R-03-22

Estimation of 3D positions and orientations of reflectors identified in the reflection seismic survey at the Forsmark area

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Vibrometric

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Contents

1 Introduction

Reflection seismic surveys were performed in the spring of 2002 in the Forsmark area /SKB Report R-02-43/. High-resolution seismic data were acquired along five profiles varying in length from 2 to 5 km. There were 25 reflectors interpreted, which are listed in Table 1-1, below. The last three columns of Table 1-1 are derived from R-02-43, Table 4-1 and depict the site coordinates of a point belonging to the respective reflector plane. This point is computed from the values given in columns 3–6 and, together with the dip and the strike, determines the reflector plane completely.

Table 1-1. Reflectors interpreted in the SKB Report R-02-43, Table 4-1.

Current Nr.	Reflector ID	Strike	Dip	Distance from origin (m)	Depth under origin (m)	Northing (m)	Easting (m)	Elevation re. ground (m)
1	A1	75	45	3200		6701685	1631259	0
2	A2	80	22	790		6698776	1632242	0
3	A3	65	25	–10		6699004	1632991	0
4	A4	65	25	–950		6699388	1632133	0
5	A5	75	30	–1450		6697783	1633789	0
6	A6	75	30	–1875		6697427	1634020	0
7	B1	30	25	–600		6699013	1633600	0
8	B2	30	25	950		6698979	1632050	0
9	B3	30	21	1750		6698961	1631250	0
10	B4	50	28	1460		6700319	1632375	0
11	B5	50	25	2600		6701350	1631887	0
12	C1	15	20		3300	6699000	1633000	–3300
13	C2	355	10		3300	6699000	1633000	–3300
14	D1	320	65	2500		6697031	1631460	0
15	D2	120	50	2500		6699386	1630530	0
16	D3	320	65	3200		6696479	1631029	0
17	E1	270	9		2020	6699000	1633000	–2020
18	F1	20	20		400	6699000	1633000	–400
19	G1	180	3		100	6699000	1633000	–100
20	G2	180	3		200	6699000	1633000	–200
21	G3	0	2		1120	6699000	1633000	–1120
22	G4	0	2		1220	6699000	1633000	–1220
23	H1	123	70	–150		6699002	1632850	0
24	H2	123	70	–50		6699001	1632950	0
25	**I1**	**30**	**70**	**–1100**		**6699024**	**1634100**	**0**

2 Objectives

The original objective of this study was to compute the extent of the reflectors reported in R-02-43, with the coverage offered by the measured profiles. In other words, the initial objective was to confine the infinite planes defined in Table 1-1 above to line segments on such planes where reflections would actually occur. However, depicting reflectors as line segments is not completely suggestive to the viewer. The reflecting segments are therefore represented in all the figures of this report as plane elements with a transverse dimension of 100 m, which corresponds roughly to 3-4 signal wavelengths.

While proceeding with the analysis, it became apparent that planes computed according to Table 1-1 did not produce intersections with the data profiles consistent with the ones presented in R-02-43. A likely reason has been that the data submitted to this study were DMO – rather than migrated – profiles, which was bound to produce positioning errors, as explained in Section 3 below. A procedure aimed at converting the DMO representation to spatial dimensions was set up and used. The procedure included a reassessment of the velocity field based on Section 4.2 of R-02-43, as explained in Section 4 below.

Even after including to the analysis geometrical corrections to the DMO representation and adjusting the velocity field, a precise match between reflectors derived from Table 1-1 and actual reflection events presented in the relevant figures of R-02-43 could not be found. The objective of the study was therefore extended to choosing eligible reflector candidates in terms of proximity to their positions, as reported in R-02-43, and their amplitude standout in the data profiles. With a few exceptions discussed further, this produced matches within +/– 10° dip and +/– 20° strike, with respect to the original estimates.

The last objective of the present exercise consisted of computing the orientations and extent of reflectors not visible throughout the profiles and/or visible as a sequence of articulated segments with different orientations.

3 DMO representation and reflector positioning

The DMO (dip moveout) procedure is used to compensate for time stretches due variable source-receiver offsets. After DMO, reflection onsets on different traces originating at the same point in space are brought to the same time mark and can therefore be stacked. The horizontal axis of a DMO profile is the distance along the measured seismic line. However, the vertical axis is still time, not depth. To transfer the representation from *X–t* (distance – time) to *X–R* (distance – depth) coordinates, one must first consider a velocity field. *R*, rather than *Z* is taken here to represent the depth, as there is no reason to assume a priori that reflectors are positioned vertically beneath the seismic line. Let a constant velocity ***V = const***. be considered. In Figure 3-1, a reflection event picked at A1 on trace S1 can arrive from any reflector tangent to the sphere with the center in S1 and the radius $\mathbf{R_1 = V \cdot t_1 / 2}$. Likewise, a reflection event picked at time A2 on trace S2 can arrive from any reflector tangent to the sphere with the center in S2 and the radius $\mathbf{R_2 = V \cdot t_2 / 2}$.

Let us assume that the segment A1A2 is picked in the *X–t* data profile along a visible reflection event extending from trace S1 to trace S2. The corresponding reflection segment in the *X–R* space is B1B2, which is tangent at the two spheres with diameters R_1 and R_2. The dip and position errors are negligible for deep sub-horizontal reflectors where $R_1 \sim R_2$ but may become significant for steep and/or shallow reflectors where R_1 # R_2. By simple geometrical considerations it can be proven that the intersection point with the surface is the same for A1A2 and any realization of B1B2. Therefore, the error will not appear when intercepting the reflectors at surface but will become apparent in boreholes, or when attempting to match in depth reflectors from crossing profiles. The geometrical relation between segments A1A2 and B1B2 depends only on the slant of the segment A1A2 in the *X–t* representation and the velocity. B1B2 can therefore be computed without reference to the possible out-of-vertical position of B1B2. The locus of B1B2 is a conical sheet with its axis along the measuring line.

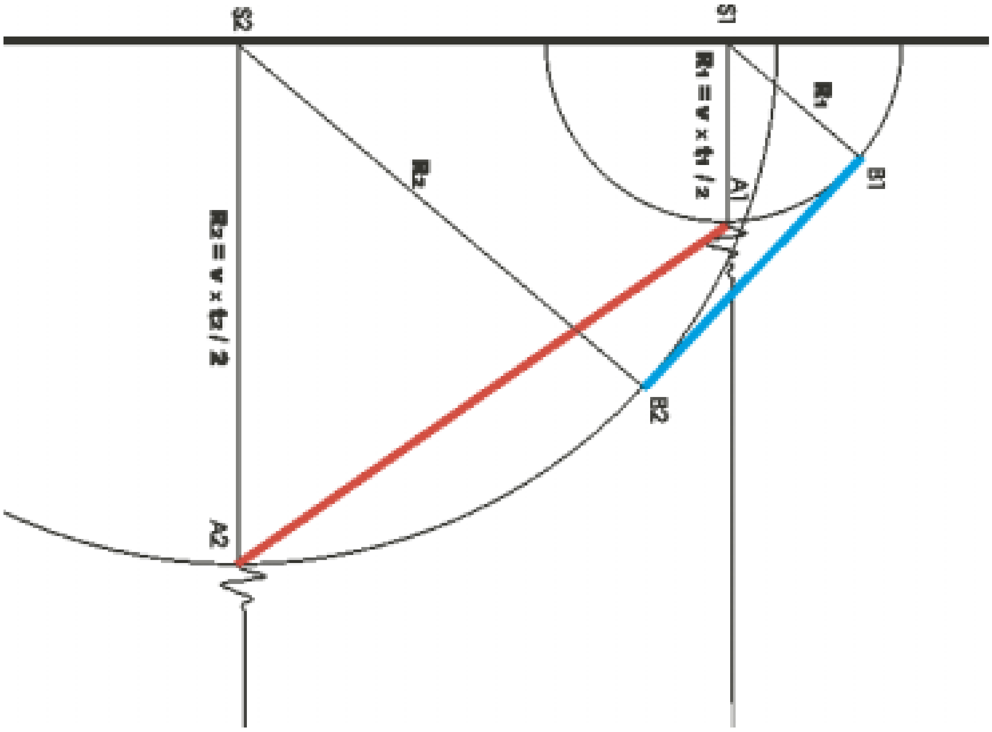

Figure 3-1. *Schematic representation of a DMO-corrected profile. The survey line runs horizontally. The vertical axis is the* ***time*** *to the reflector, which becomes* ***distance*** *to the reflector by taking* $\boldsymbol{d = t \cdot V / 2}$ *with* $\boldsymbol{V = const}$. *The distance is the same with the vertical depth only for horizontal reflectors. Dipping reflectors lining with the segment A1A2 in the DMO profile are actually located along B1B2, i.e. tangent to the spheres with the centers in S1 and S2 and the radii* $\boldsymbol{R_1 = t_1 \cdot V / 2}$, $\boldsymbol{R_2 = t_2 \cdot V / 2}$.

4 Velocity field and reflector positioning

The figures from Section 4.1.5 of R-02-43 contain an "approximate depth" axis which is derived from the time axis and a constant velocity V = 5850 m/s. Firstly, let us note that "depth" should not refer to "vertical depth", but to the distance from the measuring line, as explained in Section 3 above. Secondly, a discussion is needed to determine whether 5850 m/s is in deed the constant velocity value providing the minimum estimation error in depth. Figure 4-1 below is drawn based Figure 4-19 of R-02-43 and presents the estimated average variation of the velocity with the depth.

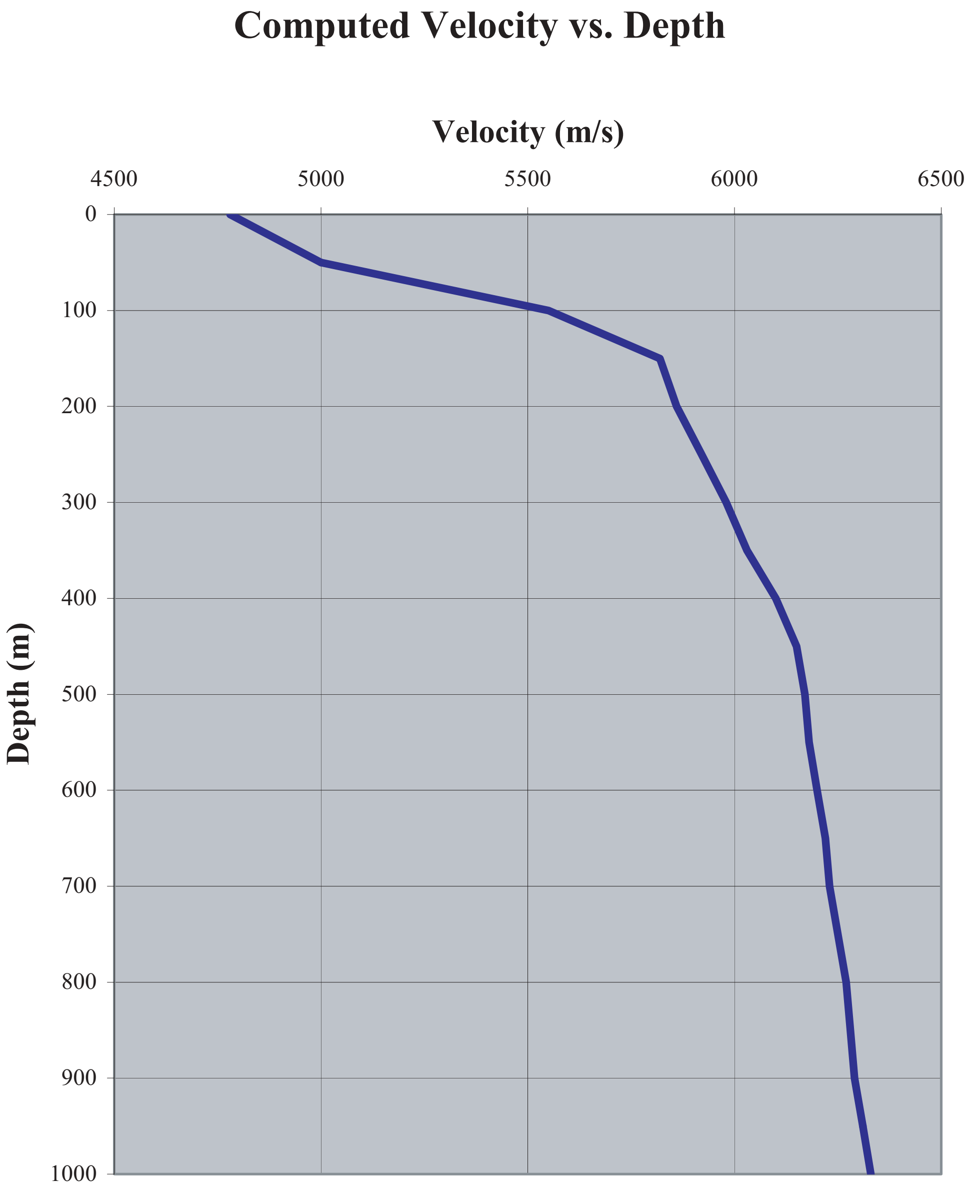

Figure 4-1. *Computed velocity vs. depth (cf. Figure 4-19 of R-02-43).*

Two-way travel times have been computed vs. depth for the velocity model of Figure 4-1, for V = 5850 m/s and for V = 6000 m/s with a 4 ms delay. This delay would be introduced by the low velocity zone between 0 m and 150 m depth. The aim is to minimize the errors in estimating the actual depth of the reflectors introduced by the use of constant velocity, with respect to the "true" depth computed by the variable velocity model. Of course, the meaning of "true" is relative, depending on how accurate the variable velocity model is and on how inclined the path to any given reflector is with respect to the vertical depth. The velocity model is likely to be sufficiently accurate through most of the site, as proven by the velocity analysis performed in Section 4.2 of R-02-43. Likewise, the velocity variations at depths over 150 m is relatively small and therefore the errors possibly induced by non-vertical reflection paths is likely to be within approximately +/– 12 m, i.e. less than +/– half of a wavelength. The introduction of an additional delay to compensate for the near surface low velocity will distort events from reflectors shallower than 150 m, which are not interpretable anyway, but will reduce the errors in estimating the depth of deeper reflectors. This point is proven in Figure 4-2, which presents the depth error vs. depth, relative to the "true" velocity model, for V = 5850 m/s (magenta) and for V = 6000 m/s, with 4 ms delay (yellow). The letter approximation is clearly better, as it brings the errors at any depth to within +/– 12 m, i.e. to less than +/– half of a wavelength.

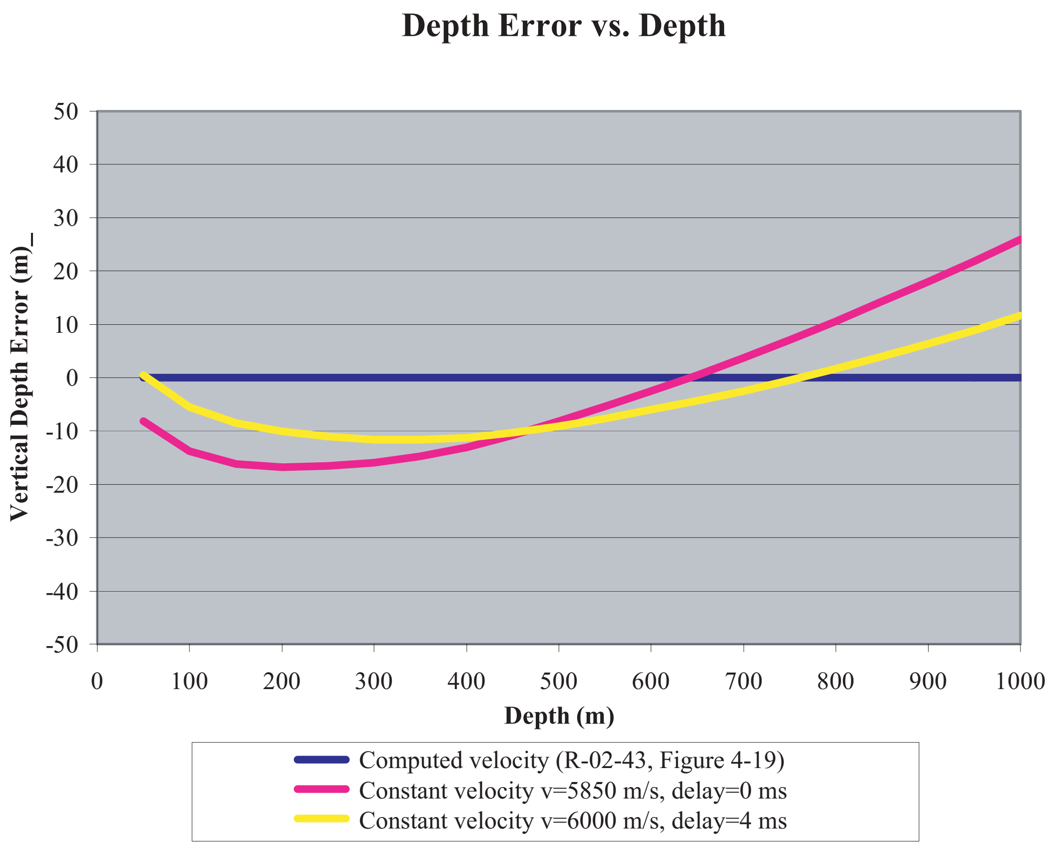

Figure 4-2. *Depth error relative to the computed variable velocity model for V = 5850 m/s and V = 6000 m/s with 4 ms delay.*

5 The Crux Point Method

Seismic reflection profiles are two-dimensional distance-time representations. Even after transforming the *X–t* axes into *X–R* axes, as described in Section 3, a reflecting plane can not be fully determined from a single 2D profile. What can be determined is the relative slope of the reflector with respect to the acquisition line (assuming that the line is straight). The reflection on a plane will occur along a line segment, with the reflector plane being perpendicular to the plane formed by this segment and the measuring line. The non-determination when going from 2D to 3D will turn the locus of the reflection segment into a conical surface having the measuring line as its axis. Determining fully the position of a reflector from two or more profiles could then be done by finding a plane, which is tangent to several conic surfaces with axes oriented differently in space. However, one may find this procedure quite cumbersome in practice and a more user-friendly approach has been used here.

The "Crux Point" of a plane is defined as the foot of the perpendicular descended on a plane from a chosen origin. The locus of the Crux Point of a reflector appearing as a line segment in a 2D profile is a curve in space, rather than a conical surface. The best-fit plane solution for the reflector is found at the intersection of the Crux Point loci. If all profiles are horizontal and on ground surface, there will be two mathematical solutions, symmetrical with respect to the ground surface. Obviously, the solution up in the sky can be neglected. Estimating interactively the intersection of Crux Point curves is far easier than the common tangent plane to conical surfaces, which makes Crux Point method more tractable.

Once the plane of the reflector determined by Crux Point match, the positions of the reflection segments along the reflecting planes corresponding to the events observed in the data profiles can be calculated. In practice however, depicting reflectors by line segments is not completely suggestive to the viewer. The reflecting segments are therefore represented as plane elements with a transverse dimension of roughly to 3–4 signal wavelengths.

The Crux Point method is exemplified in Figure 5-1. One can notice the intersection of the crux point loci determining the position and orientation of the reflector plane (red dot) and the alternative "up in the sky" solution, which was discarded. The second red dot, near the investigation lines at ground surface, is the crux point origin, common for all profiles. The actual reflector elements corresponding to the three profiles are also presented.

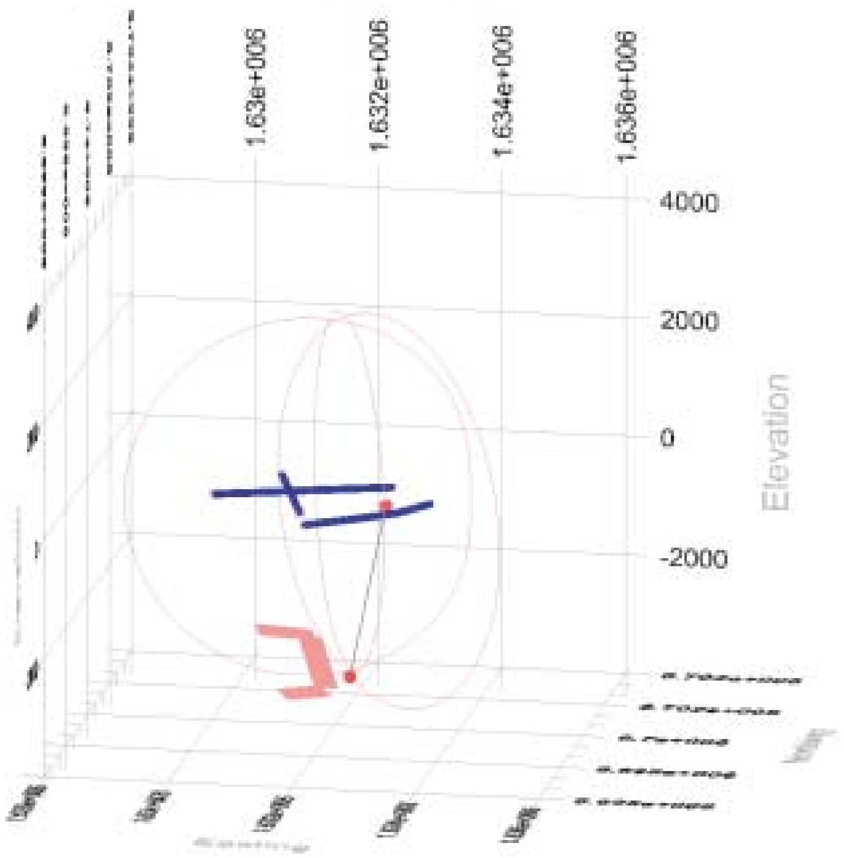

Figure 5-1. *Crux Point definition and reflection elements for three surface profiles.*

6 Survey layout

Reflection seismic data were acquired along five profiles varying in length from 2 to 5 km. The investigation lines were not straight and, to apply the considerations given in the previous sections, the investigation lines with significant deviations from linearity were split in several roughly linear parts as follows:

- Line 2 in line 2.1(stations 1 to 325) and line 2.2 (stations 326 to 485).
- Line 5 in line 5.1 (stations 1 to 319), line 5.2 (stations 320 to 499), and line 5.3 (stations 500 to 979).

The investigation lines and naming conventions are shown in Figure 6-1. The start station on each profile is marked with a green dot.

The crux point origin (the red dot in Figure 6-1) was chosen at (6699Km N, 1633 Km W), the same as the origin taken R-02-43 Section 4.

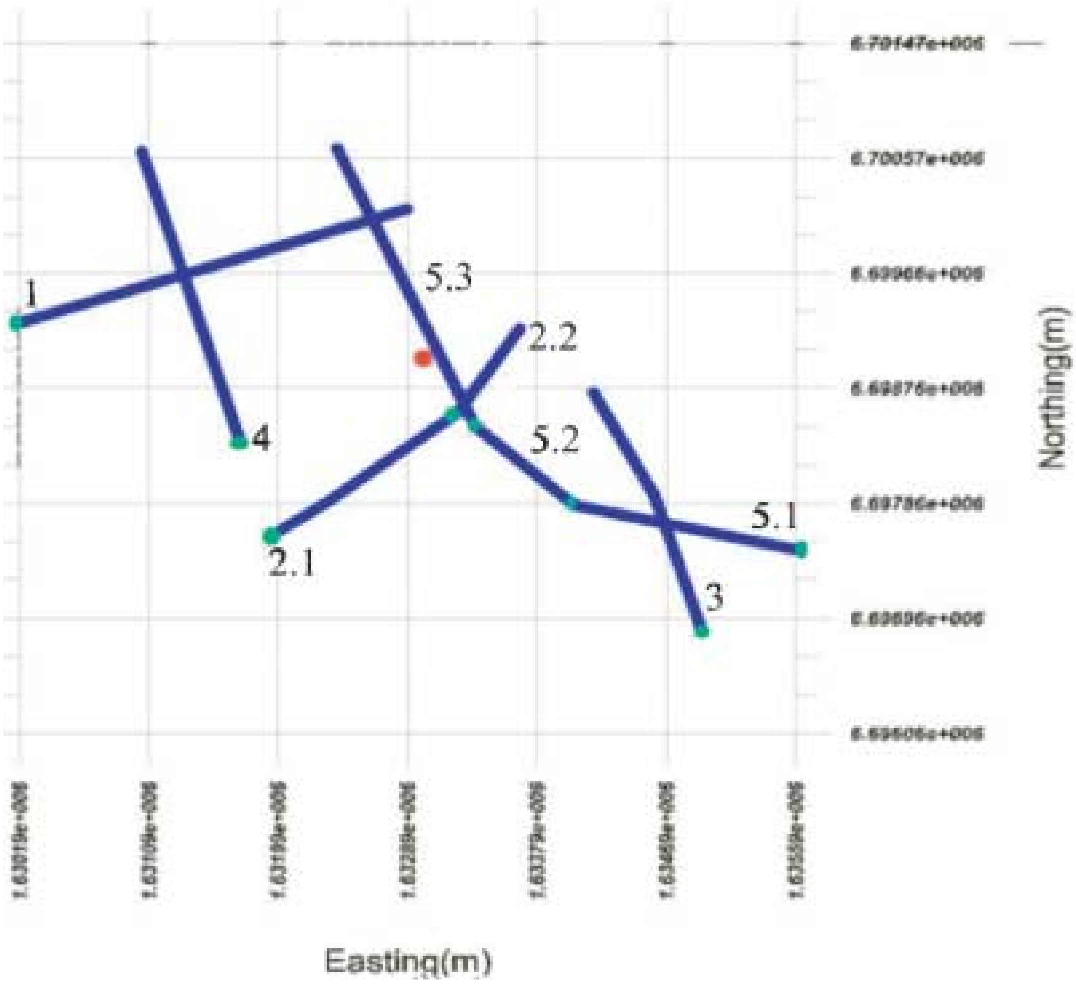

***Figure 6-1**. Survey lines and naming conventions. Lines 2 and 5 are split into linear segments. The green dots represent the first station (lower ID) in each line segment. The red dot is the crux point origin at 6699 Km N, 1633 Km W.*

7 Results

The results of the geometrical reinterpretation of the Forsmark seismic reflectors described in R-02-43 are summarized in Table 7-1, for reflector sets A, B and in Table 7-2, for reflector sets C through I. Columns 2 and 3 reproduce the original dips and strikes from Table 1-1. Columns 3 and 4 give the dip and strike in each profile where a reflector is visible, as reinterpreted from events matching more or less the original interpretation. In the profiles where the events associated with reflectors are curved, they have been approximated by several articulated line segments and the respective dips and strikes are given in sequence. Columns 5 to 7 show the profiles and the station numbers between which the orientations from columns 3 and 4 have been determined.

Events roughly compatible with the original orientations have been found for reflector sets A, B, C, E and F. Significantly different orientations have been found for reflectors in set D. Reflector sets G, H and I could not reliably be associated with any event in the profiles. Their original positions and orientations have however been kept and used to compute the positions of associated elements, if they however exist.

