail. Most of these differences are probably due to different statics and velocity functions being used in the processing. Since the VIBSIST source is a surface source, the shot statics show significantly more variance than what is found for the explosive source data. The uppermost 1–1.5 m produce a significant delay in the seismic signals. Therefore, even more care must be taken in the static corrections for the VIBSIST data than for the explosive source data.

6 Discussion and conclusions

6.1 Acquisition

Signal to noise ratios were lower than on the Laxemar 1999 profiles /2, 3/, sufficient to image the uppermost 1 km. The deeper reflections below 1 s are not imaged as clearly as on the Laxemar 1999 data. Similar lower signal to noise ratios were observed on the Ävrö 2003 data /7/. Noise conditions appear to have increased in the area since 1999.

The VIBSIST test shows that the mechanical VIBSIST source is suitable for high resolution surface seismic surveys. Advantages of the VIBSIST system over dynamite are (i) lower cost, (ii) can be used where dynamite is prohibited, (iii) repeatable signal, and (iv) shorter startup times (no drilling of shot holes prior to acquisition). One disadvantage at present is that it is more difficult to use in the terrain, resulting in that profiles have to more closely follow roads.

6.2 Processing

Processing followed standard methods. The set C reflections dip up to 75° and can be traced to depths of about 1 km. These are the steepest reflections imaged up to now in Sweden. Generation of constant velocity stacks was important for verifying the presence of the K and L reflections.

6.3 Interpretation

Reflectors which clearly intersect the surface on the new profiles are the K, L and C reflectors (Figure 4-9). However, only the C reflector can be reliably oriented and it corresponds to zone ZSMEW002A (Mederhultszonen). It is imaged as a steep (75°) south dipping reflector on all profiles. On the Laxemar 1999 data /2, 3/, it was interpreted to dip at about 50°, but this dip was poorly constrained since the reflector could not be traced to the surface on those profiles. The K and L reflectors are clearly seen on profiles 5 (LSM000706) and 3 (LSM000704), respectively, but corresponding clear reflections are not observed on crossing profiles. This may be due to the orientation of the reflectors or that the crossing profiles are running too obliquely to the strike of the reflectors.

The clear A reflector on the Laxemar 1999 data /2, 3/, is clearly seen on the easternmost shot gathers of profile 4 (LSM000705), but does not appear to extend to profile 3. Instead, another reflector with opposite dip intersects the profile (the K reflector) where the A reflector projects into profile 3. We conclude that the A reflector does not correspond to a regional zone. More gently (20–25°) south dipping reflections (set M) are present on all profiles. However, this set does not appear to intersect the surface. The set M reflections are the only reliably oriented reflections that are expected to be penetrated by the KLX03 and KLX04 boreholes

The potential O reflector (Figure 4-9) is speculative, but signs of it are seen in the shot gather and on the stacked section.

6.4 Recommendations

In order to better image reflectors K, L, the possible O reflector and the topographic low crossing the southern parts of profiles 3 and 5 (Figure 4-9) the following profiles are suggested:

An E–W profile crossing over the KLX03 borehole will provide better information on the orientation of the K and L reflectors.

An extension of profile 4 to the west will determine if the O reflector corresponds to the N–S running topographic low.

A N–S running profile starting at about KLX03 and extending a few km south of the marked topographic low at 6,365.5 km N will verify that there is no major zone dipping to the south corresponding to this low.

In addition, we recommend that VIBSIST sources be used, wherever possible, in future high resolution seismic surveys.

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