The positions and orientations for all reflectors reinterpreted are shown in detail in Figures 7-1 through 7-30. The figures form pairs and in each pair a view from up and perspective view are shown. Curved reflectors are termed as “reflector groups”. Following each pair of figures, the site coordinates of all reflector elements displayed are given in groups of four. The elements describe the same orientations as presented in Tables 7-1 and 7-2. The transverse dimension of the elements has been set to 100 m. In each figure, only the investigation lines along which the respective reflectors have been identified are presented.

Comprehensive images of the positions and orientations of all reinterpreted reflectors are shown in Figures 7-31 and 7-32.

Table 7-1. Summary of orientations found for reflector sets A and B.

Reflector ID	Original Dip	Original Strike	New Dip	New Strike	In Profile	First station	Last station
A1	45	75	50	82	1	148	441
			39	81	2.1	35	247
			39	81	4	2	175
			50	82	4	238	436
			45	81	4	176	244
			36	82	5.3	258	480
A2	22	80	25	94	2.2	14	63
			12	98	2.2	69	86
			24	94	5.3	20	109
			12	98	5.3	114	141
A3	25	65	25	65	5.3	1	131
			21	45	2.2	1	160
A4	25	65	26	61	3	18	274
			26	61	5.1	1	319
			26	61	5.2	1	91
A5	30	75	32	75	3	1	177
			32	74	5.1	1	222
A6	30	75	31	77	3	1	68
			31	77	5.1	1	34
B1	25	30	27	32	3	1	333
			27	32	5.1	1	284
B2	25	30	27	25	3	65	286
			27	25	5.1	68	319
B3	21	30	24	30	3	179	402
			24	30	5.1	111	319
B4	28	50	29	50	2.1	243	325
			29	50	2.2	1	96
			29	50	5.2	1	179
			29	50	5.3	1	336
B5	25	50	26	62	3	54	287
			26	62	5.1	158	319
			9	**50**	**5.1**	**1**	**146**

Table 7-2. Summary of orientations found for reflector sets C – I.

Reflector ID	Original Dip	Original Strike	New Dip	New Strike	In Profile	First station	Last station
C1	20	15	18	38	1	153	338
			18	37	2.1	1	161
			18	37	4	1	426
C2	10	355	13	35	1	241	492
			13	35	2.1	1	325
			13	35	4	83	276
			8	72	4	1	286
			13	35	5.3	1	62
D1	65	320	36	62	5.1	1	319
			36	62	3	122	400
D2	50	120	30	40	5.1	1	319
			30	40	3	1	402
D3	65	320	28	37	5.1	1	319
			28	37	3	1	402
E1	9	270	12	297	2.1	234	325
			12	297	2.2	1	39
			12	297	5.2	143	180
			12	297	5.3	1	92
F1	20	20	18	23	2.2	1	69
			2	27	5.2	145	178
			18	20	5.3	15	120
			4	20	5.3	120	220
G1	3	180	3	180	4	1	472
			3	180	1	1	570
G2	3	180	3	180	4	1	472
			3	180	1	1	570
G3	2	0	2	0	4	1	472
			2	0	1	1	570
G4	2	0	2	0	4	1	472
			2	0	1	1	570
H1	70	123	70	123	1	1	311
			70	123	4	1	356
			70	123	2.1	1	356
H2	70	123	70	123	1	1	324
			70	123	4	1	372
			70	123	2.1	1	372
I1	70	30	70	30	5.2	1	82
			70	30	1	1	319
			70	**30**	**3**	**1**	**402**

Reflector A1

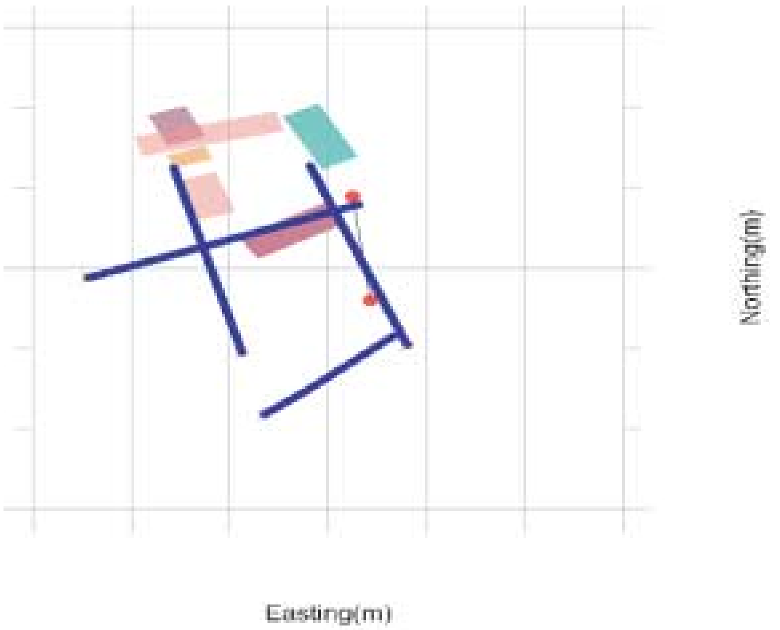

Figure 7-1. *Reflector group A1 – elements from profiles 1, 4, 2.1, 5.3. View from up.*

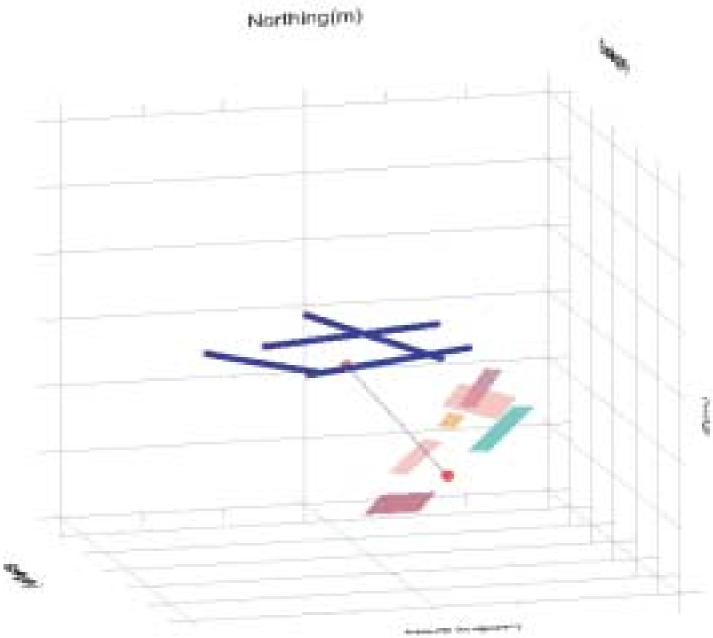

Figure 7-2. *Reflector group A1 – elements from profiles 1, 4, 2.1, 5.3. View from SE.*

Element from profile 1 (N, E, Z)

6700994.00 1630643.38 –986.930

6700750.00 1630724.13 –1293.33

6701059.00 1632137.13 –1167.33

6701303.00 1632056.38 –860.940

Elements from profile 4 (N, E, Z)

1 – pink

6699962.00 1631265.75 –2083.49

6700077.00 1631646.38 –2039.35

6700568.00 1631449.25 –1618.49

6700453.00 1631068.63 –1662.63

2 – brown

6700874.00 1630976.50 –1248.82

6700988.00 1631353.63 –1179.67

6701365.00 1631151.13 –694.86

6701251.50 1630773.88 –764.01

3 – orange

6700609.50 1631044.38 –1510.51

6700725.00 1631423.50 –1455.57

6700883.50 1631350.88 –1285.99

6700768.00 1630971.75 –1340.94

Element from profile 2.1 (N, E, Z)

6699759.00 1631684.63 –2294.04

6699498.00 1631878.63 –2526.72

6699933.00 1632753.50 –2285.06

6700194.00 1632559.38 –2052.39

Element from profile 5.3 (N, E, Z)

6700587.50 1632515.13 –1481.03

6700746.50 1632874.13 –1404.54

6701395.50 1632478.63 –895.29

6701236.50 1632119.50 –971.79

Reflector A2

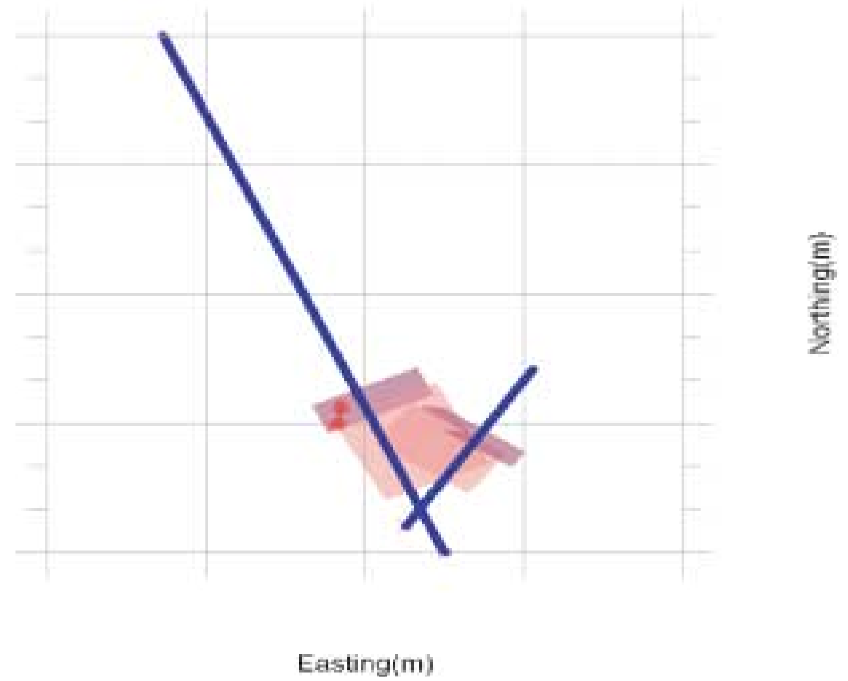

Figure 7-3. *Reflector group A2 – elements from profiles 5.3, 2.2. View from up.*

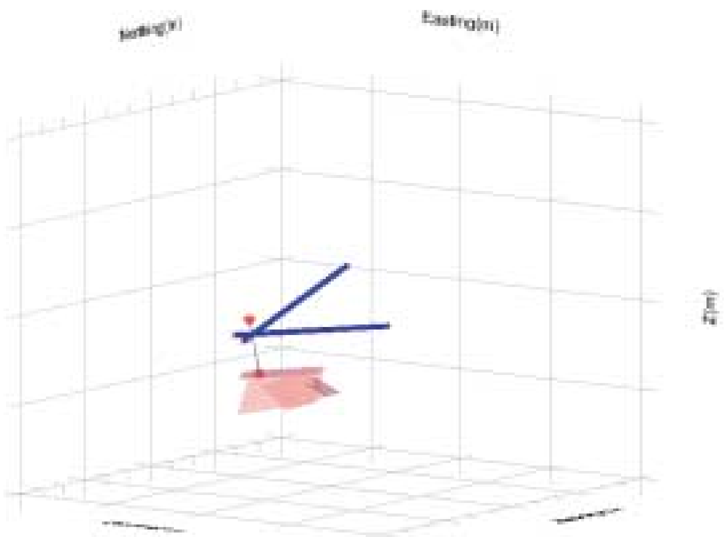

Figure 7-4. *Reflector group A2 – elements from profiles 5.3, 2.2. View from SE.*

Elements from profile 2.2 (N, E, Z)

1 – pink

6698919.00 1633122.00 –367.95

6698703.50 1633447.63 –454.87

6698870.50 1633579.63 –373.28

6699085.50 1633254.13 –286.36

2 – brown

6699037.00 1633265.75 –326.11

6698817.50 1633597.88 –363.67

6698885.00 1633644.38 –347.41

6699104.50 1633312.25 –309.85

Elements from profile 5.3 (N, E, Z)

1 – pink

6698669.50 1633164.13 –499.69

6698827.50 1633521.88 –415.86

6699168.00 1633336.63 –268.58

6699010.00 1632979.00 –352.42

2 – brown

6698958.50 1632965.25 –350.10

6699121.00 1633328.13 –305.90

6699239.00 1633272.50 –283.01

6699077.00 1632909.50 –327.21

Reflector A3

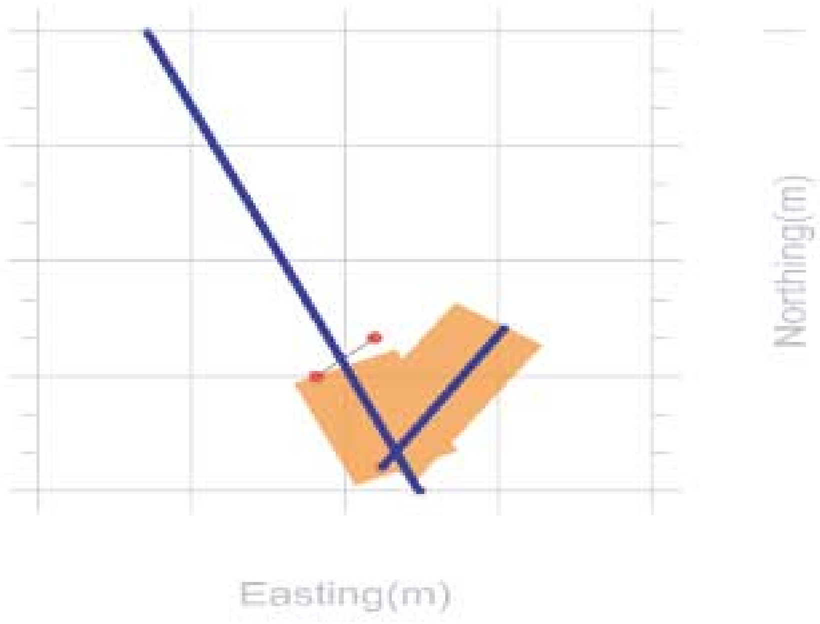

Figure 7-5. *Reflector A3 – elements from profiles 5.3, 2.2. View from up.*

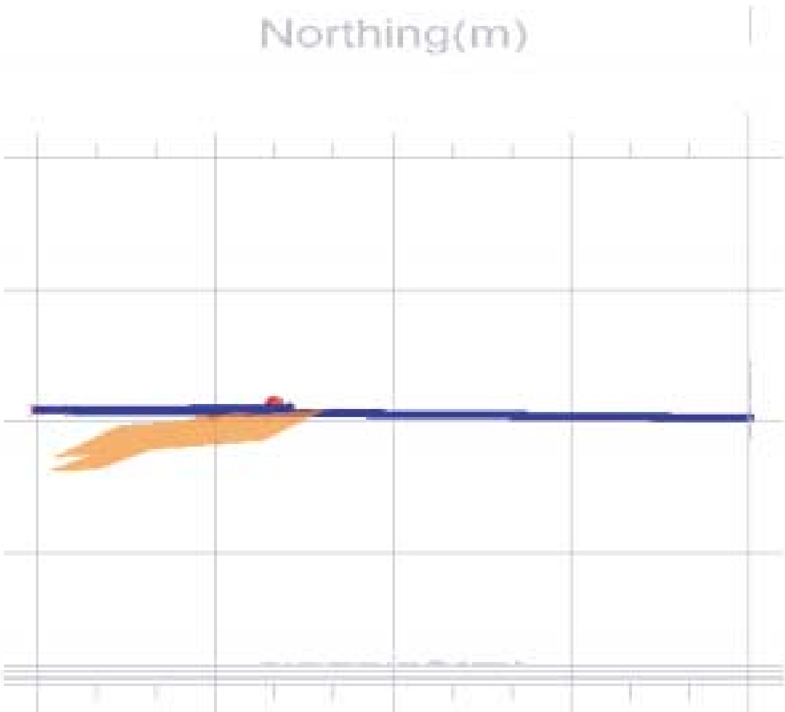

Figure 7-6. *Reflector A3 – elements from profiles 5.3, 2.2. View from E.*

Element from profile 2.2 (N, E, Z)

6698501.50 1633354.00 –199.07

6698706.00 1633042.75 –53.46

6699355.50 1633495.38 2.11

6699150.50 1633806.75 –143.50

Element from profile 5.3 (N, E, Z)

6698644.00 1633500.75 –250.66

6698481.00 1633139.00 –248.21

6698997.50 1632907.50 –67.76

6699160.50 1633269.25 –70.21

Reflector A4

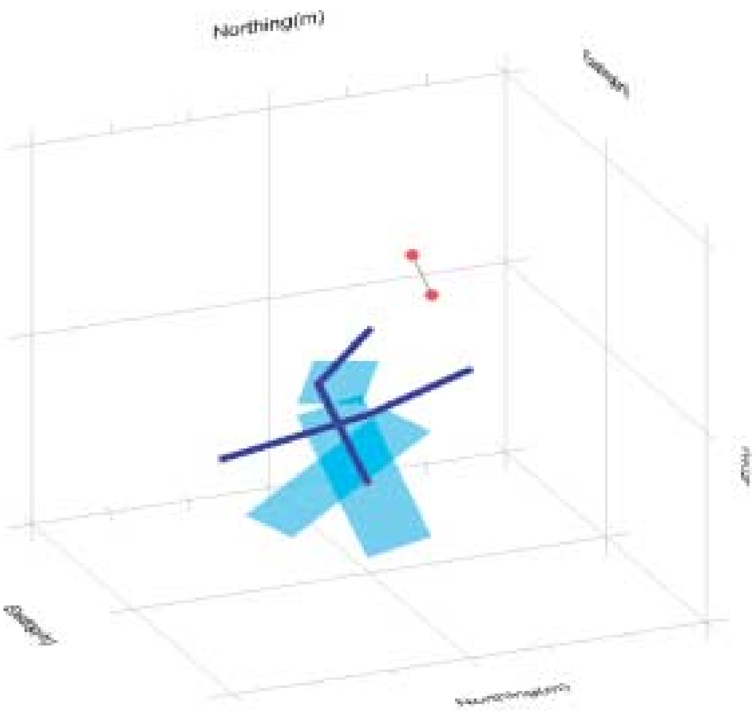

Figure 7-7*. Reflector A4 – elements from profiles 5.1, 5.2, 3. View from SE.*

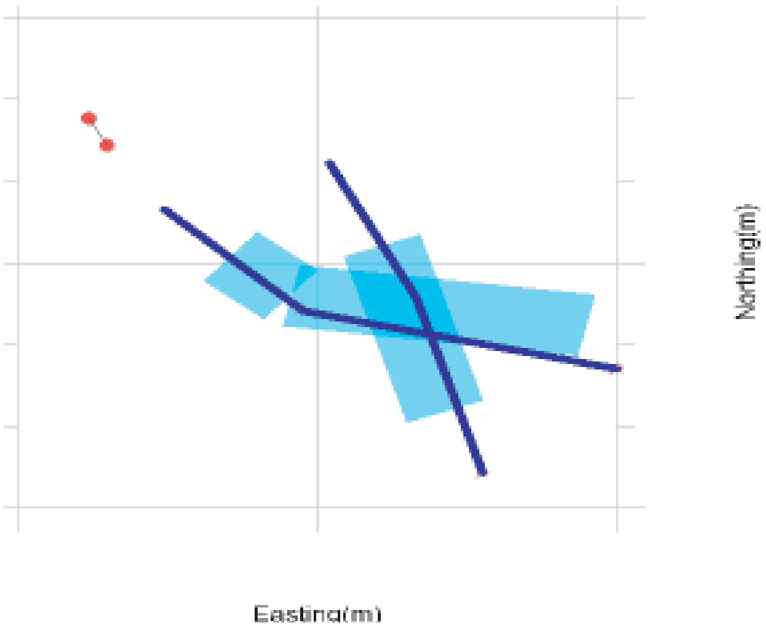

Figure 7-8. *Reflector A4 – elements from profiles 5.1, 5.2, 3. View from up.*

Element from profile 5.2 (N, E, Z)

6698088.00 1634125.63 –163.33

6697792.50 1633862.88 –225.10

6698022.00 1633566.25 –58.260

6698317.00 1633828.88 3.51000

Elements from profile 5.1 (N, E, Z)

6697940.50 1635489.50 –546.45

6697573.50 1635405.38 –680.49

6697752.50 1633956.25 –260.41

6698119.50 1634040.50 –126.37

Elements from profile 3 (N, E, Z)

6697307.00 1634939.25 –681.39

6697174.00 1634563.38 –648.54

6698169.50 1634254.75 –150.39

6698302.50 1634630.63 –183.24

Reflector A5

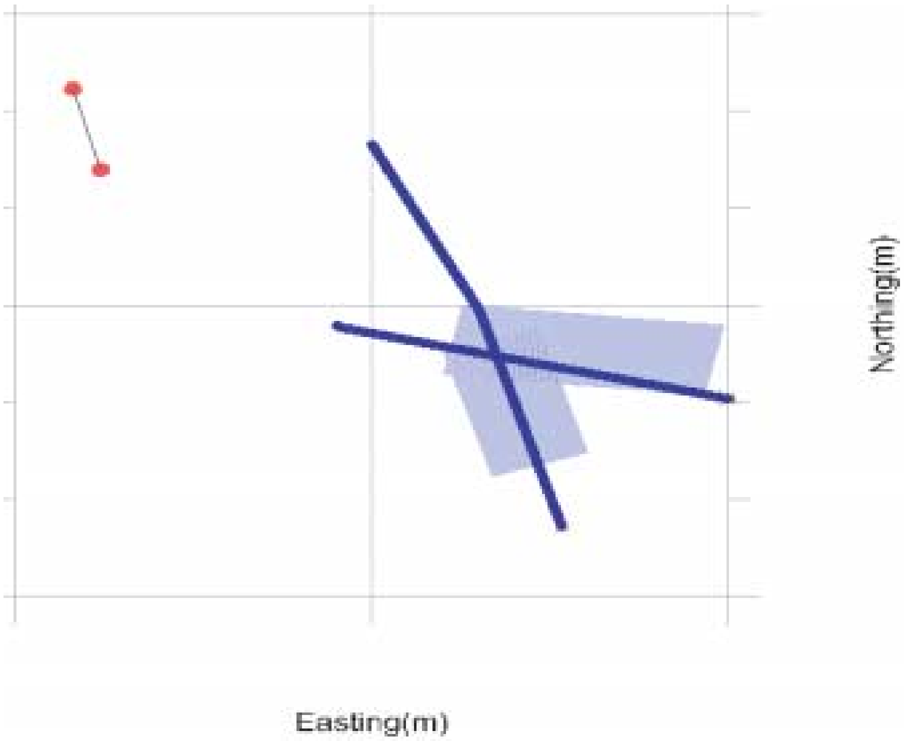

Figure 7-9. Reflector A5 – elements from profiles 5.1, 3. View from up.

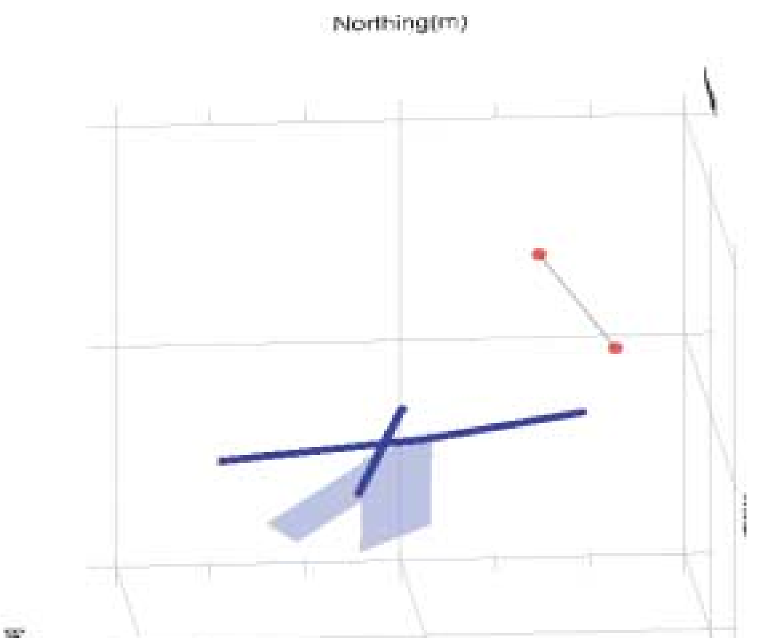

Figure 7-10. Reflector A5 – elements from profiles 5.1, 3. View from SE.

Element from profile 5.1 (N, E, Z)

6697852.50 1635579.50 –206.22

6697510.00 1635502.38 –398.31

6697609.50 1634464.75 –159.06

6697952.00 1634541.88 33.0300

Elements from profile 3 (N, E, Z)

6697233.50 1635044.00 –481.88

6697115.00 1634662.13 –490.57

6697718.00 1634466.00 –95.730

6697836.50 1634848.00 –87.040

Reflector A6

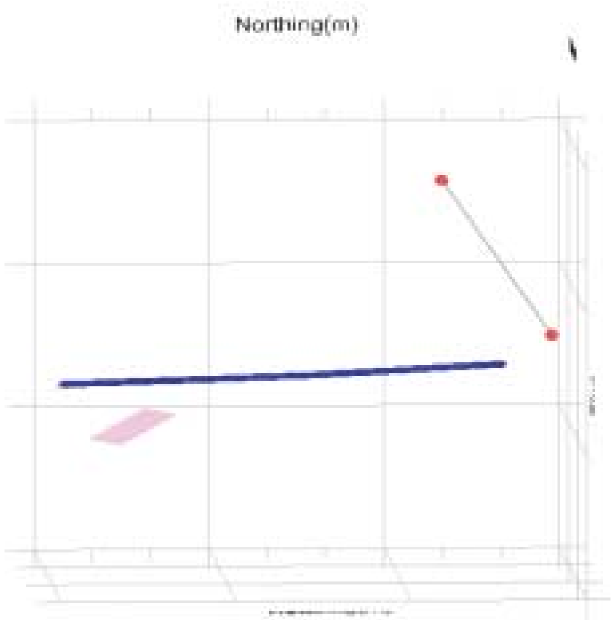

Figure 7-11. *Reflector A6 – element from profile 5.1. View from E.*

Element from profile 3 (N, E, Z)

6697106.50 1635084.13 –282.16	6
6696989.00 1634702.13 –297.38	6
6697225.50 1634623.25 –151.24	6
6697343.50 1635005.25 –136.02	6

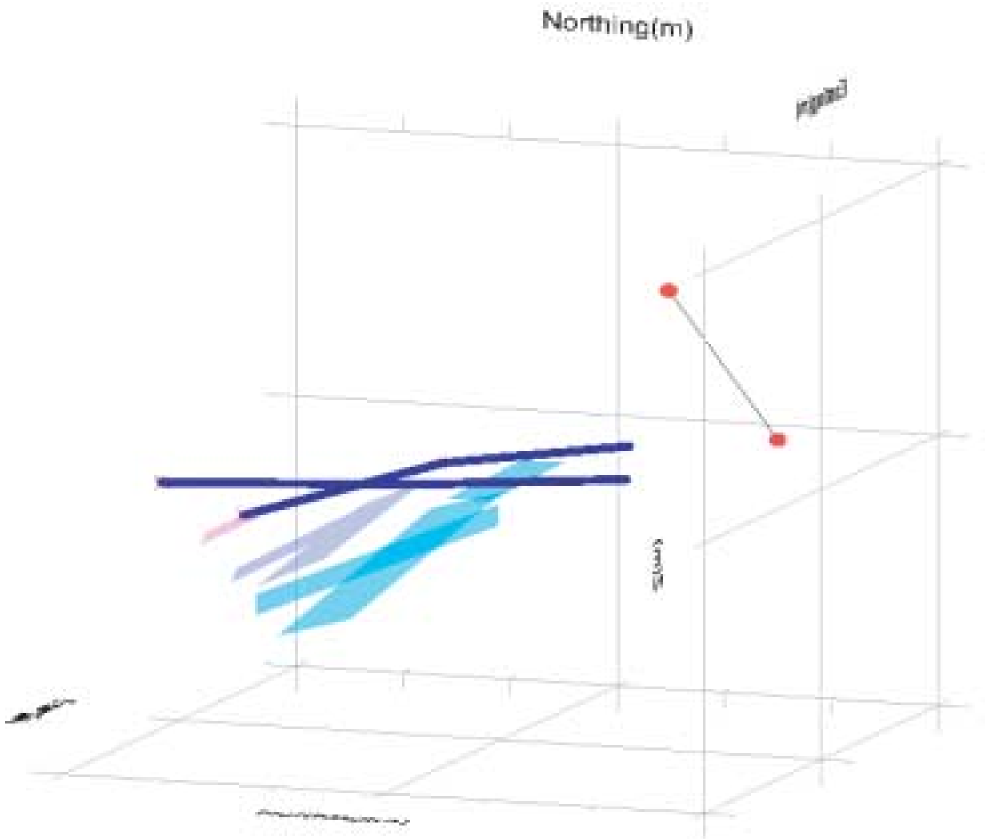

Figure 7-12. *Reflectors A4, A5, A6 – elements from profiles 5.1, 5.2, 3. General view from NE.*

Reflectors B1, B2

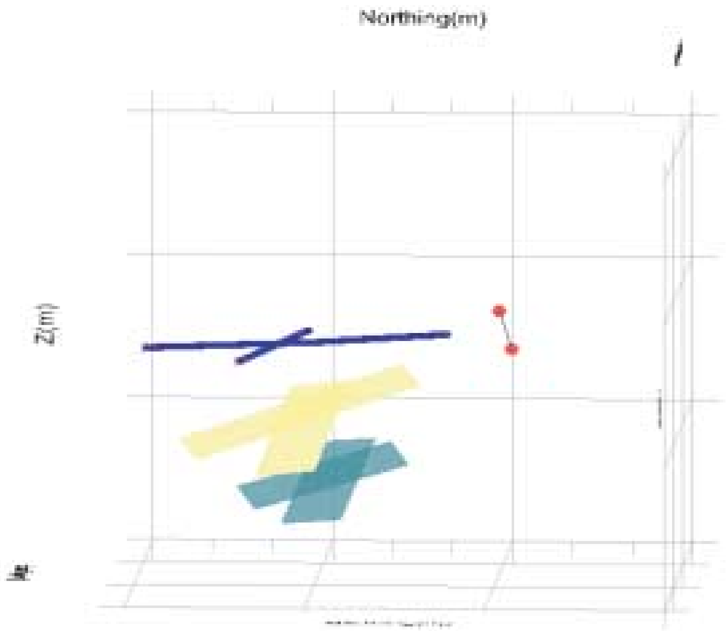

Figure 7-13. *Reflectors B1, B2 – elements from profiles 3, 5.1. View from E.*

Elements from profile 3 (N, E, Z)

B1– yellow

6697184.00 1634742.50 –914.34

6697048.00 1634385.13 –797.57

6698441.50 1634033.50 –247.18

6698578.00 1634390.88 –363.95

B2 – green

6697403.00 1634063.00 –1226.43

6697534.50 1634416.00 –1361.11

6698494.50 1634184.88 –1030.56

6698363.00 1633831.88 –895.88

Elements from profile 5.1 (N, E, Z)

B1 – yellow

6697948.00 1635226.75 –911.88

6697563.50 1635140.00 –978.49

6697727.00 1633995.38 –434.17

6698112.00 1634082.13 –367.56

B2 – green

6697685.00 1634567.25 –1435.62

6698072.50 1634656.75 –1393.20

6698246.50 1633666.38 –893.69

6697859.00 1633576.88 –936.11

Reflectors B3, B5

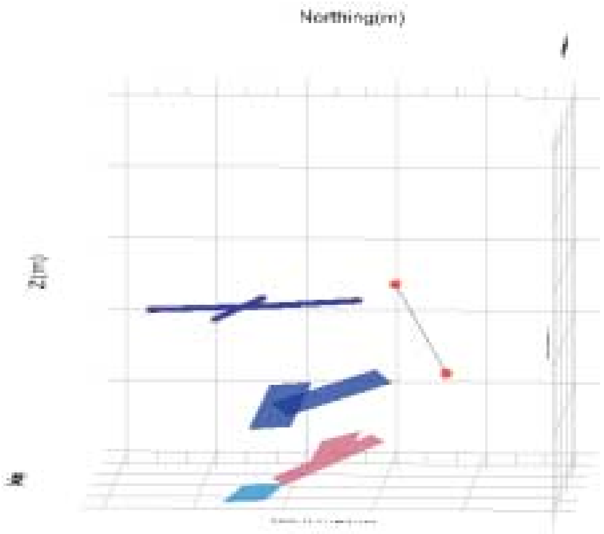

***Figure 7-14**. Reflectors B3 and group B5 – elements from profiles 3, 5.1. View from E.*

Elements from profile 3

B3 – light blue

6697923.00 1634014.88 –1187.13

6698092.50 1634363.88 –1284.54

6699020.00 1634006.25 –953.95

6698850.50 1633657.25 –856.54

B5 – brown

6697945.00 1634196.00 –2021.27

6698084.00 1634570.25 –2047.99

6698973.50 1634273.00 –1587.42

6698834.50 1633898.88 –1560.70

Elements from profile 5.1

B3 – light blue

6697742.50 1634475.13 –1421.04

6698129.00 1634564.63 –1368.17

6698279.50 1633695.75 –997.61

6697893.00 1633606.38 –1050.48

B5 – brown:

6698270.50 1634367.25 –1890.38

6698636.50 1634452.50 –1753.07

6698729.00 1633718.13 –1544.54

6698363.00 1633632.88 –1681.85

B5 – blue:

6697560.00 1635333.75 –2119.87

6697948.50 1635421.13 –2081.79

6698096.50 1634723.25 –1991.67

6697708.00 1634636.00 –2029.75

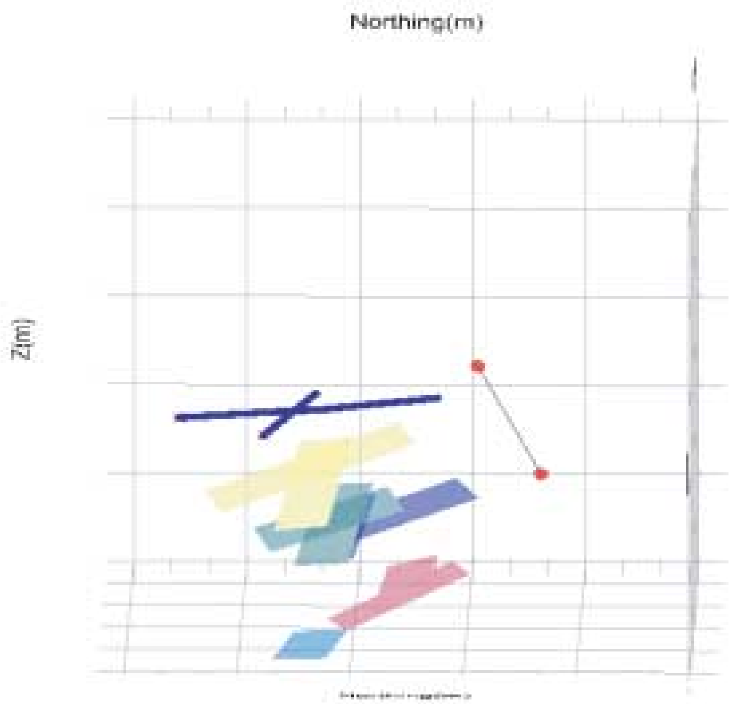

__Figure 7-15__. Reflectors B1, B2, B3, and group B5 – elements from profiles 5.1, 3. View from E.

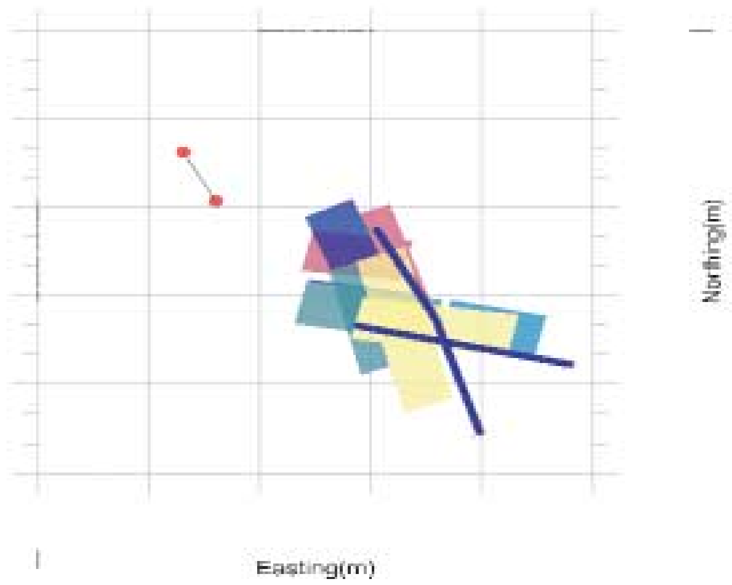

Figure 7-16. *Reflectors B1, B2, B3, and group B5 – elements from profiles 5.1, 3. View from E.*

Reflectors C1, C2

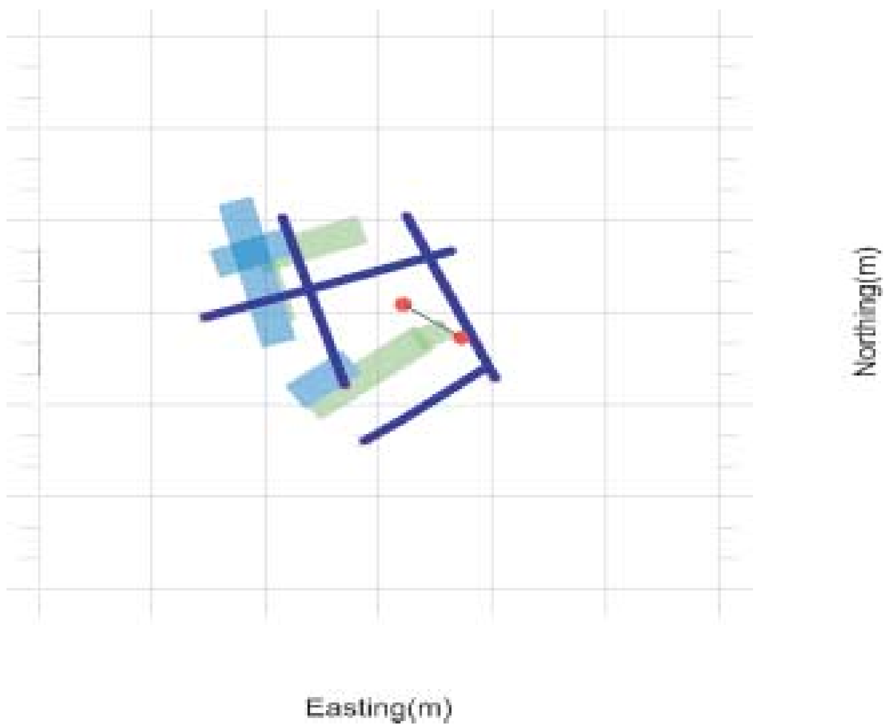

Figure 7-17. *Reflectors C1, C2 – elements from profiles 1, 2.1, 4, 5. 3. View from top.*

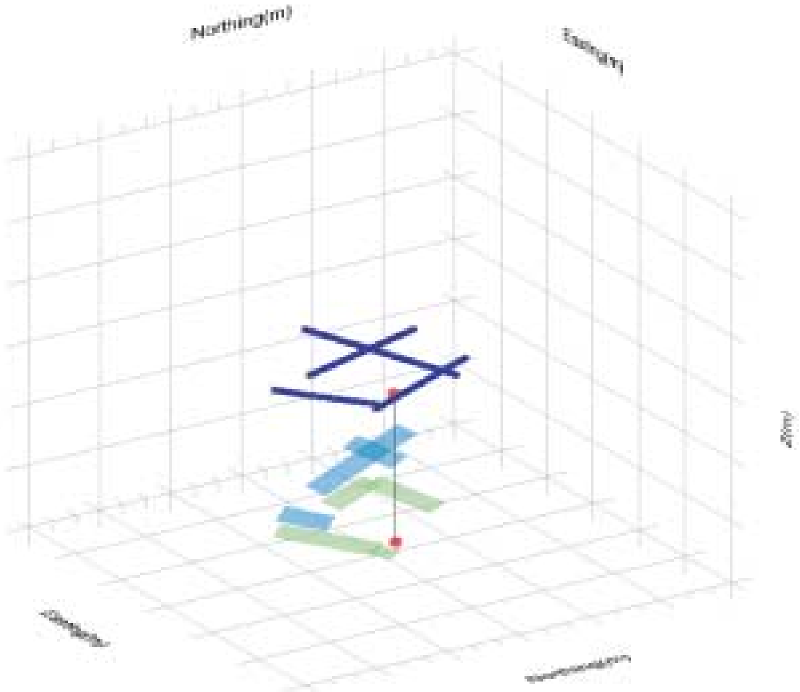

***Figure 7-18**. Reflectors C1, C2 – elements from profiles 1, 2.1,4, 5. 3. View from SE.*

Elements from profile 1 (N, E, Z)

C1 – blue

6700172.50 1630230.38 –2340.20

6699805.50 1630351.50 –2444.07

6700126.00 1631189.88 –2597.92

6700493.00 1631068.75 –2494.05

C2 – green

6700237.50 1630697.25 –2966.48

6699864.00 1630820.88 –3039.24

6700280.00 1631980.75 –3204.41

6700653.50 1631857.13 –3131.65

Elements from profile 2.1 (N, E, Z)

C1 – blue

6698348.00 1631059.25 –2913.83

6698038.00 1631281.88 –3032.68

6698515.50 1631913.13 –3097.38

6698826.00 1631690.50 –2978.53

C2 – green

6698186.00 1631218.75 –3155.52

6697872.00 1631451.88 –3241.02

6698847.00 1632722.88 –3352.00

6699160.50 1632489.88 –3266.50

Elements from profile 4 (N, E, Z)

C1 – blue

6698859.00 1630810.00 –2748.02

6698973.00 1631186.13 –2822.62

6700906.00 1630702.63 –2313.10

6700792.00 1630326.50 –2238.50

C2 – green

6699118.50 1630810.38 –3134.04

6699233.00 1631189.50 –3190.56

6700134.00 1630942.00 –3023.75

6700019.00 1630563.00 –2967.23

Element from profile 5.3

C2 – green

6698823.00 1632551.50 –3342.98

6698988.50 1632912.75 –3389.23

6699258.00 1632796.63 –3331.45

6699092.50 1632435.50 –3285.20

Reflectors D1, D2, D3

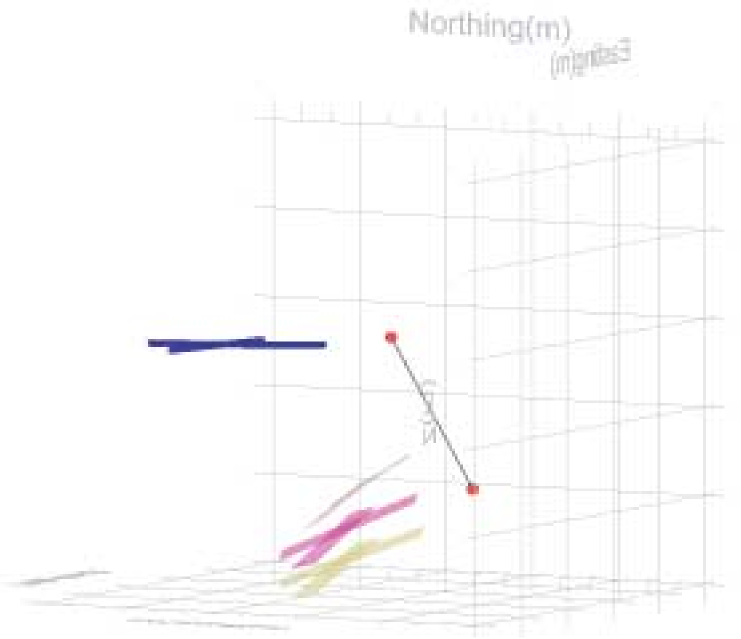

Figure 7-19. *Reflectors D1, D2, and D3 – elements from profiles 3, 5.1. View from NE.*

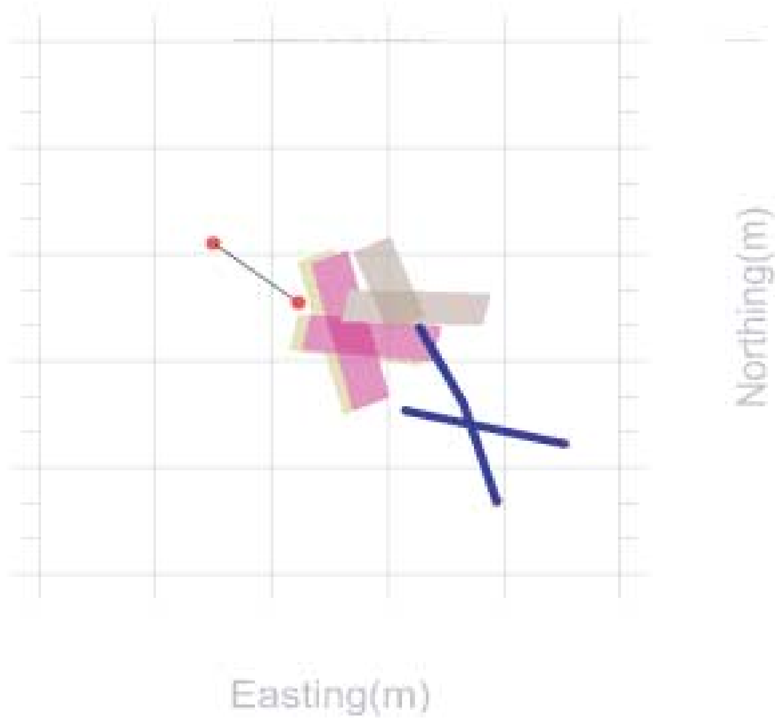

Figure 7-20. *Reflectors D1, D2, and D3 – elements from profiles 3, 5.1. View from up.*

Elements from profile 3 (N, E, Z)

D1 – brown

6698685.00 1633877.25 –2049.05

6698848.00 1634241.88 –2068.16

6699694.00 1633897.75 –1409.44

6699530.50 1633533.13 –1390.33

D2 – violet

6697847.00 1633536.38 –2716.94

6697992.00 1633894.63 –2820.03

6699552.50 1633485.38 –2045.27

6699407.50 1633127.13 –1942.19

D3 – yellow

6697802.00 1633444.88 –3086.28

6697947.00 1633803.00 –3189.72

6699572.50 1633350.00 –2477.73

6699427.50 1632992.00 –2374.29

Elements from profile 5.1 (N, E, Z)

D1 – brown

6698747.00 1634800.75 –2328.23

6699089.50 1634879.25 –2137.14

6699129.50 1633498.38 –1641.02

6698786.50 1633419.75 –1832.11

D2 – violet

6698366.50 1634312.38 –2863.32

6698743.00 1634398.75 –2760.03

6698867.50 1633121.00 –2145.30

6698490.50 1633034.63 –2248.60

D3 – yellow

6698322.50 1634213.50 –3242.03

6698704.00 1634300.88 –3157.81

6698869.00 1633003.00 –2558.32

6698488.00 1632915.50 –2642.54

Reflector E1

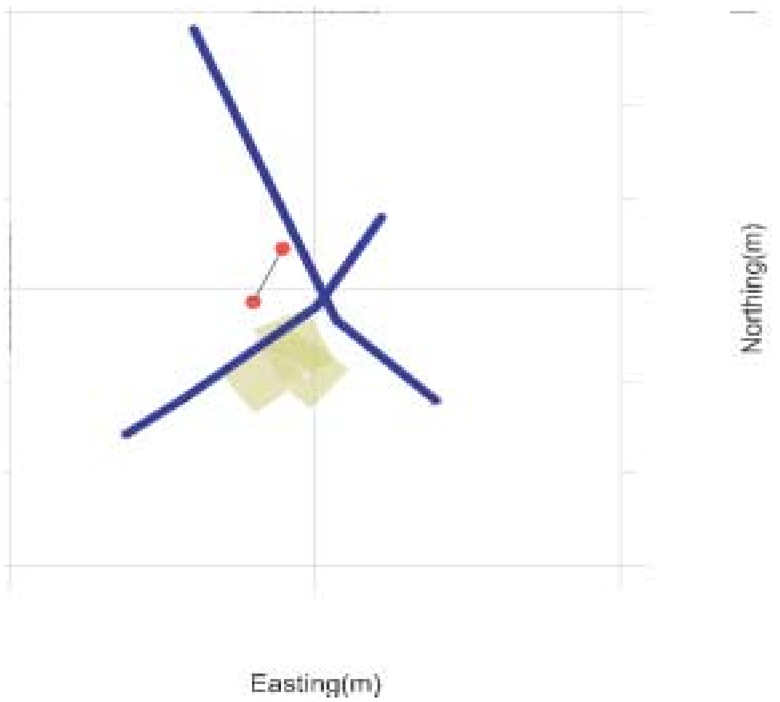

Figure 7-21. *Reflector E1– elements from profiles 5.2, 5.3, 2.1 and 2.1. View from up.*

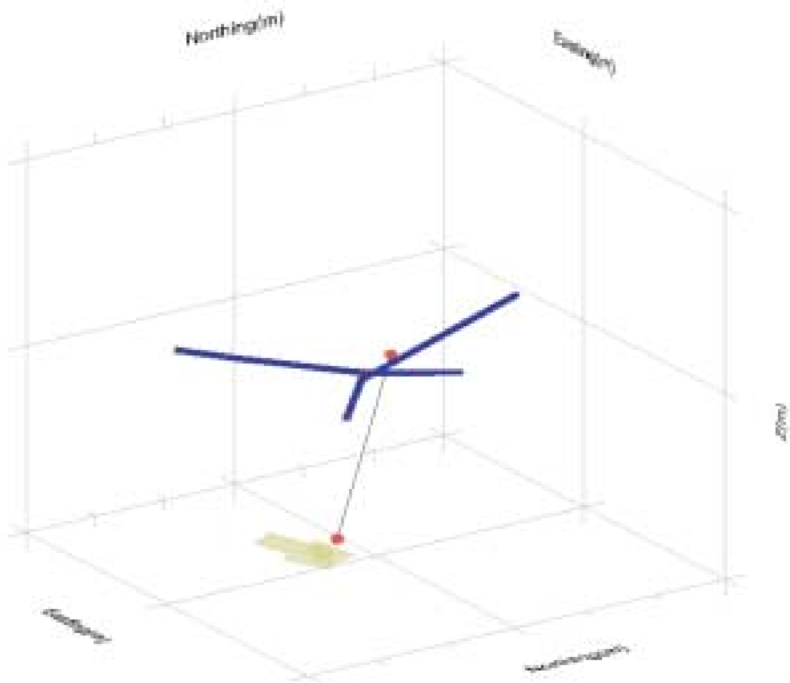

Figure 7-22. *Reflector E1– elements from profiles 5.2, 5.3, 2.1 and 2.1. View from SE.*

Element from profile 2.1 (N, E, Z)

6698080.00 1632567.25 –1882.82

6697764.00 1632809.63 –1844.27

6698021.00 1633158.13 –1929.68

6698337.00 1632915.75 –1968.23

Element from profile 2.2 (N, E, Z)

6698292.50 1632874.25 –1953.00

6698072.00 1633207.88 –1942.40

6698223.00 1633309.00 –1982.55

6698443.50 1632975.25 –1993.15

Element from profile 5.2 (N, E, Z)

6697804.50 1633189.75 –1888.31

6698095.50 1633451.25 –1971.42

6698217.50 1633312.25 –1981.60

6697926.50 1633050.75 –1898.50

Element from profile 5.3 (N, E, Z)

6697991.50 1632997.50 –1905.57

6698154.50 1633356.38 –1973.40

6698556.00 1633162.25 –2034.71

6698393.00 1632803.38 –1966.87

Reflector F1

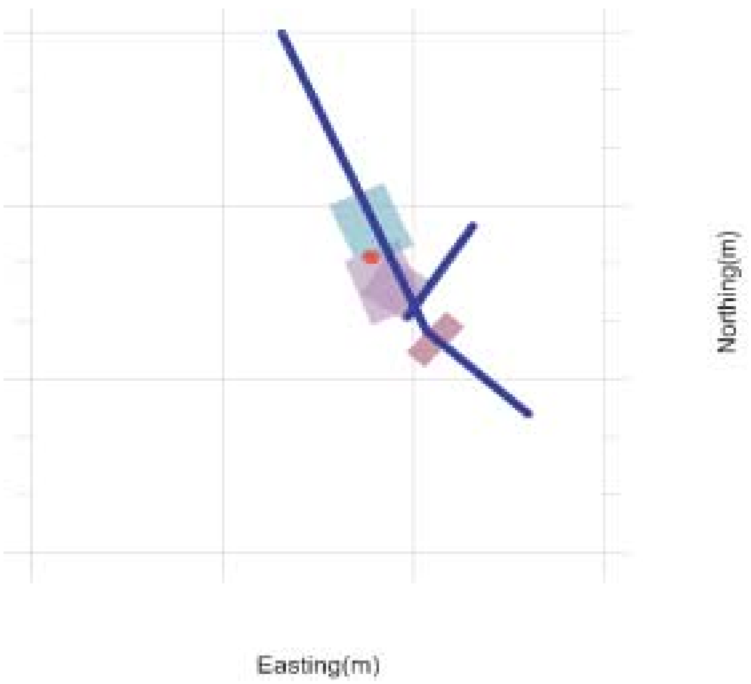

Figure 7-23. *Elements from reflector group F1: violet (profile 5.3, 2.2), green (5.3) and brown (5.2). View from top.*

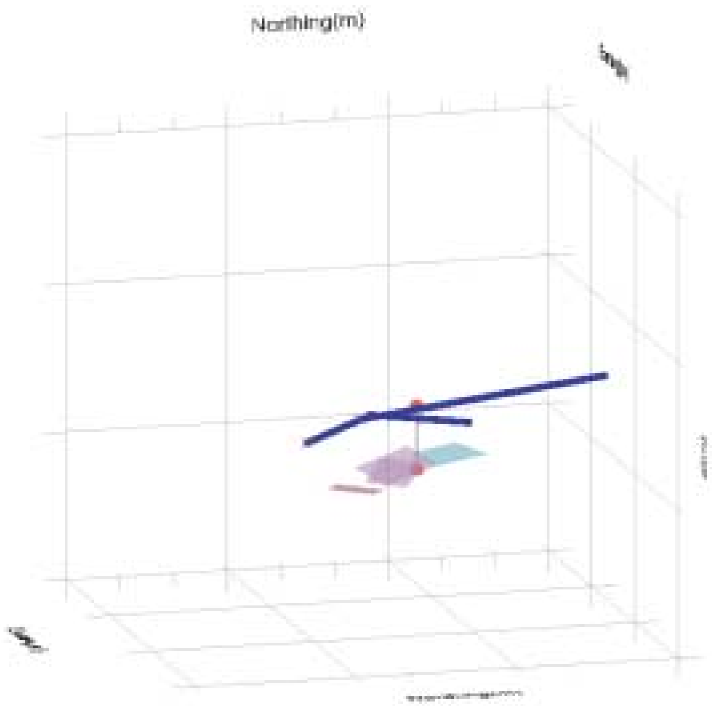

Figure 7-24. *Elements from reflector group F1: violet (profile 5.3, 2.2), green (5.3) and brown (5.2). View from SE.*

Element from profile 2.2

violet

6698735.00 1632925.00 –442.17

6698525.50 1633243.50 –563.07

6698812.00 1633425.00 –581.59

6699021.50 1633106.50 –460.69

Elements from profile 5.3

violet

6698500.00 1632996.00 –487.63

6698657.00 1633352.25 –578.84

6699125.00 1633173.13 –471.41

6698968.00 1632816.88 –380.20

green

6698928.50 1632913.75 –426.84

6699090.50 1633278.88 –446.98

6699547.00 1633077.38 –422.82

6699384.50 1632712.38 –402.68

Elements from profile 5.2

brown

6698199.00 1633349.13 –572.14

6698497.50 1633615.75 –576.36

6698607.50 1633492.88 –569.96

6698309.00 1633226.25 –565.74

Reflectors G1, G2, G3, and G4

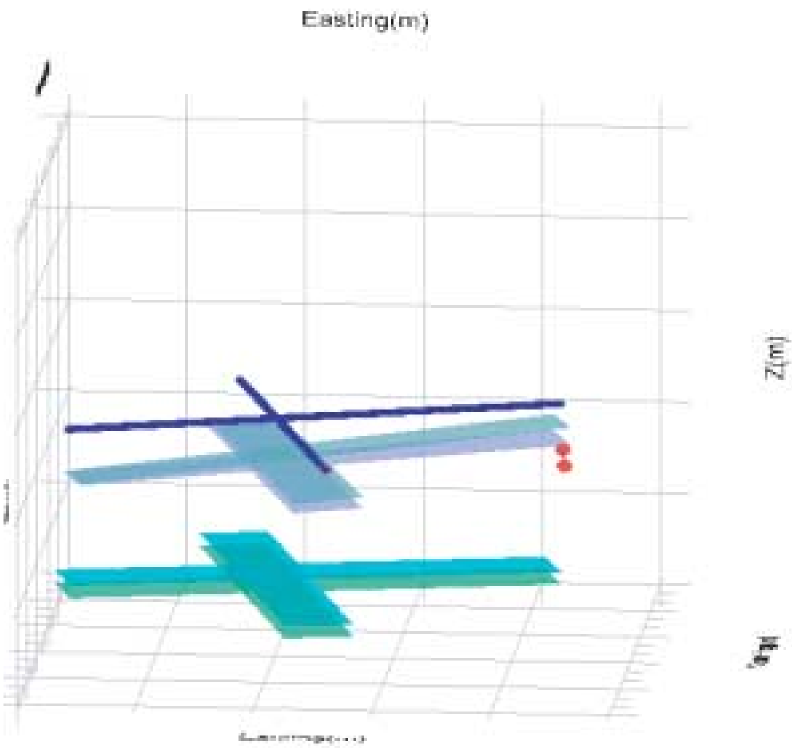

Figure 7-25. *Reflectors D1, D2, D3, and D4 – elements from profiles 1 and 4. View from W.*

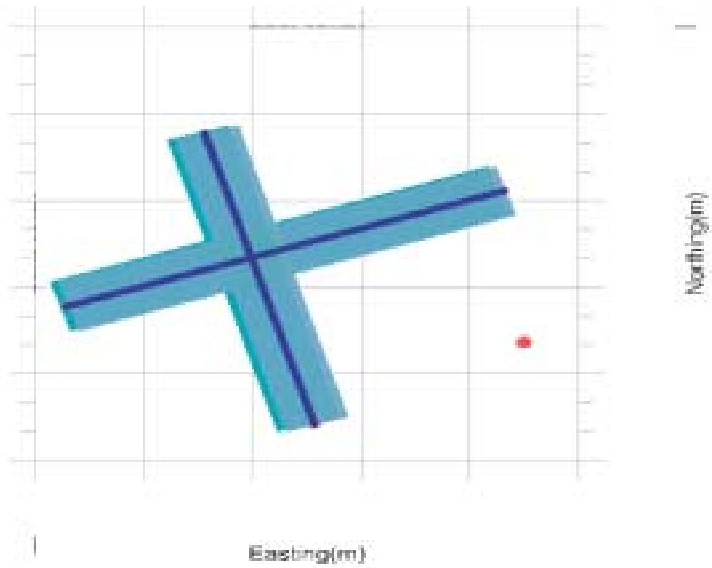

Figure 7-26. *Reflectors D1, D2, D3, and D4 – elements from profiles 1 and 4. View from up*

Elements from profile 1 (N, E, Z)

G1

6699467.00 1630135.50 –257.110

6699087.00 1630261.00 –250.550

6699980.00 1632954.63 –108.840

6700360.00 1632829.13 –115.400

G2

6699467.00 1630142.13 –383.770

6699087.00 1630267.63 –377.200

6699980.00 1632961.25 –235.280

6700360.00 1632835.75 –241.840

G3

6699467.00 1630084.88 –1068.71

6699087.00 1630210.38 –1073.10

6699980.00 1632908.13 –1168.03

6700360.00 1632782.50 –1163.64

G4

6699467.00 1630081.88 –1155.40

6699087.00 1630207.38 –1159.79

6699980.00 1632905.13 –1254.66

6700360.00 1632779.50 –1250.28

Elements from profile 4 (N, E, Z)

G1

6698307.50 1631534.88 –183.99

6698422.50 1631917.25 –164.01

6700677.50 1631238.13 –199.56

6700562.50 1630855.75 –219.54

G2

6698307.50 1631541.50 –310.57

6698422.50 1631924.00 –290.56

6700677.50 1631244.75 –326.20

6700562.50 1630862.38 –346.20

G3

6698307.00 1631486.38 –1117.63

6698423.00 1631869.13 –1130.99

6700678.00 1631188.88 –1107.15

6700562.00 1630806.25 –1093.79

G4

6698307.00 1631483.38 –1204.15

6698423.00 1631866.13 –1217.51

6700678.00 1631185.88 –1193.67

6700562.00 1630803.25 –1180.32

Reflectors H1 and H2

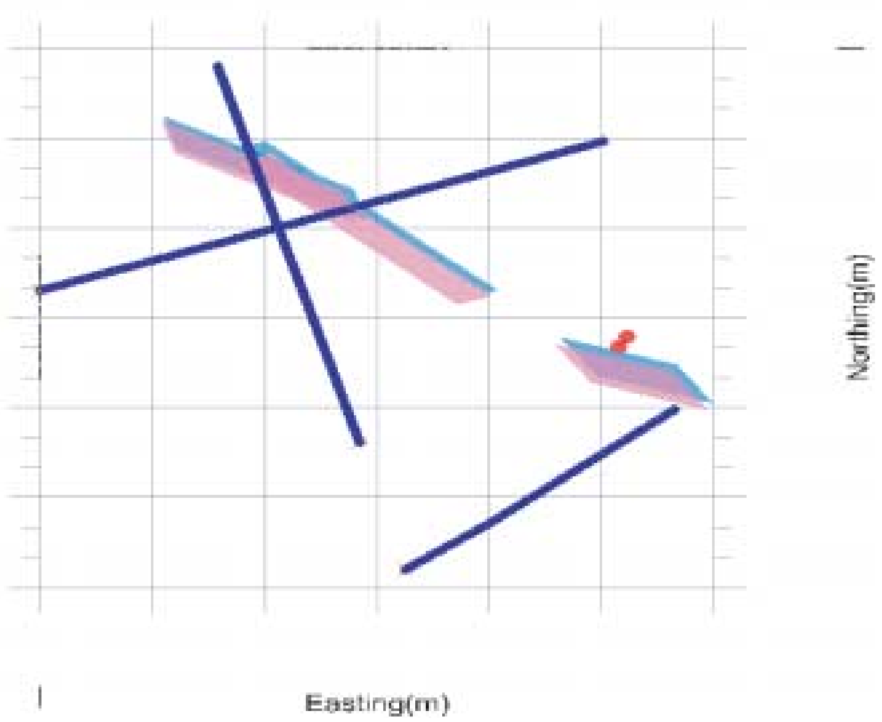

Figure 7-27. *Reflectors H1, H2 – elements from profiles 1, 4 and 2.1. View from up.*

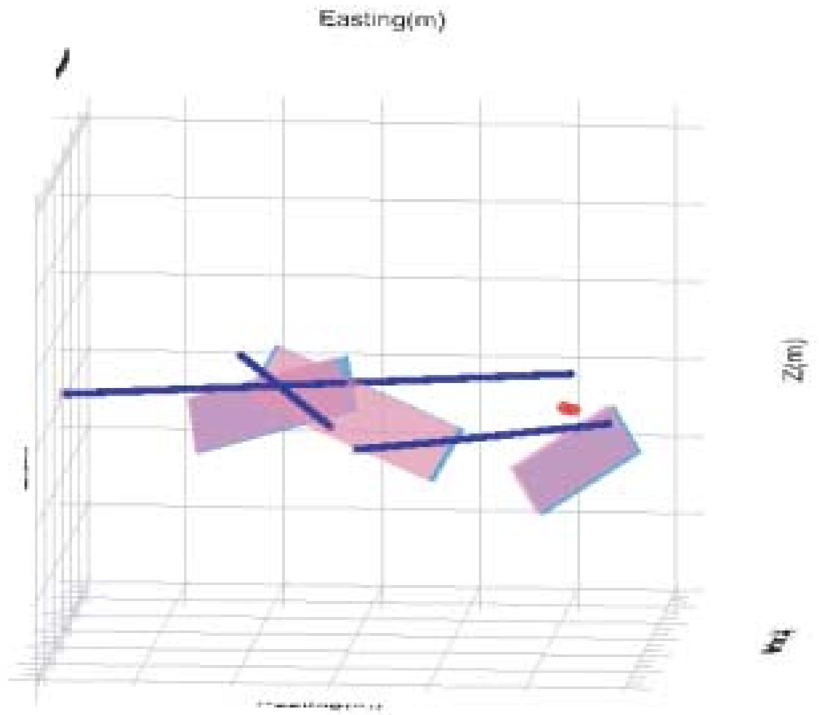

Figure 7-28. *Reflectors H1, H2 – elements from profiles 1, 4 and 2.1. View from W.*

Elements from profile 1

H1

6700108.00 1630784.38 –498.630

6700231.00 1630743.88 –276.170

6700811.50 1632277.75 –317.520

6700688.50 1632318.13 –539.980

H2

6700152.00 1630821.88 –524.470

6700279.00 1630779.88 –296.910

6700830.50 1632342.75 –316.810

6700703.50 1632384.75 –544.370

Elements from profile 2.1

H1

6698775.50 1632750.75 –630.11

6698884.50 1632714.75 –433.20

6699790.00 1634626.88 –584.46

6699681.00 1634662.88 –781.38

H2

6698809.00 1632783.50 –651.77

6698921.00 1632746.50 –451.14

6699810.50 1634709.00 –585.54

6699698.00 1634746.13 –786.17

Elements from profile 4

H1

6699225.50 1632325.88 –227.59

6699187.50 1632200.25 –503.03

6700981.50 1631747.63 –544.05

6701019.50 1631873.25 –268.61

H2

6699265.50 1632359.50 –244.48

6699226.50 1632230.75 –526.53

6701054.00 1631727.63 –549.11

6701093.00 1631856.38 –267.06

Reflector I1

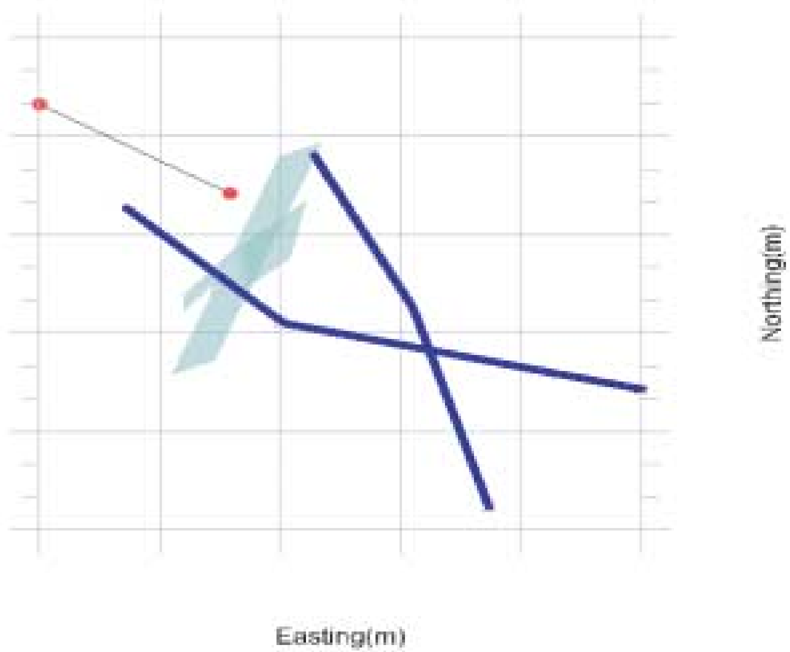

***Figure 7-29**. Reflector I1, H2 – elements from profiles 5.1, 5.2 and 3. View from up.*

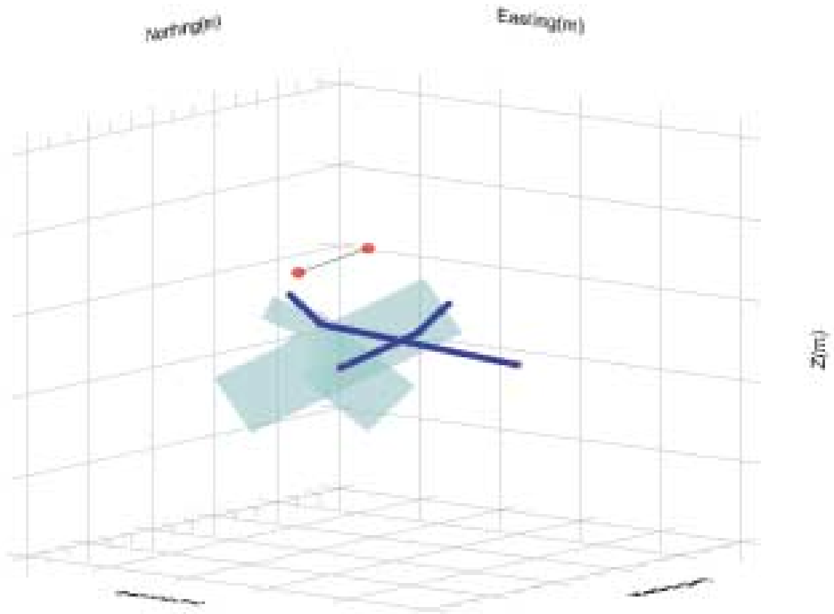

Figure 7-30. *Reflector I1, H2 – elements from profiles 5.1, 5.2 and 3. View from SW.*

Element from profile 3

6697643.50 1633763.25 –700.86

6697567.50 1633575.38 –356.02

6698721.50 1634041.13 152.36

6698797.50 1634229.00 –192.48

Element from profile 5.1

6698497.00 1634162.38 –489.86

6698193.50 1634092.88 –741.04

6697873.50 1633714.63 –249.39

6698176.50 1633784.25 1.79

Element from profile 5.2

6698063.50 1633773.88 –150.30

6697994.50 1633712.50 –97.97

6698359.00 1633243.75 –167.65

6698428.00 1633305.25 –219.99

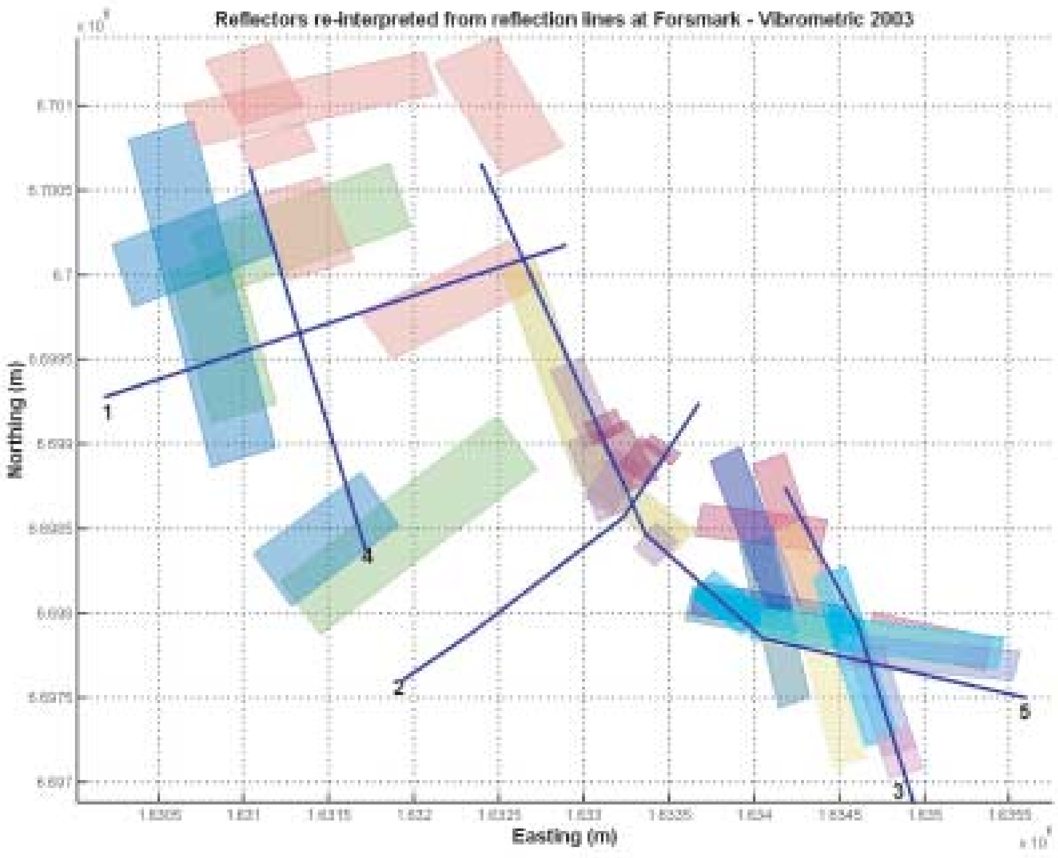

__Figure 7-31__. Synopsis of all reflectors reinterpreted. View from up.

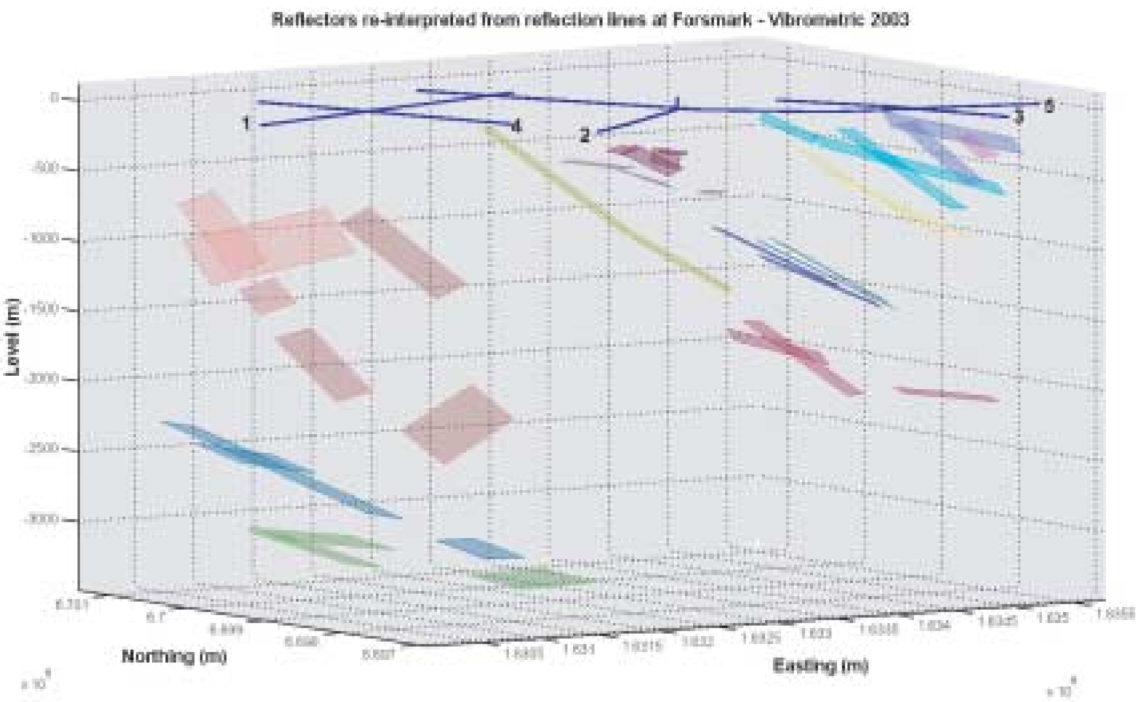

__Figure 7-32__. Synopsis of all reflectors reinterpreted. View from SW.

8 Discussion and conclusions

The reinterpretation of the seismic data collected in the spring of 2002 in the Forsmark area confirms that the bedrock has been imaged down to depths of at least 3 km. The data quality in general and the frequency content in particular seem to allow a good resolution in identifying and discriminating reflection events *in the time domain*.

The main difficulty resides nonetheless in determining reliably the actual 3D positions and orientations of the reflector imaged with the relatively sparse investigation layout used. If a dense survey grid on the surface were used, it would be possible to apply 3D migration procedures, which would in principle provide the locations and orientations of outstanding reflectors directly by stacking the data. The work volume to acquire and process a full 3D seismic data set would however be in a completely different class of magnitude, compared with the investigation strategy followed so far, and even so 3D seismics would not solve all problems related to the imaging of crystalline rock, e.g. imaging steeply inclined features.

With the sparse array at hand, the summation from the 3D migration approach is replaced by a voting principle. That implies that a given reflector is recognized as one and the same in several profiles and a geometrical match is sought amongst the classes of solutions fitting all events identified as belonging to the same reflector. Difficulties can arise when several combinations of events produce viable solutions. This is where the voting comes in.

Let it also be noted that selecting an event to form a geometrical solution makes it ineligible for alternative solutions, which raises the problem to the level of a complex combinatory approach.

Our objective with the present exercise has been to investigate viable geometrical solutions for 3D reflector positions in the vicinity of the initial guesses proposed in the SKB Report R-02-43. We ventured further from the original orientation proposed only when no group of events could be found to support it and a different grouping made more sense, as for example with the D reflector set. It is probable but however not certain that the solutions found reflect the reality in all cases. It is therefore strongly recommendable that a mathematically sound ‘objective’ approach is used. Clustering analysis and self-organizing-map methods seem to be adequate instruments for this endeavor. The Crux Point method used in this exercise would make the task more tractable, as it is easier to operate with clusters of points than with clusters of planes tangent to conical surfaces.

The task of the statistical methods mentioned above would be greatly alleviated if data could also be collected in depth, closer to the features imaged and thus producing more local but more certain inputs to the statistics. This comes in support of performing VSP surveys in the site boreholes, as they become available.

The VSP investigations would also solve another problem, which has not yet been mentioned. The discussion has so far been focused on geometrical non-determination. To get to the geometry one has however to possess an accurate velocity model in depth, at a comparable experimental scale with surface seismics. This model would more accurately be produced by VSP than e.g. by acoustic logging.

Last but by no means least regarding VSP, the dip range of the reflectors that can be imaged by surface seismics is limited and it is symptomatic that all reflectors reported in R-02-43 have relatively shallow dips, exception made for the original D, H, and I sets, which have not been confirmed anyway. Is there really no reflector at Forsmark dipping more than 45°? This is a potentially interesting question that could be answered by VSP. Moreover, steep reflectors are more difficultly interceptable by drilling, which makes direct probing a not so good alternative.

A fairly simple method has been used here to convert the DMO representation to spatial. This method deals only with a small subset of preselected events. It has briefly been stated above that a full 3D migration approach may not solve all problems of a crystalline site, in spite of the high cost. However, limited aperture migration, once the orientations of the major site features are defined, may lead to the identification of other, less outstanding features. Migration could be performed in 3D, but only around directions found as dominant at the site. This could be done for both surface and VSP data and the sparseness of the survey arrays would not be an impediment in the limited aperture case.

Appendix A

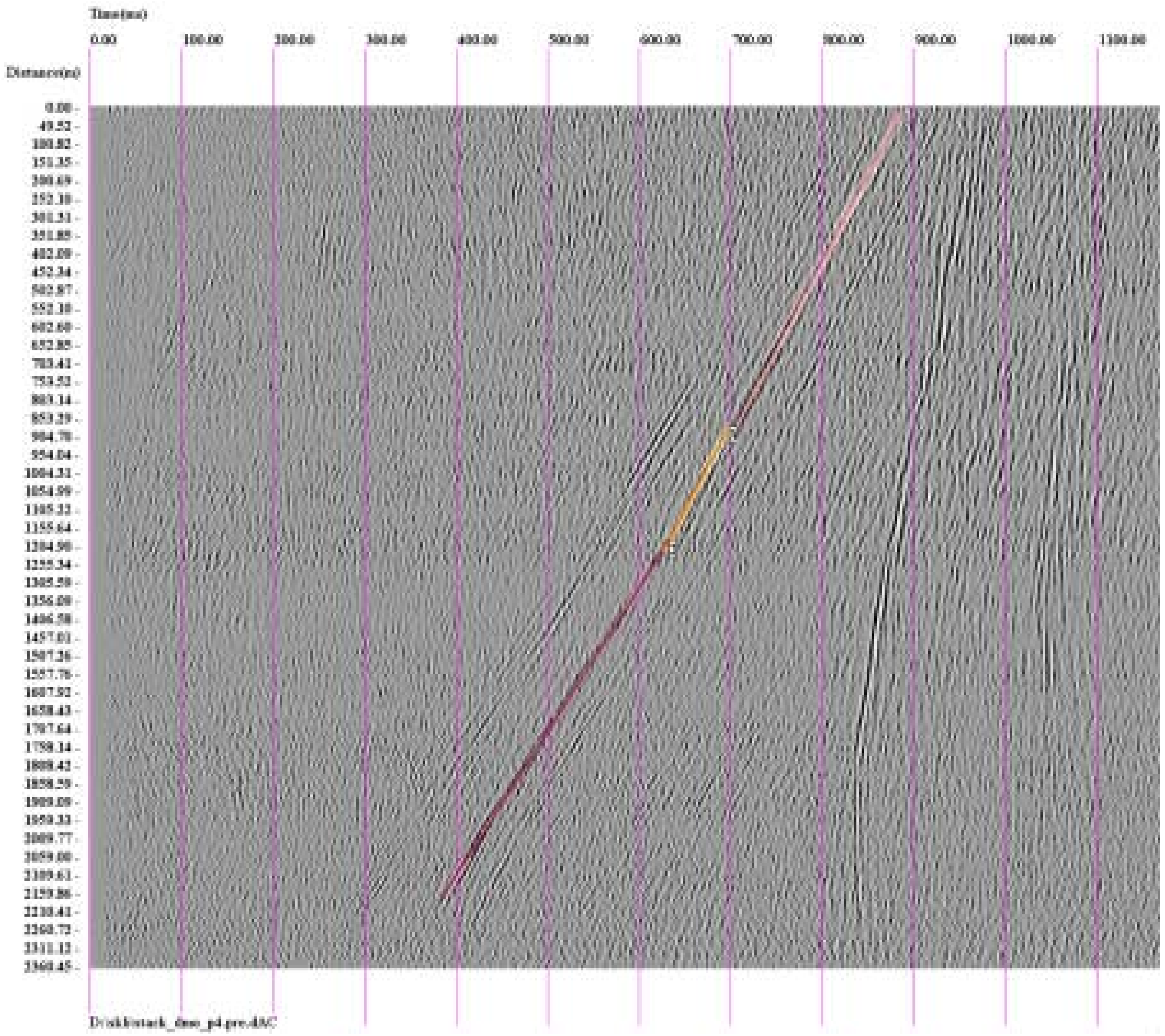

Figure A1-1. *Profile 4*
Reflector group A1
1 – pink dip = 39, strike = 81
2 – brown dip = 50, strike = 81
3 – orange dip = 45, strike = 81

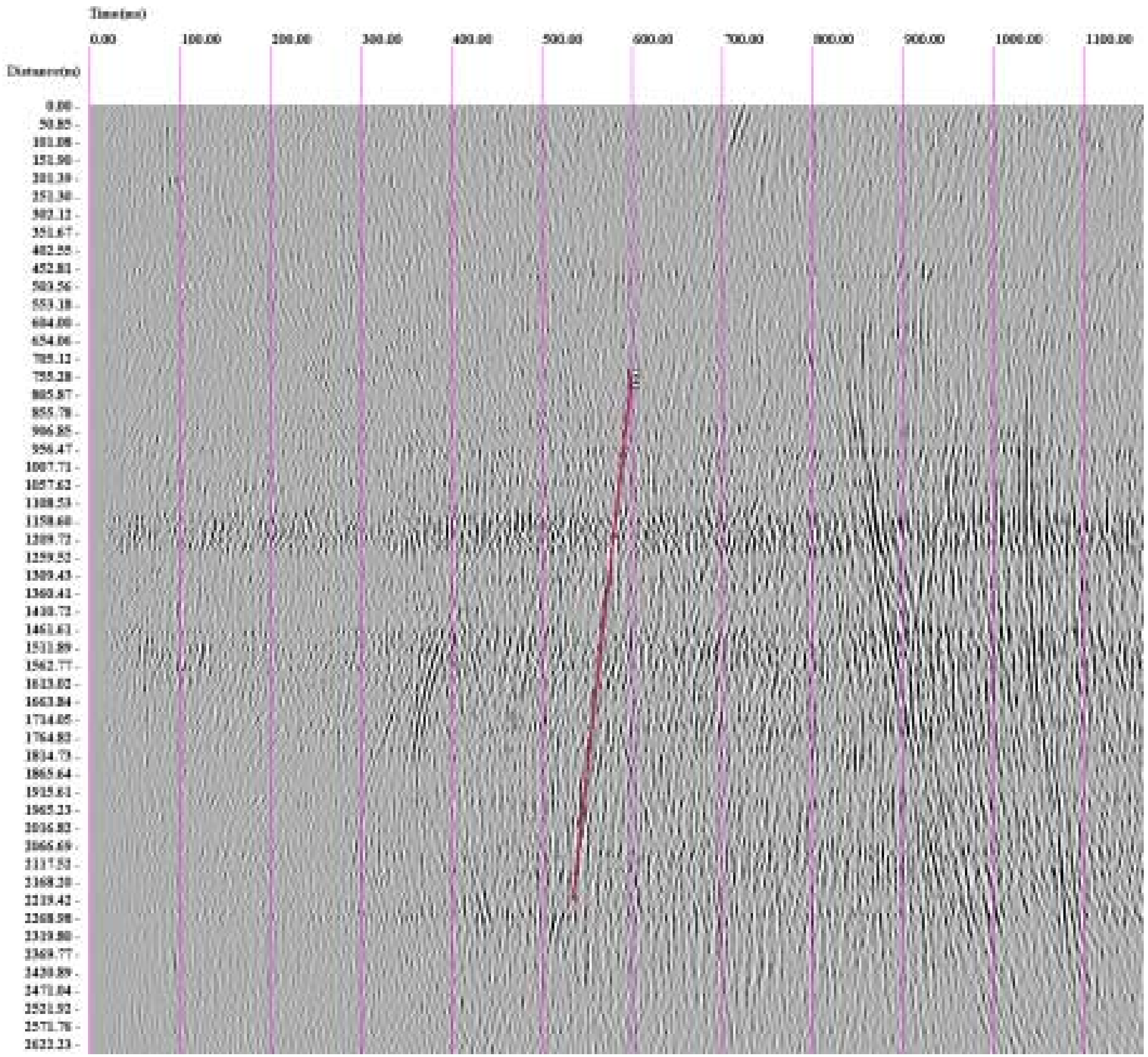

Figure A1-2. *Profile 1*
Reflector A1
dip = 50, strike = 81

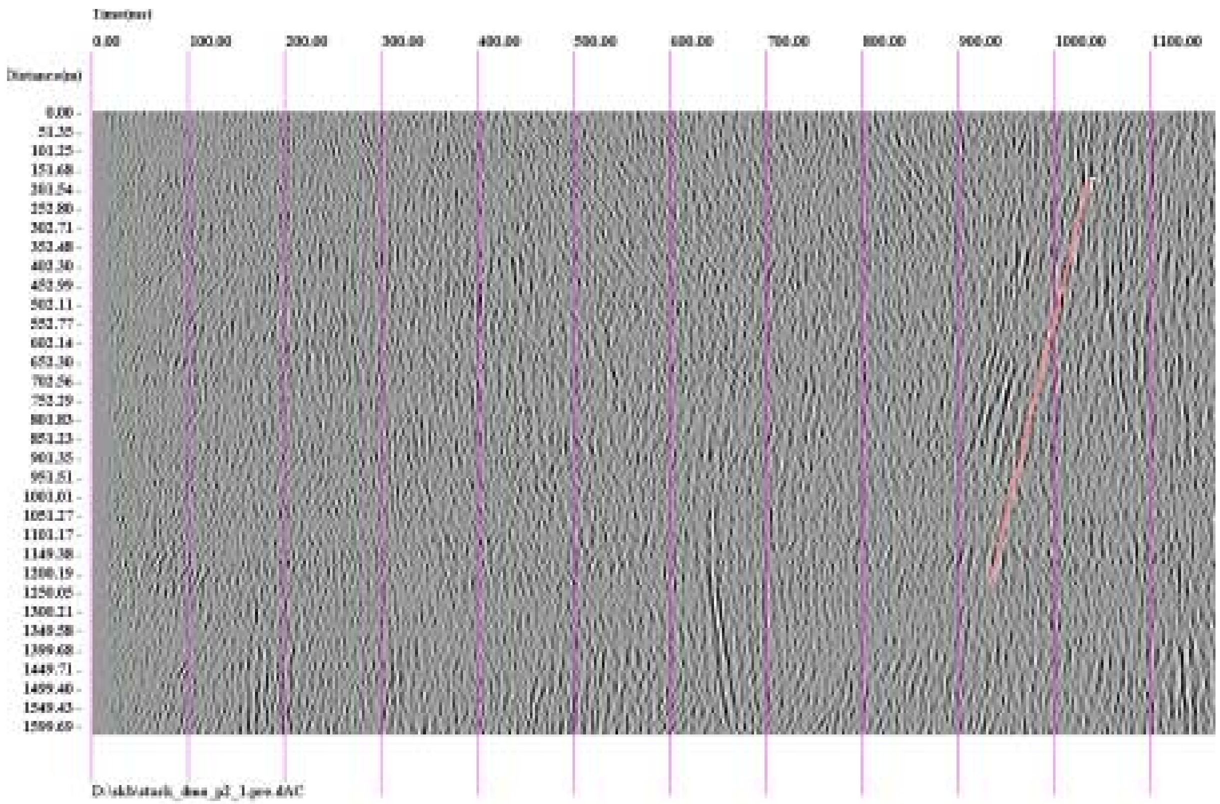

Figure A1-3. *Profile 2.1*
Reflector A1
dip = 39, strike = 81

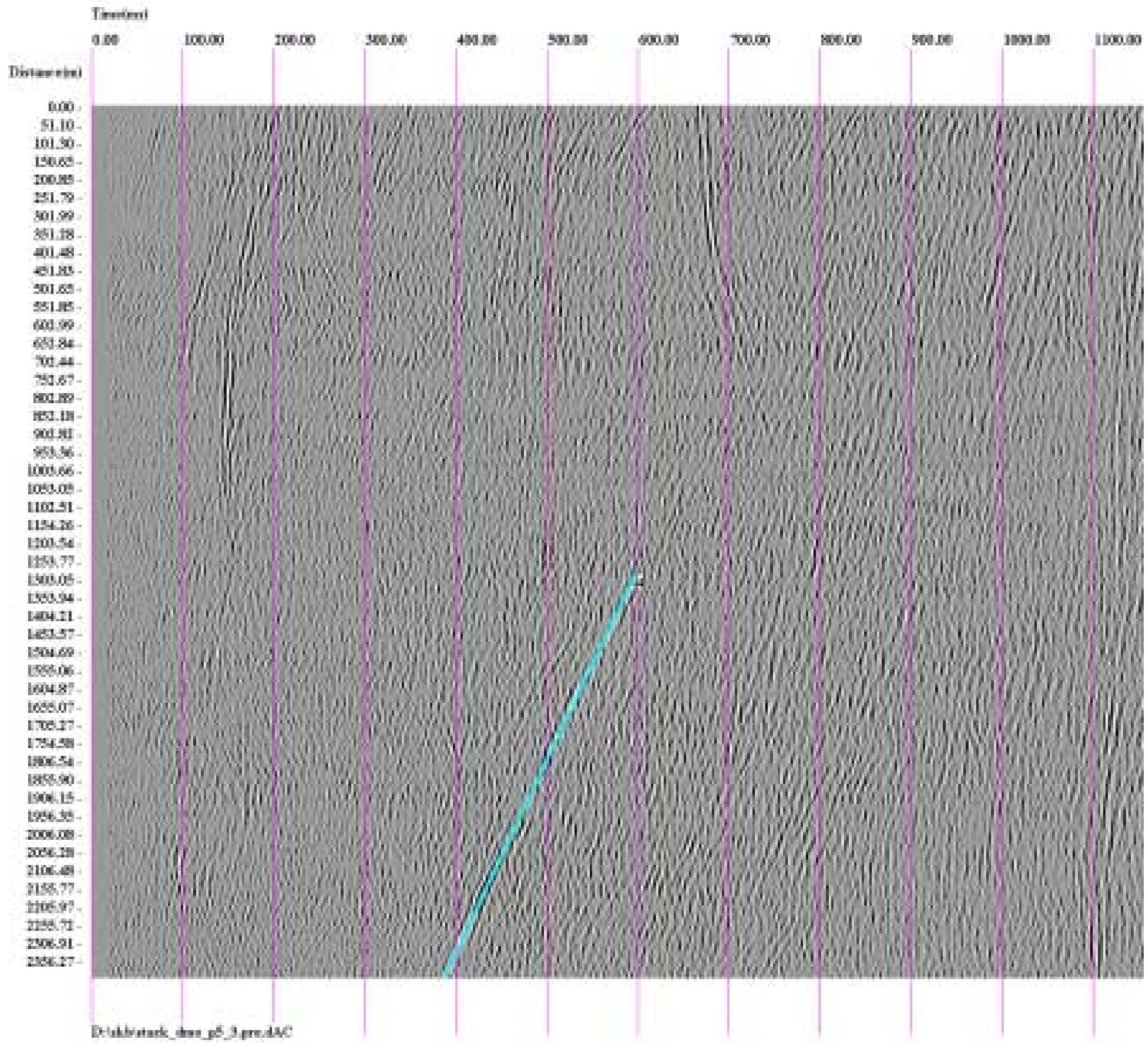

Figure A1-4. *Profile 5.3*
Reflector A1
dip = 36, strike =81

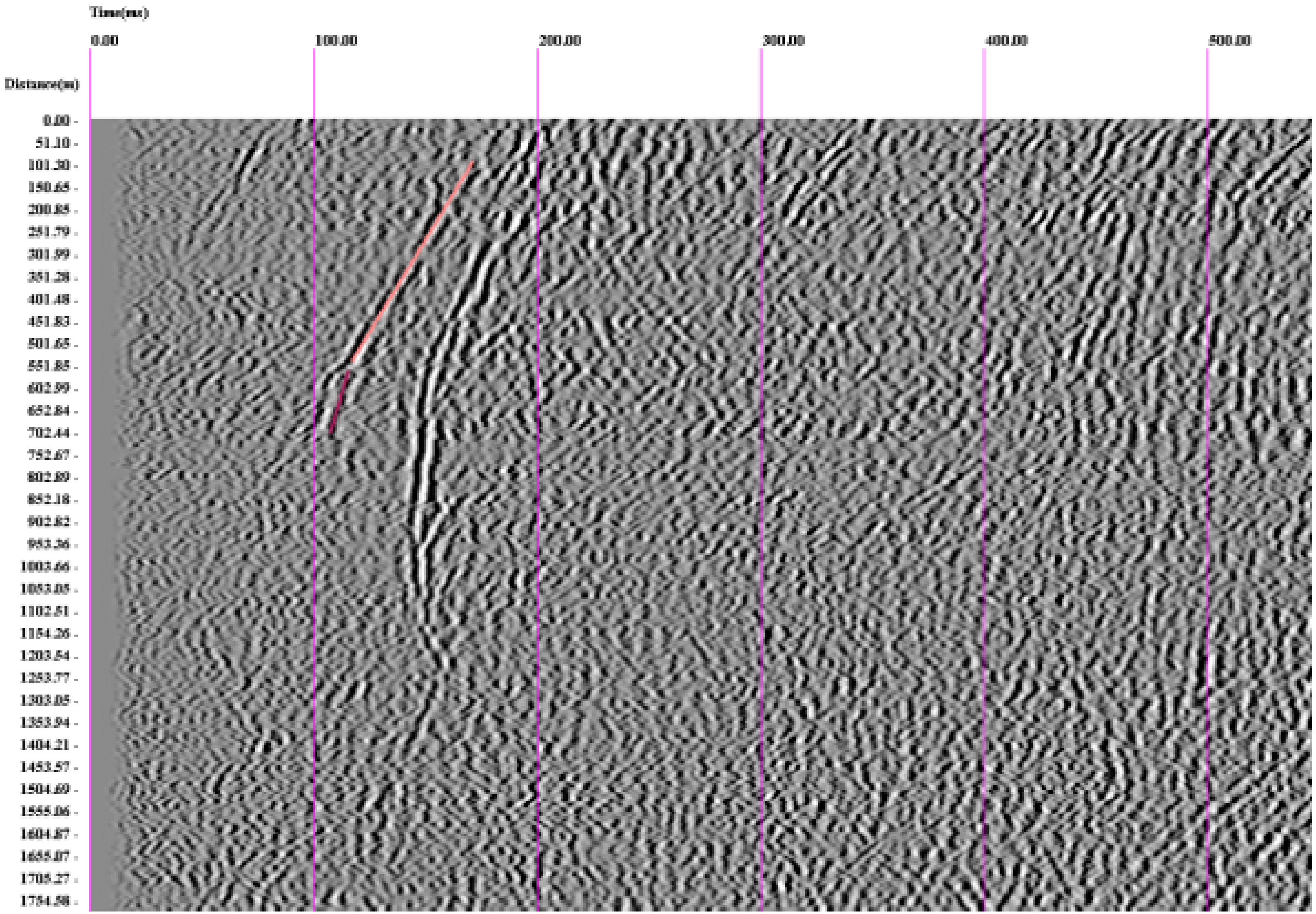

Figure A1-5. *Profile 5.3*
Reflector group A2
Pink: dip = 24, strike = 94
Brown: dip = 12, strike = 98

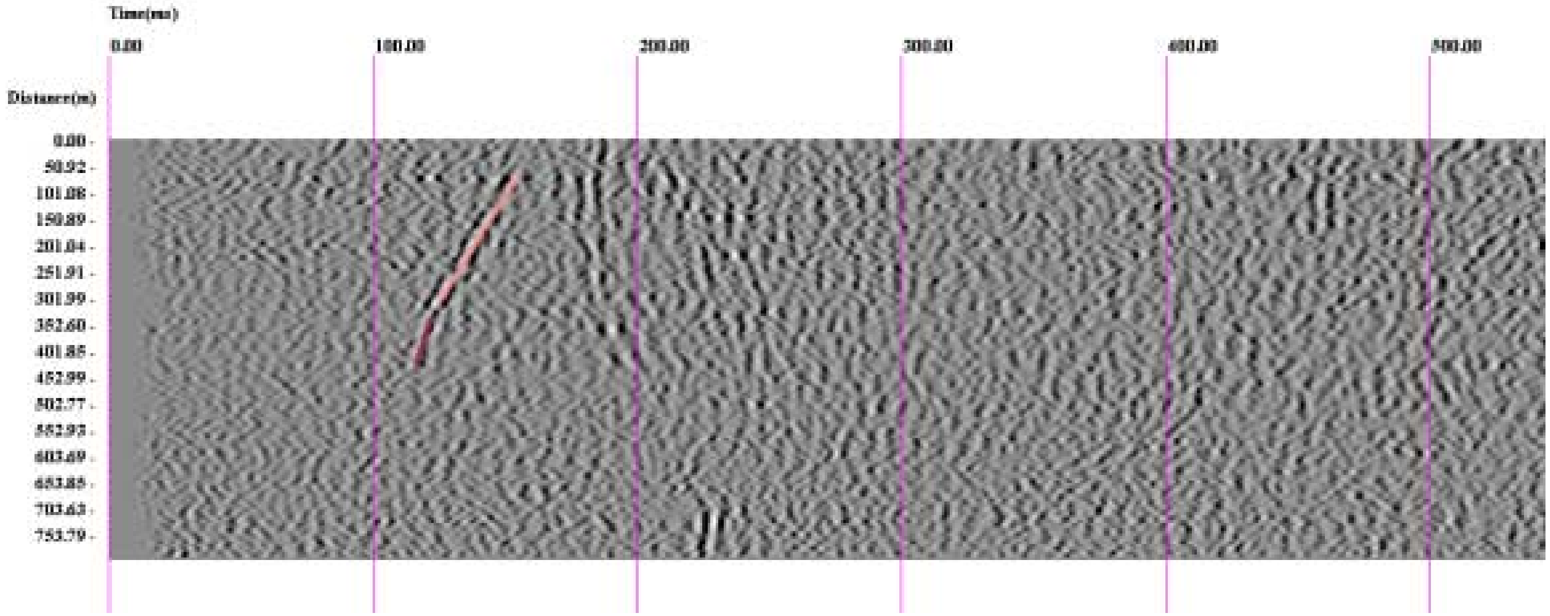

Figure A1-6. *Profile 2.2*
Reflector group A2
pink – dip = 24.7, strike = 94
brown – dip = 12, strike = 98

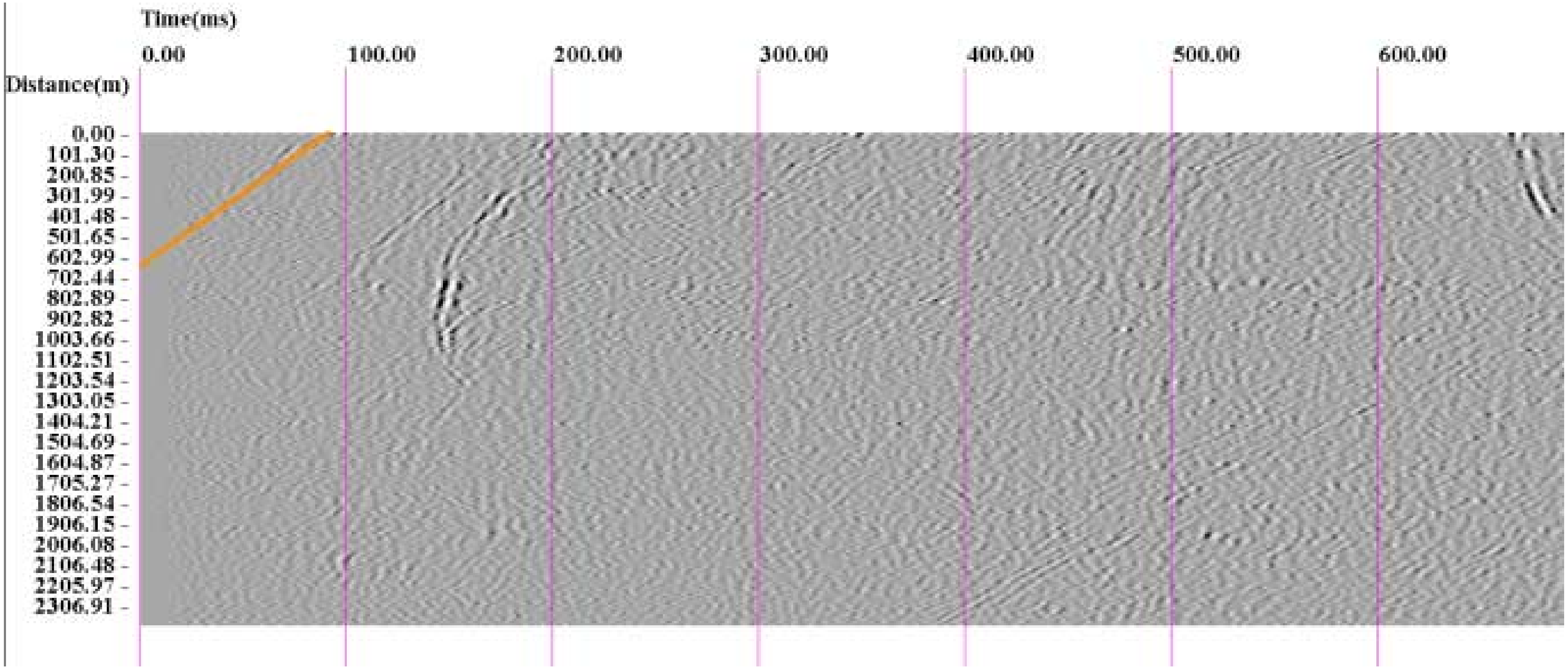

Figure A1-7. *Profile 5.3*
dip = 25, strike = 65

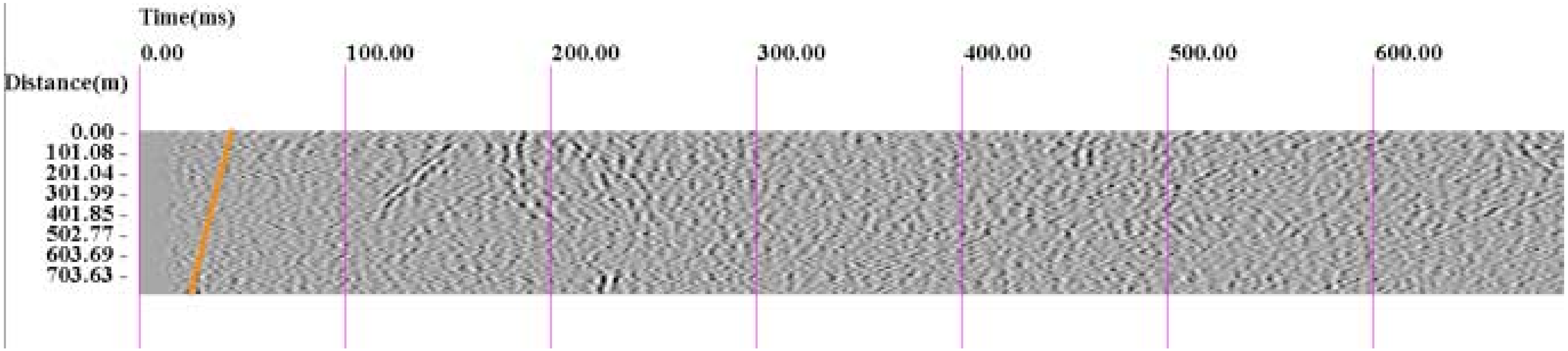

Figure A1-8. *Profile 2.2*
dip = 21, strike = 45

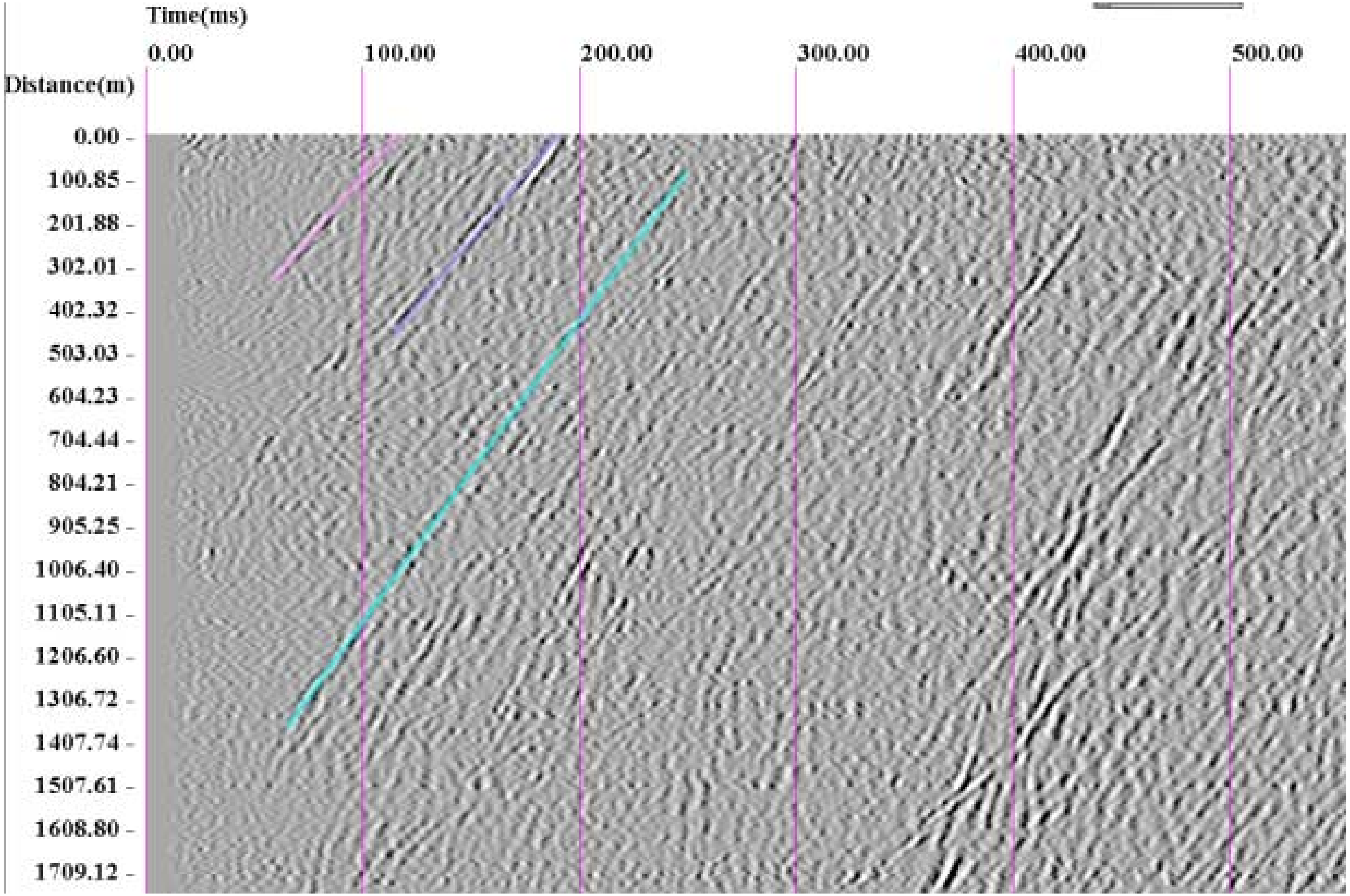

Figure A1-9. *Profile 3*
Reflectors A4, A5, A6
A4 light blue – dip = 25, strike = 60
Reflector A5 – blue: dip = 32, strike = 75
Reflector A6 – pink: dip = 30, strike = 75

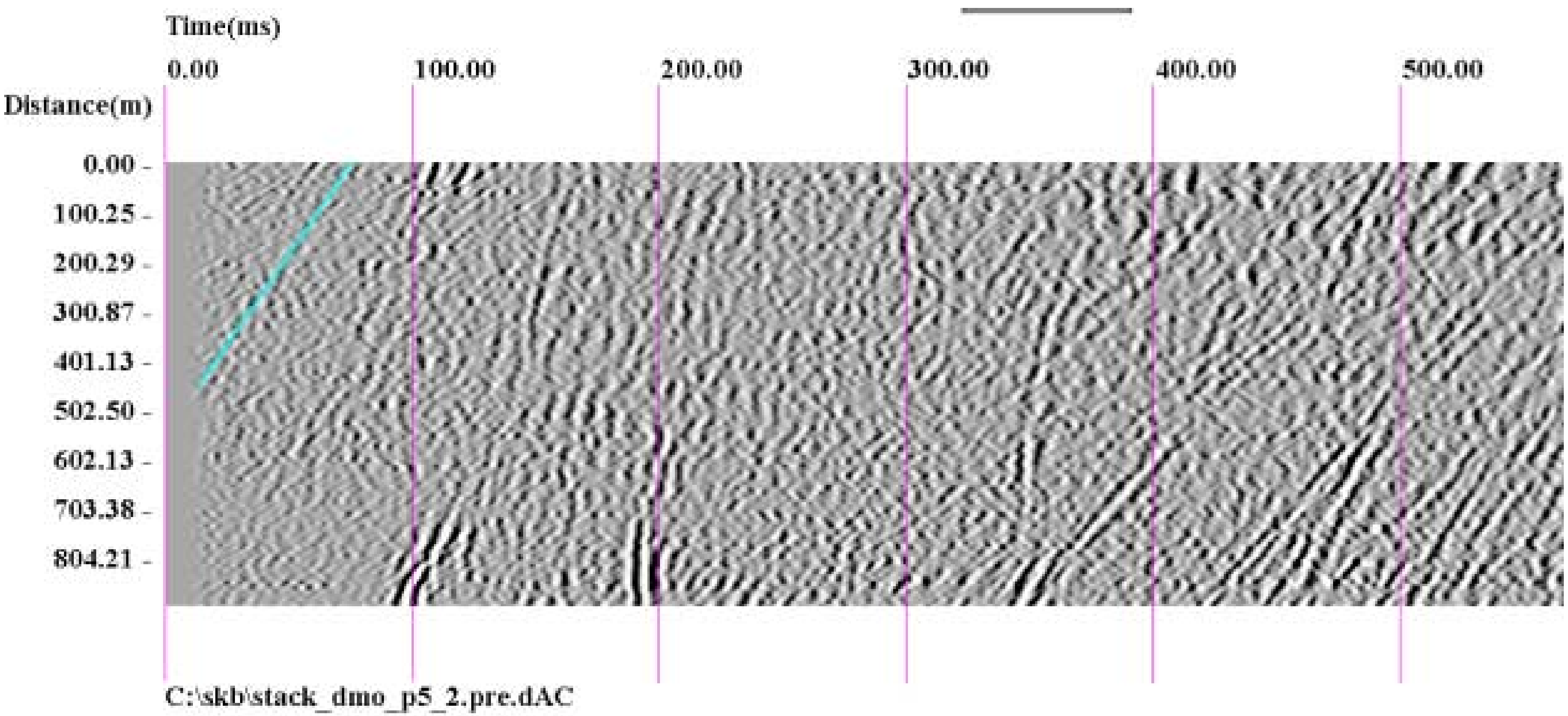

Figure A1-10. *Profile 5.2*
Reflector A4 (weak, but visible)
dip = 25, strike = 60

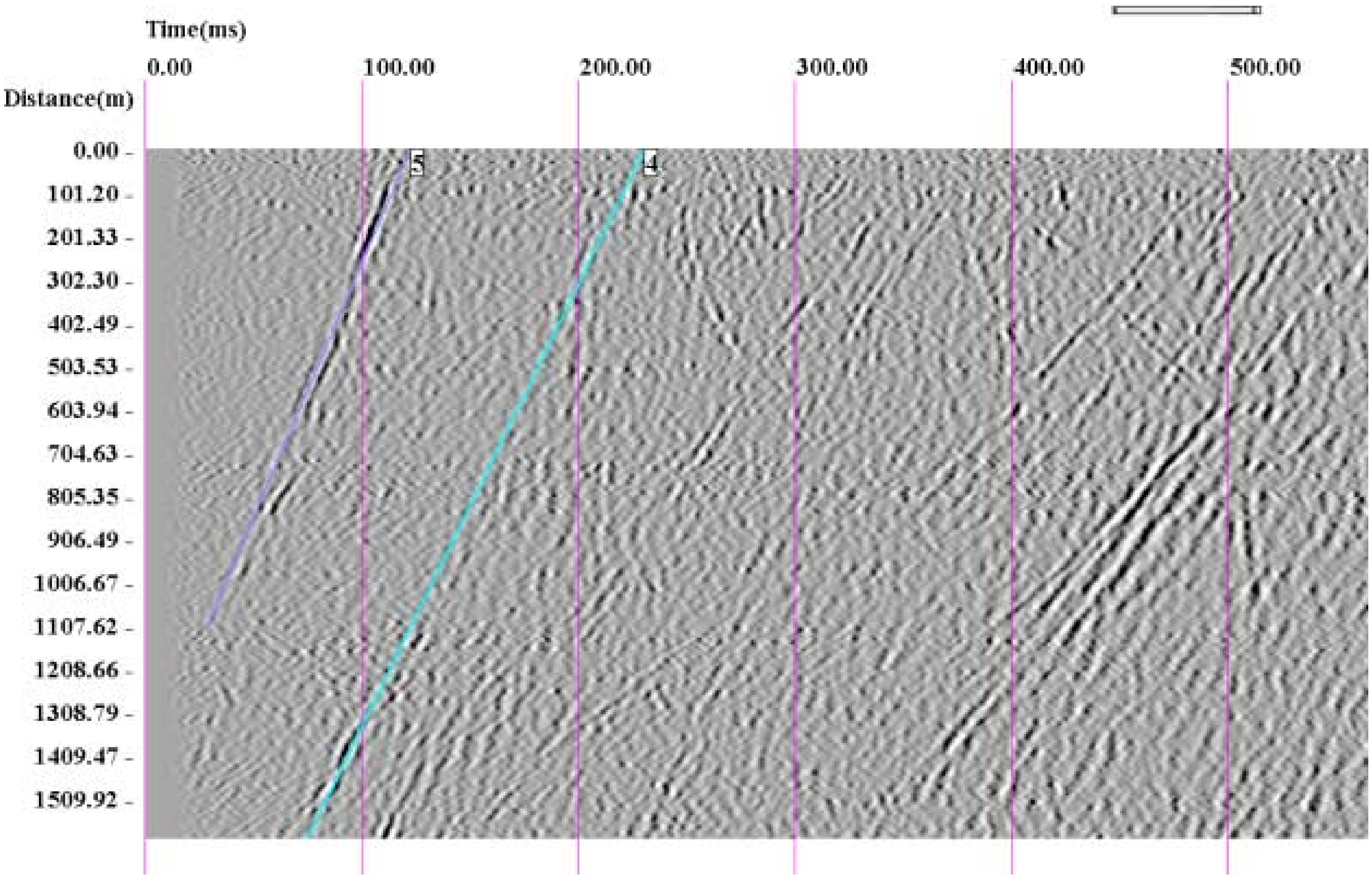

Figure A1-11. *Profile 5.1*
A4 – light blue: dip = 25, strike = 60
A5 – blue: dip = 32, strike = 75

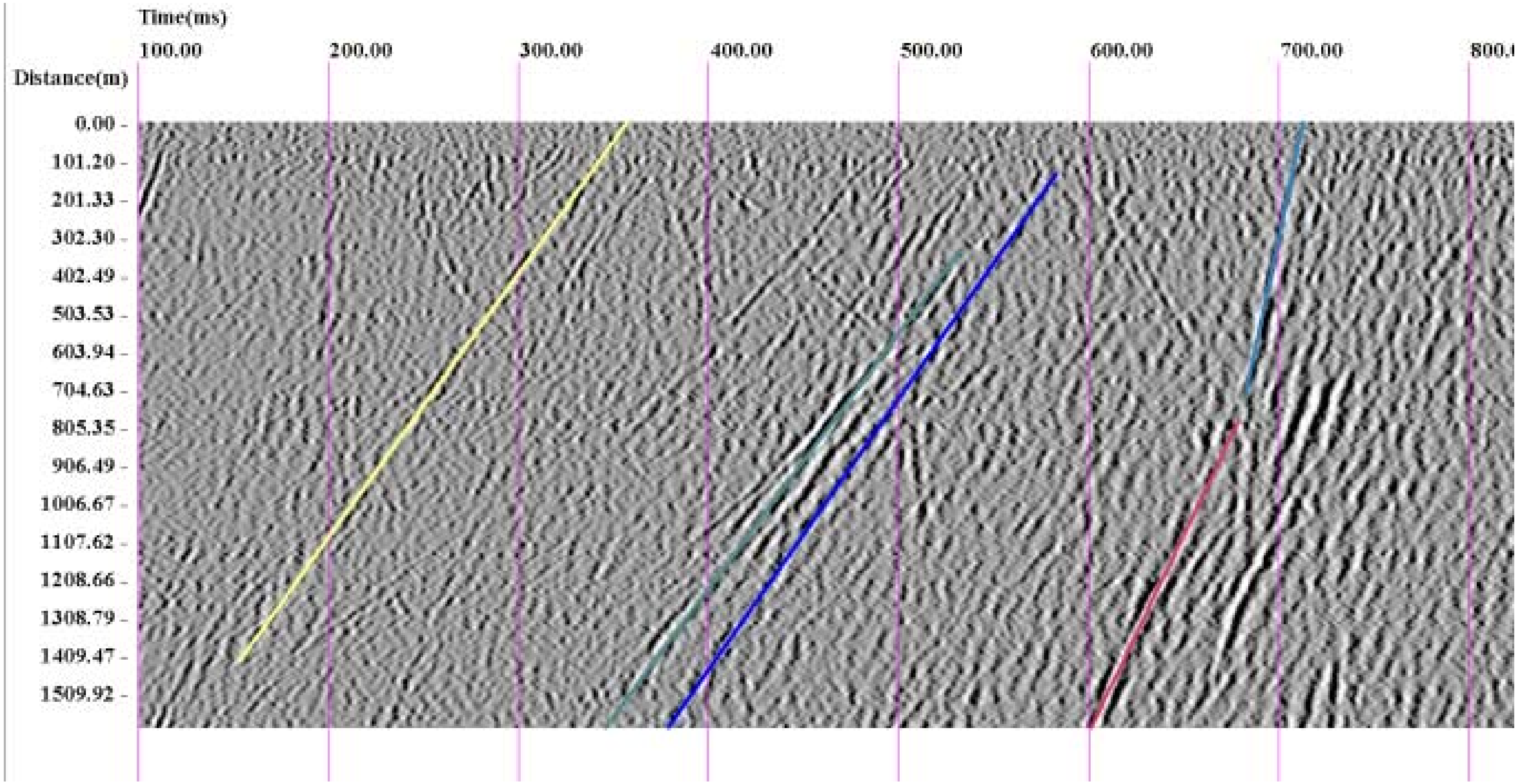

Figure A1-12. *Profile 5.1*
Reflector B1– yellow: dip = 27, strike = 32
Reflector B2 – dark green dip = 27, strike = 25
Reflector B3 – sharp blue: dip = 24, strike= 30
Reflector group B5 blue: dip 9, strike 50; brown: dip 25, strike 60

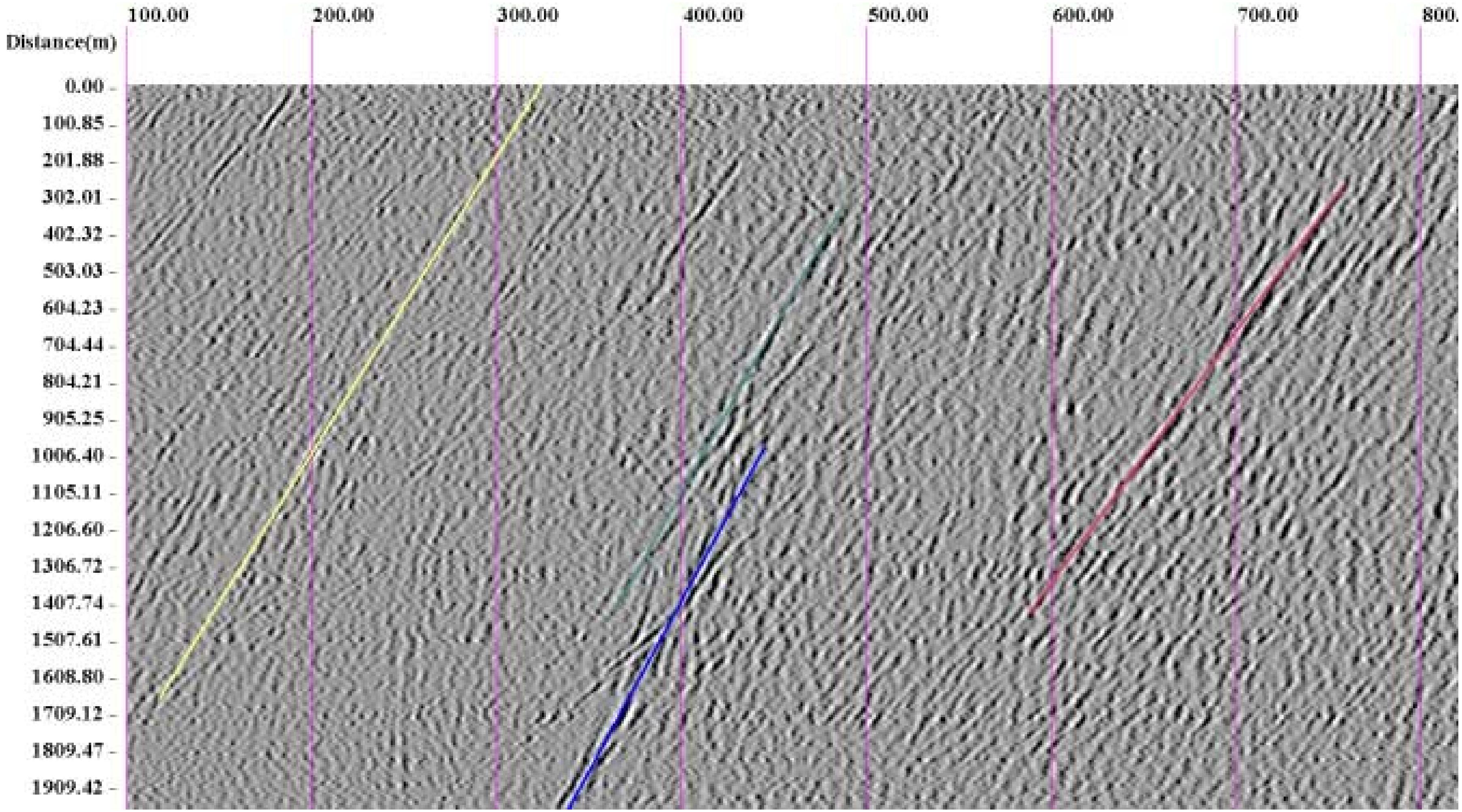

Figure A1-13. *Profile 3*
B1– yellow: dip 27, strike 32
B2 – dark green dip 27, strike 25
B3 – sharp blue: dip 24, strike 30
B5 – brown: dip 25, strike 60

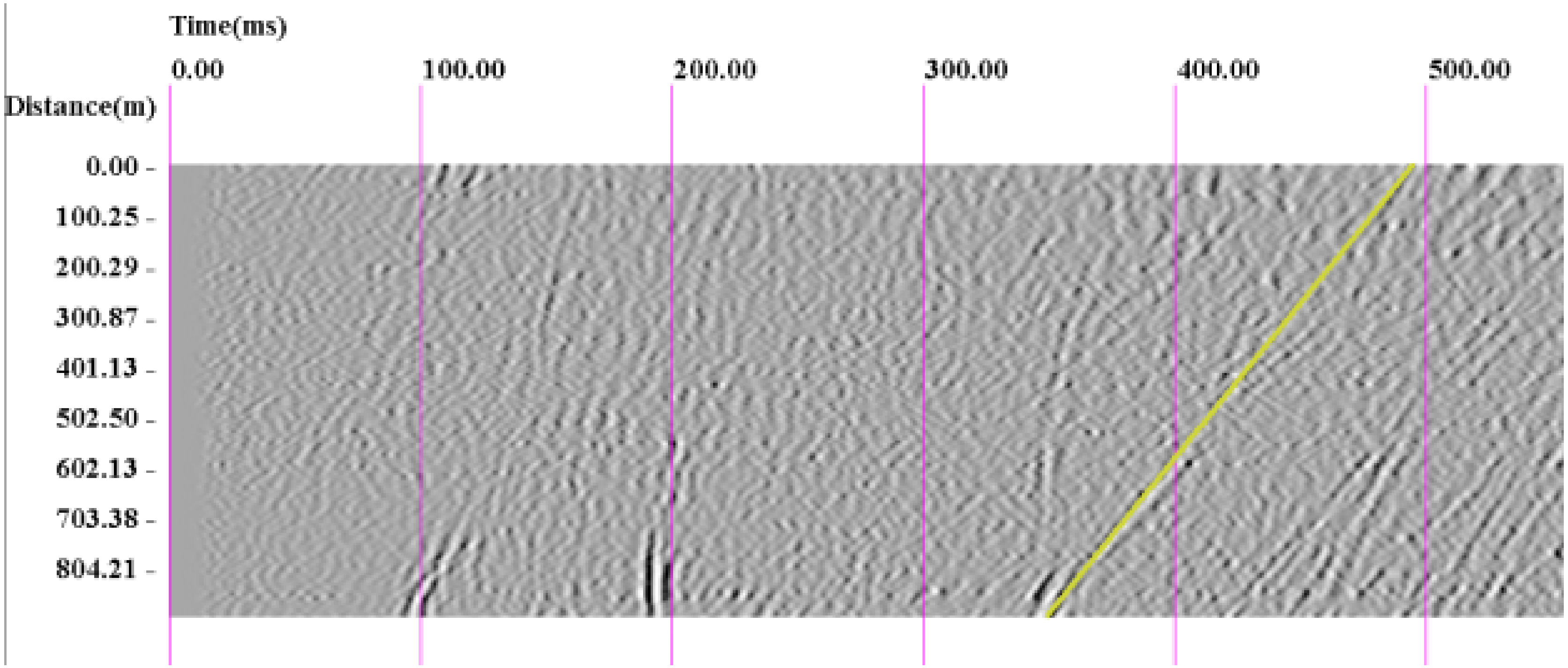

Figure A1-14. *Profile 5.2*
Reflector B4 dip= 30, strike = 50

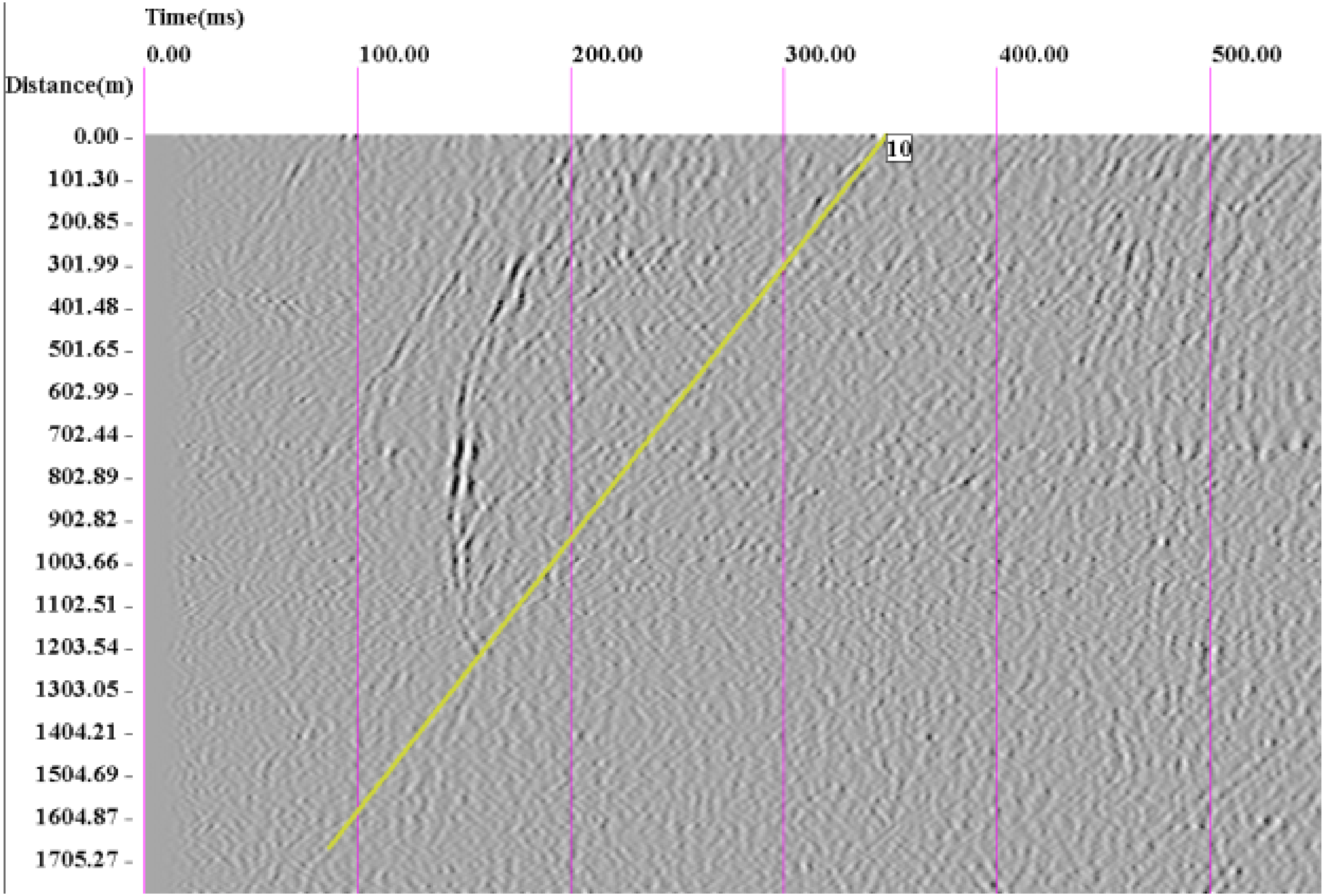

Figure A1-15. *Profile 5.3*
Reflector B4: dip= 30, strike = 50

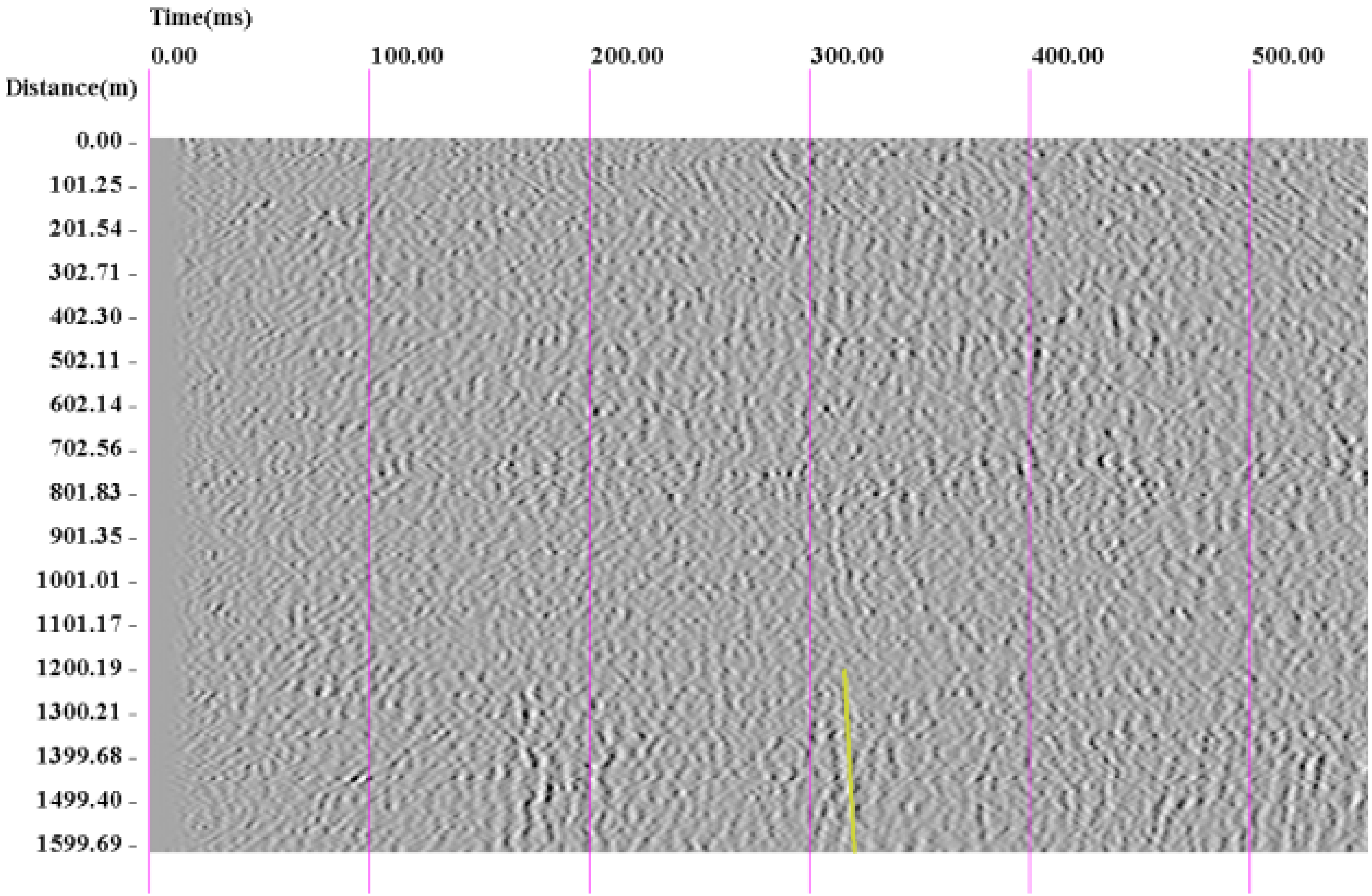

Figure A1-16. *Profile 2.1*
Reflector B4: dip= 30, strike = 50

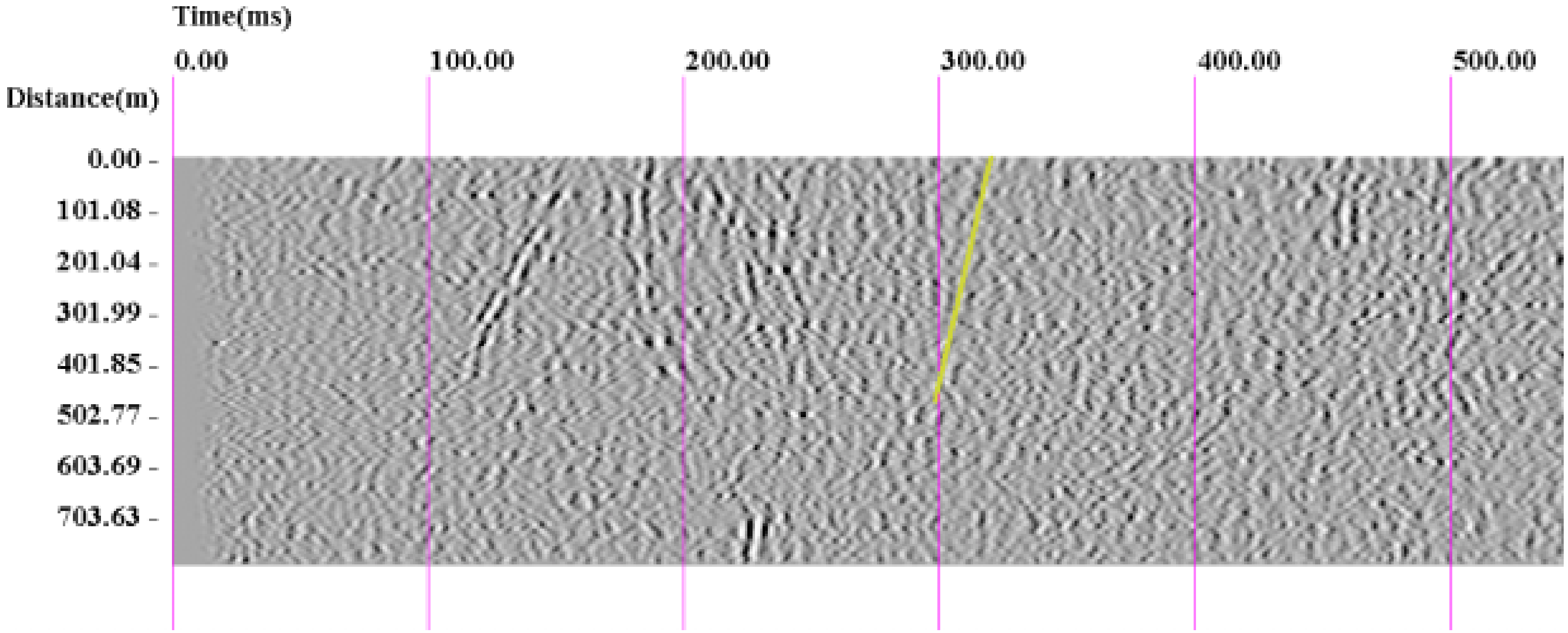

Figure A1-17. *Profile 2.2*
Reflector B4: dip= 30, strike = 50

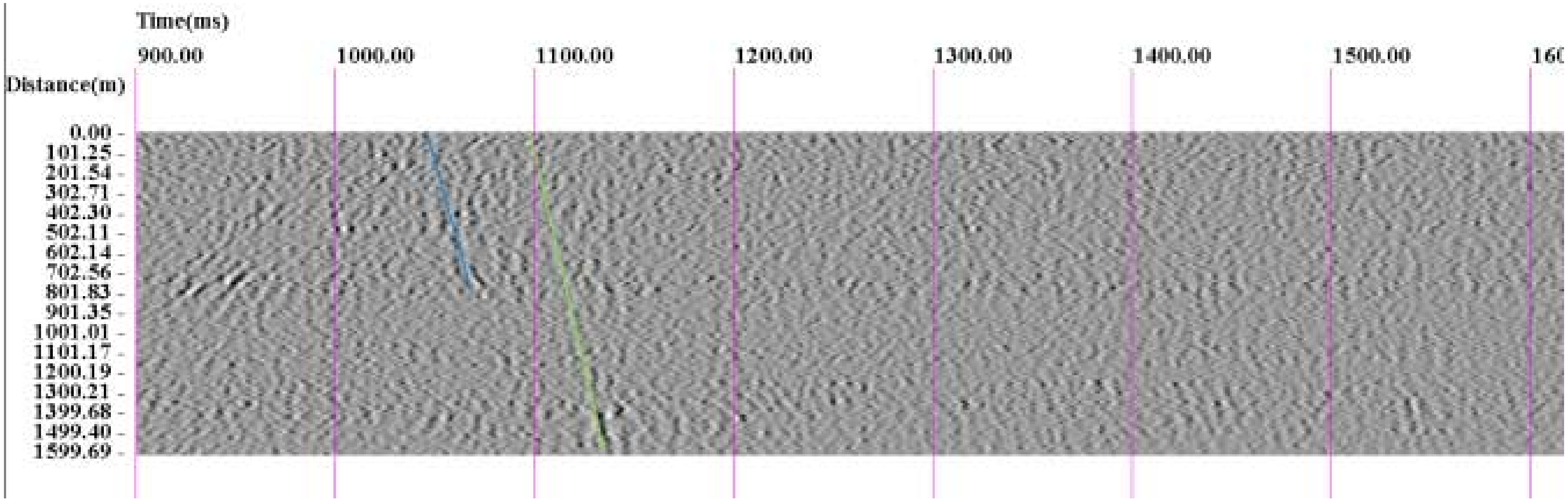

Figure A1-18. *Profile 2.1*
blue: C1 – dip 18 strike 37
green: C2 – dip 13 strike 35

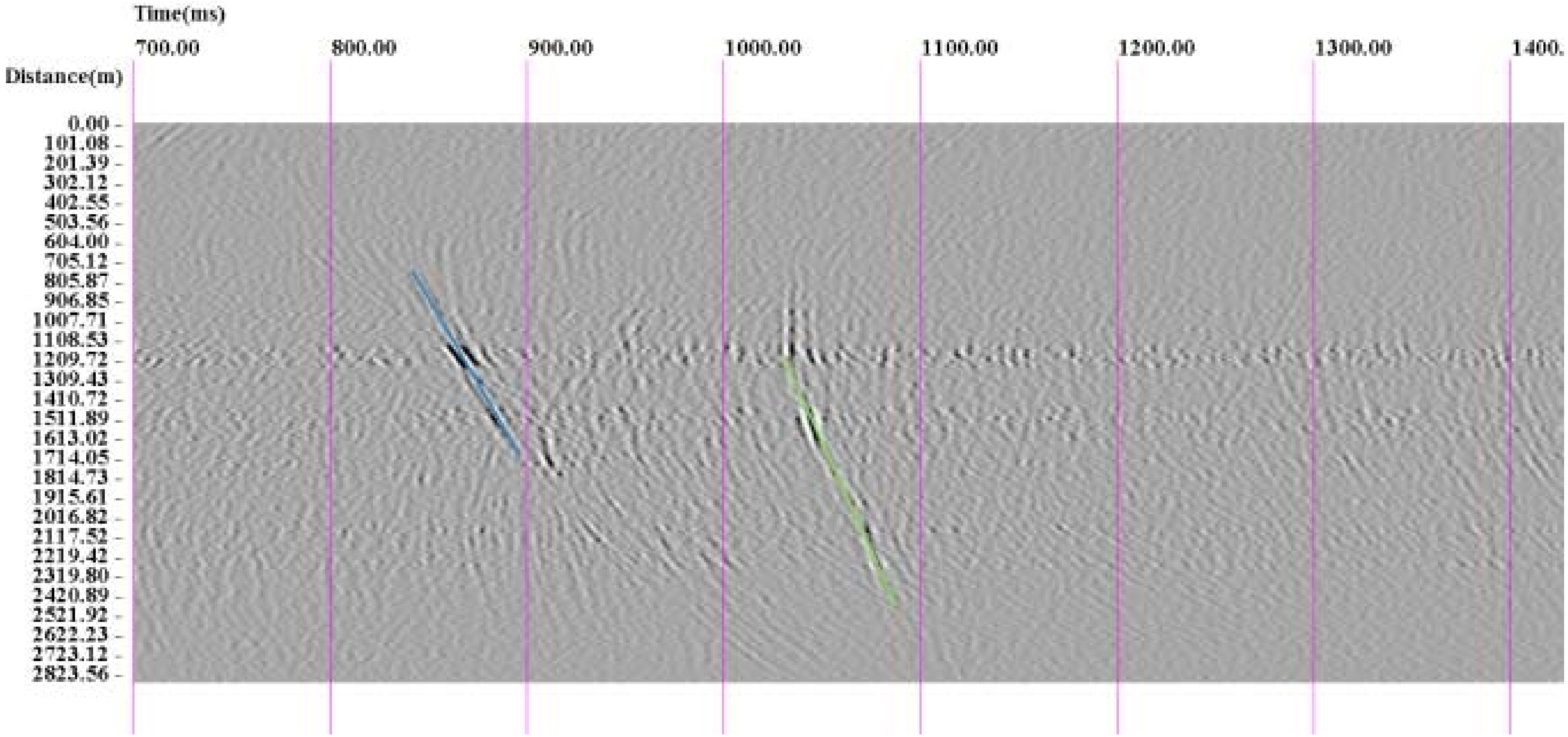

Figure A1-19. *Profile 1*
blue: C1 –dip 18 strike 37
green: C2 – dip 13 strike 35

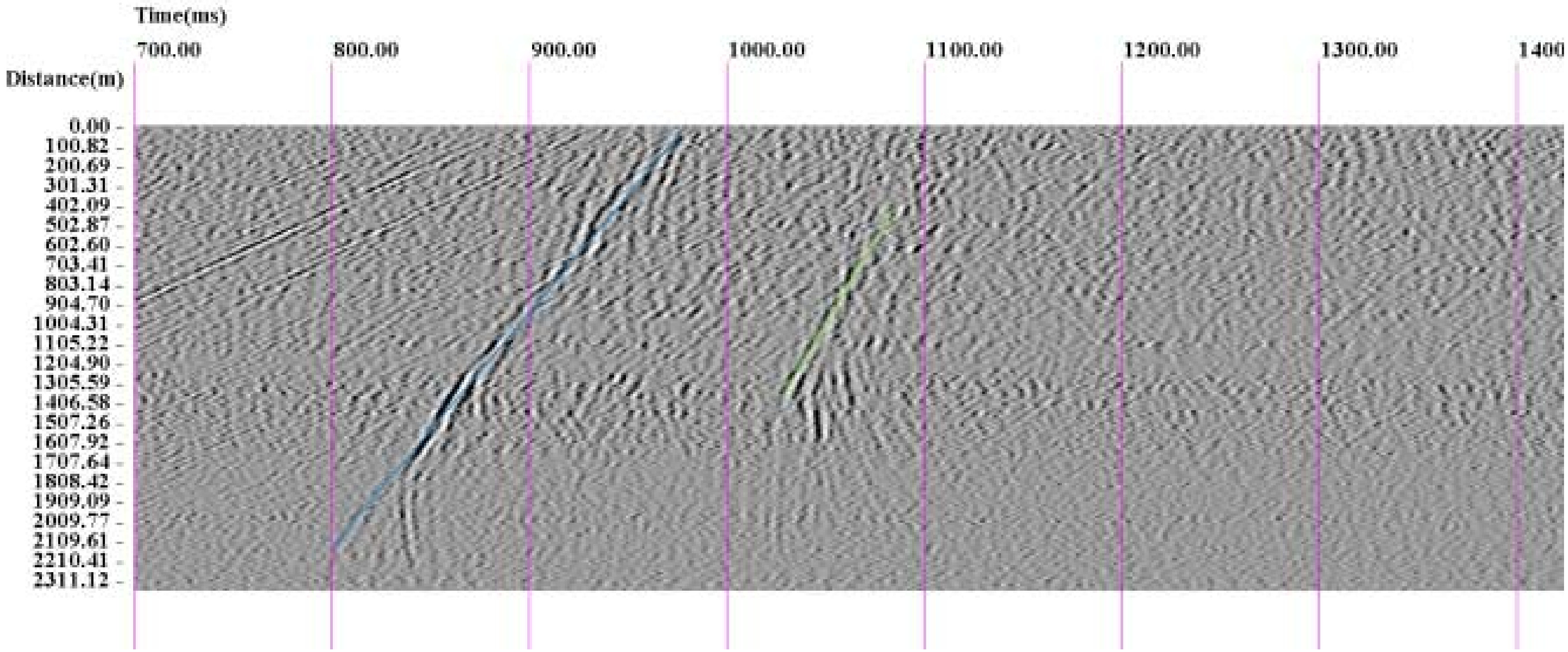

Figure A1-20. *Profile 4*
blue: C1 – dip 18 strike 37,
green: C2 – dip 13 strike 35

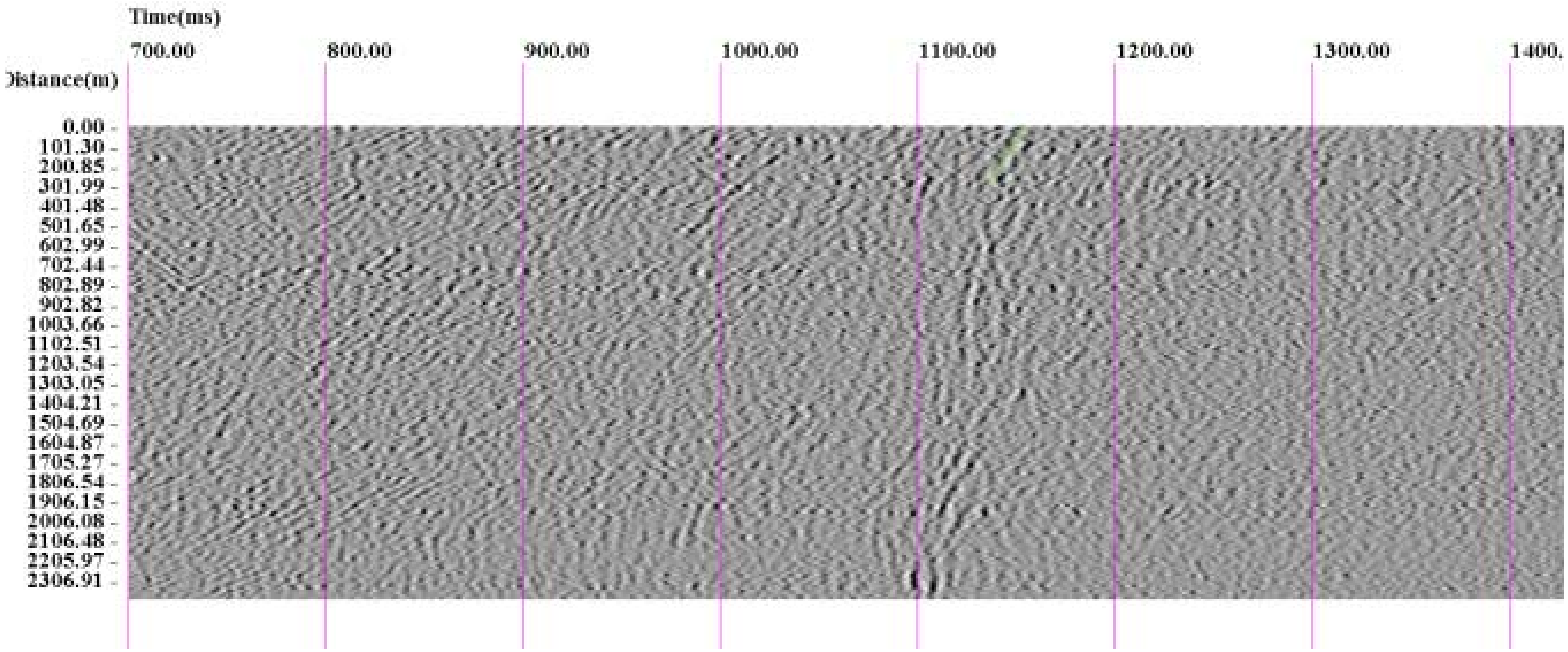

Figure A1-21. *Profile 5.3*
green: C2 – dip 13 strike 35

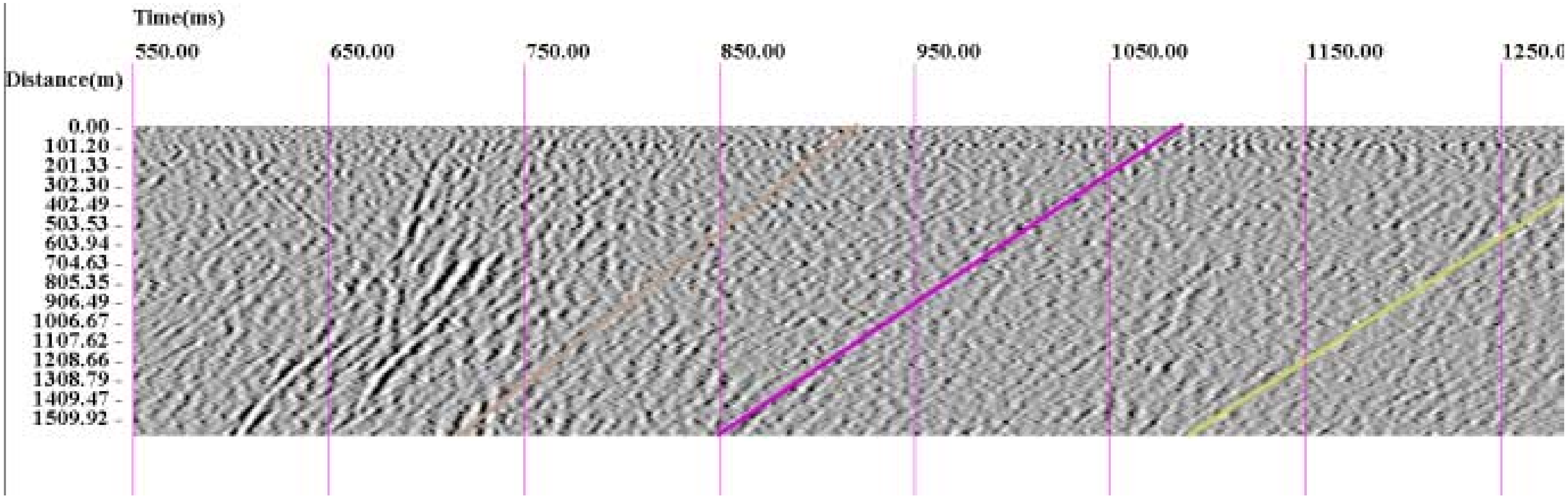

Figure A1-22. *Profile 5.1*
Alternative to D1, D2, D3 reflectors
Brown: dip 35, strike 62
Violet: dip 30, strike 40
Yellow: dip 27, strike 37

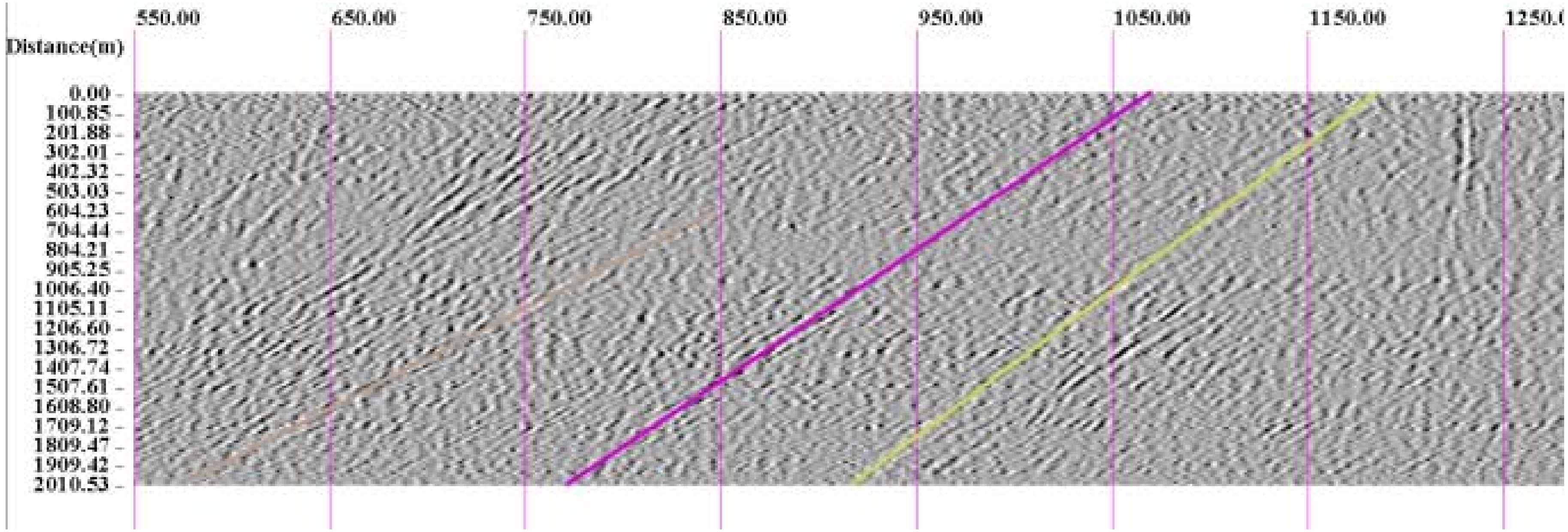

Figure A1-23. *Profile 3*
Alternative to D1, D2, D3 reflectors
Brown: dip 35, strike 62
Violet: dip 30, strike 40
Yellow: dip 27, strike 37

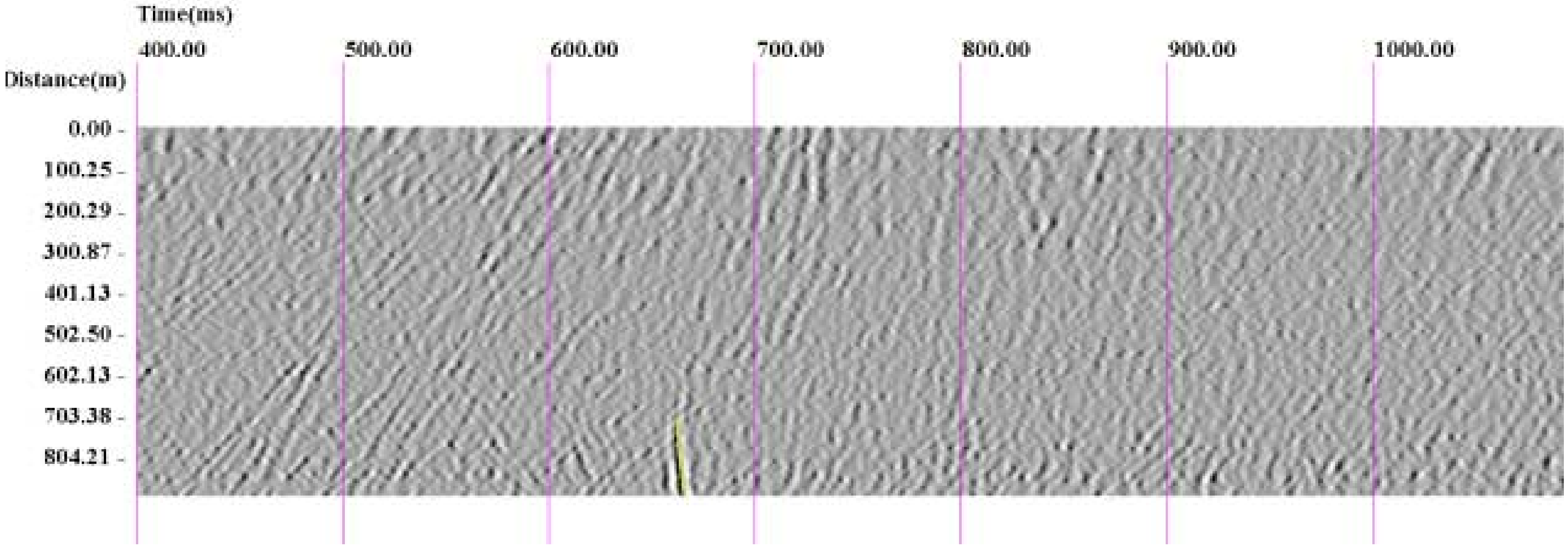

Figure A1-24. *Profile 5.2*
E1 – dip 12, strike 296

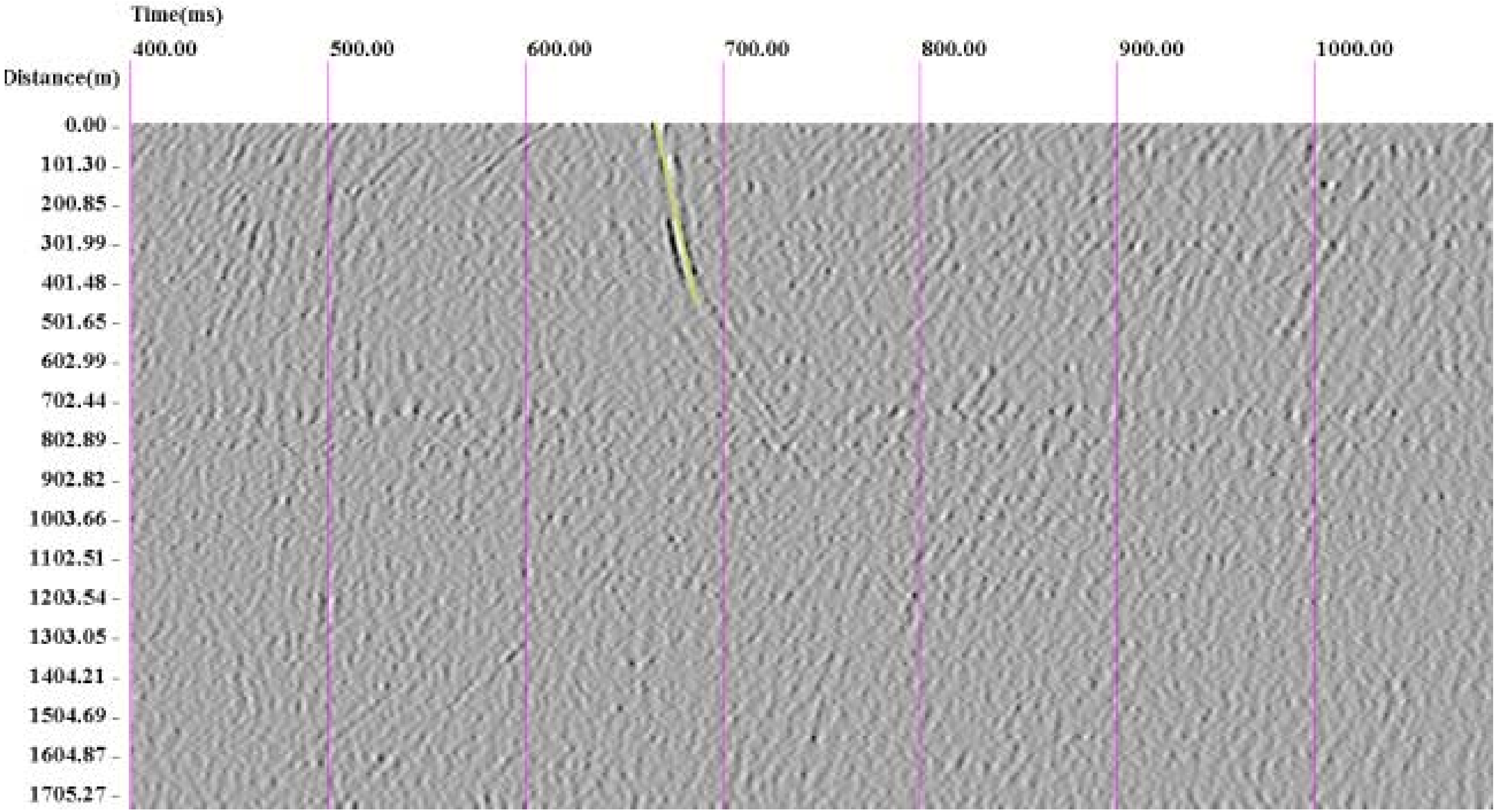

Figure A1-25. *Profile 5.3*
E1 – dip 12, strike 296

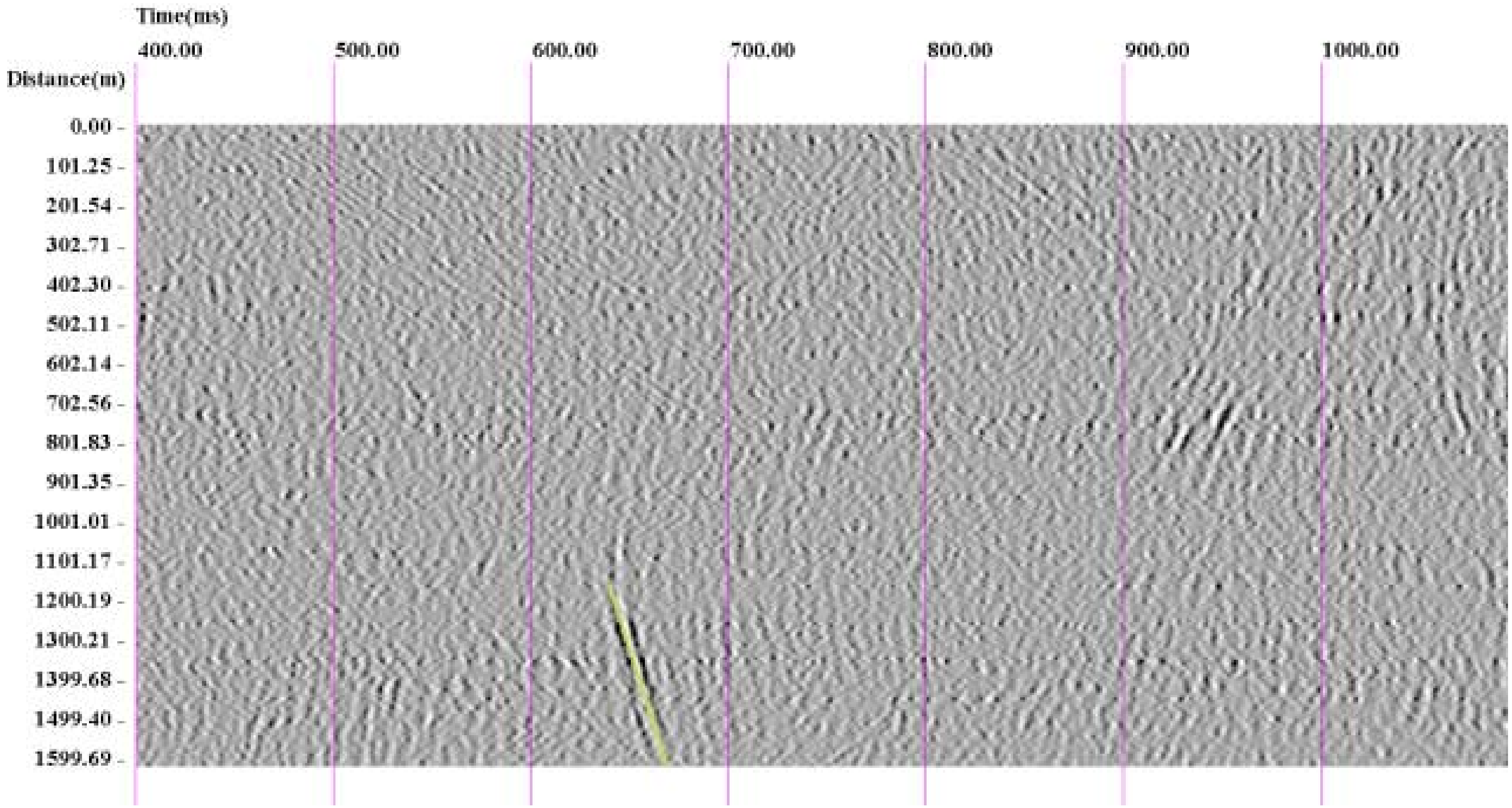

Figure A1-26. *Profile 2.1,*
E1 – dip 12, strike 296

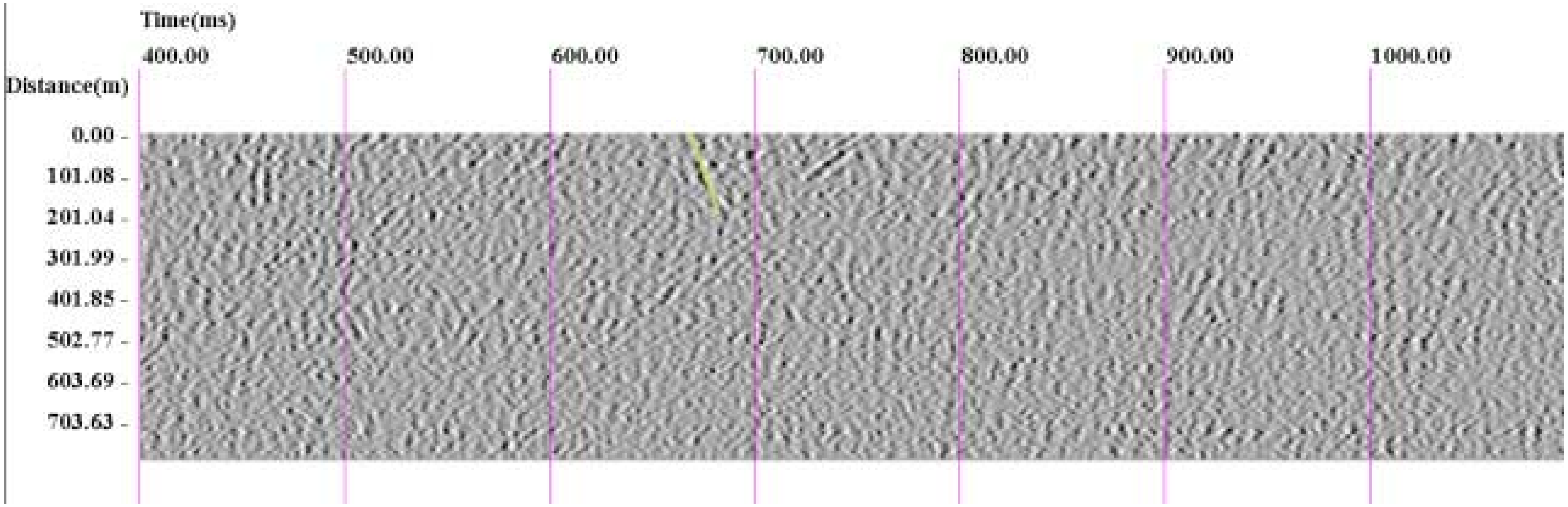

Figure A1-27. *Profile 2.2*
E1 – dip 12, strike 296

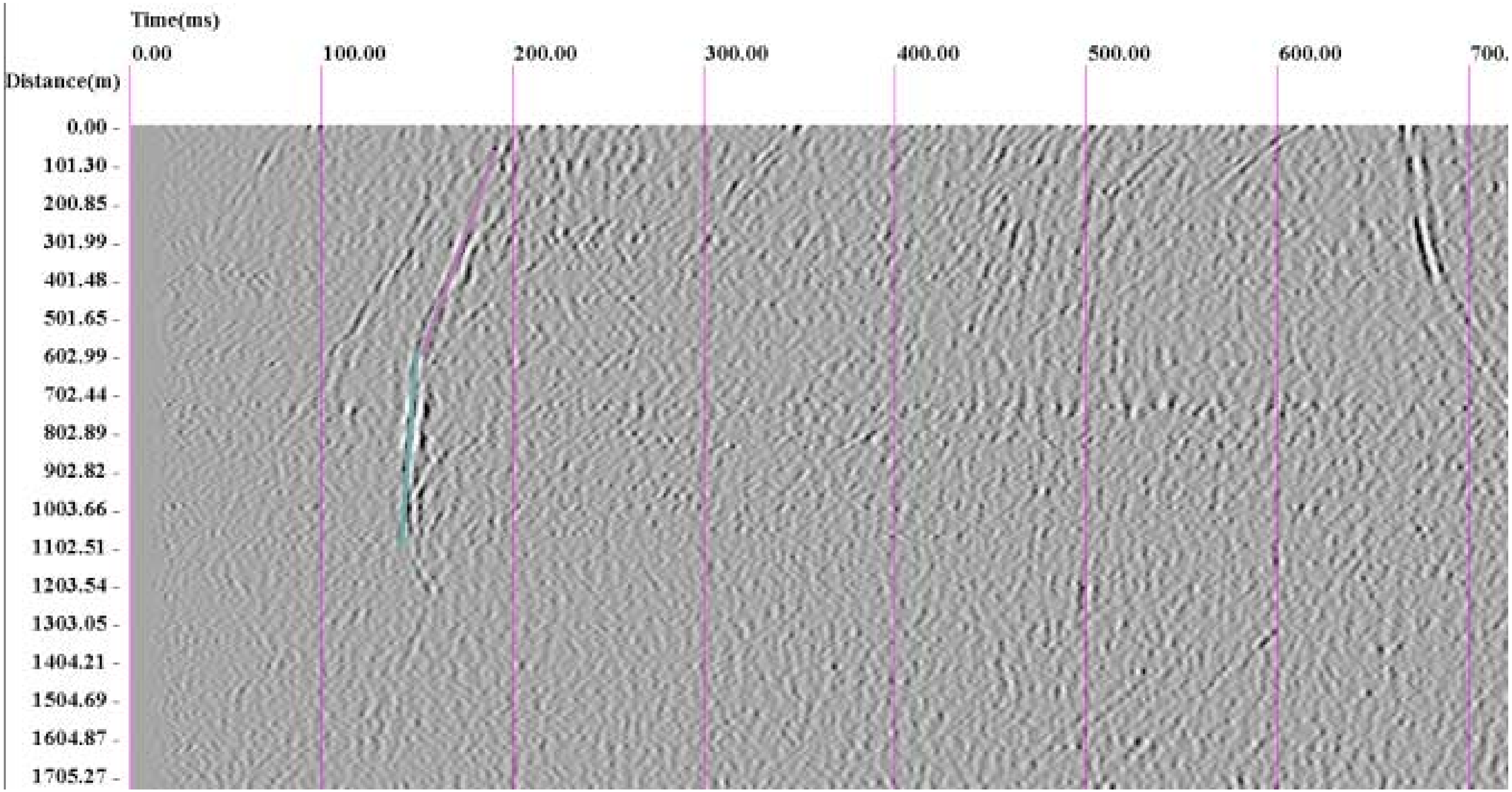

Figure A1-28. *Profile 5.3*
Reflector group F1
Violet: dip 18, strike 22
Green: dip 4, strike 20

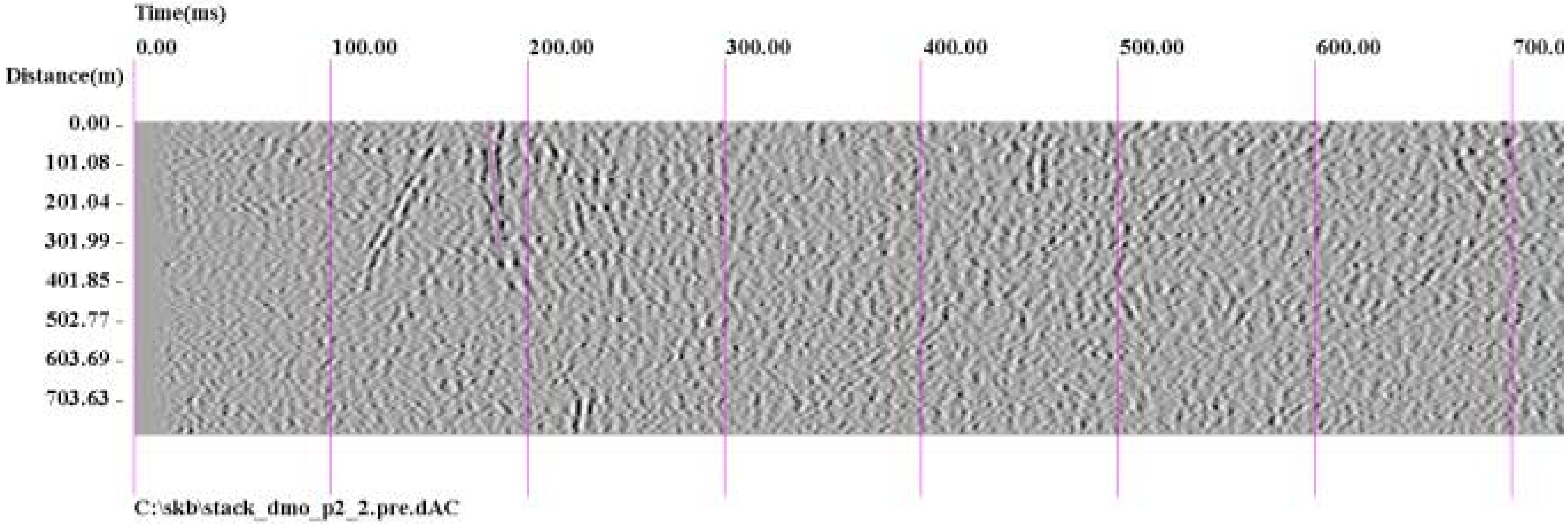

Figure A1-29. *Profile 2.2*
Violet: dip 18, strike 22

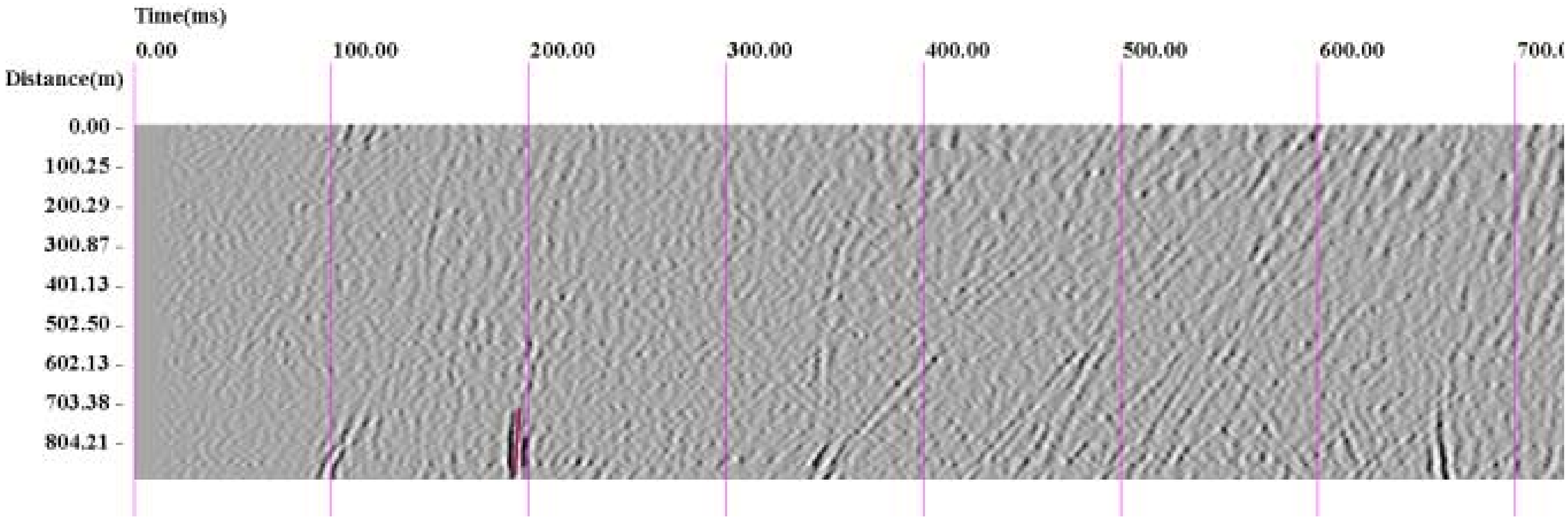

Figure A1-30. *Profile 5.2*
brown dip 2, strike 18

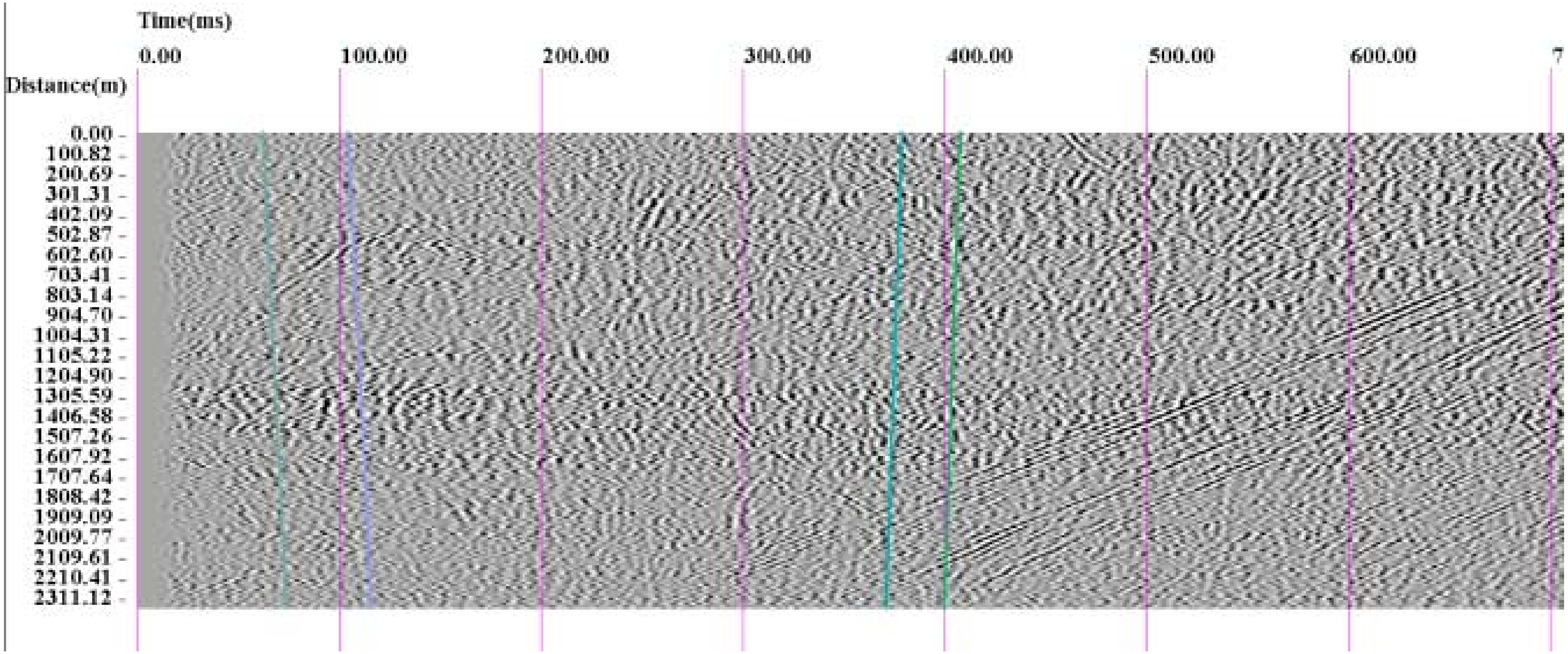

Figure A1-31. *Profile 4*
Reflectors G1, G2, G3, G4 (from left to right) as described in Table 4-1

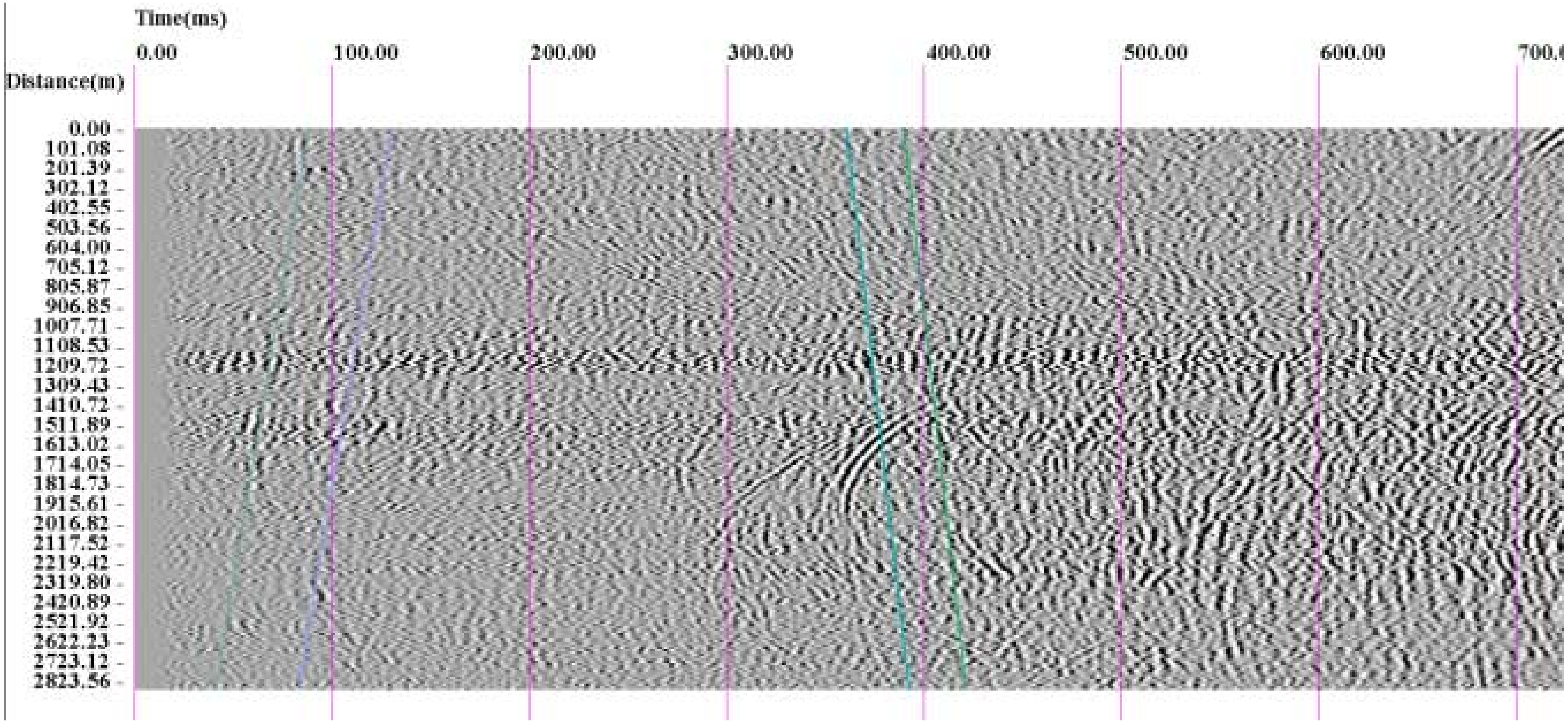

Figure A1-32. *Profile 1*
Reflectors G1, G2, G3, G4 (from left to right) as described in Table 4-1

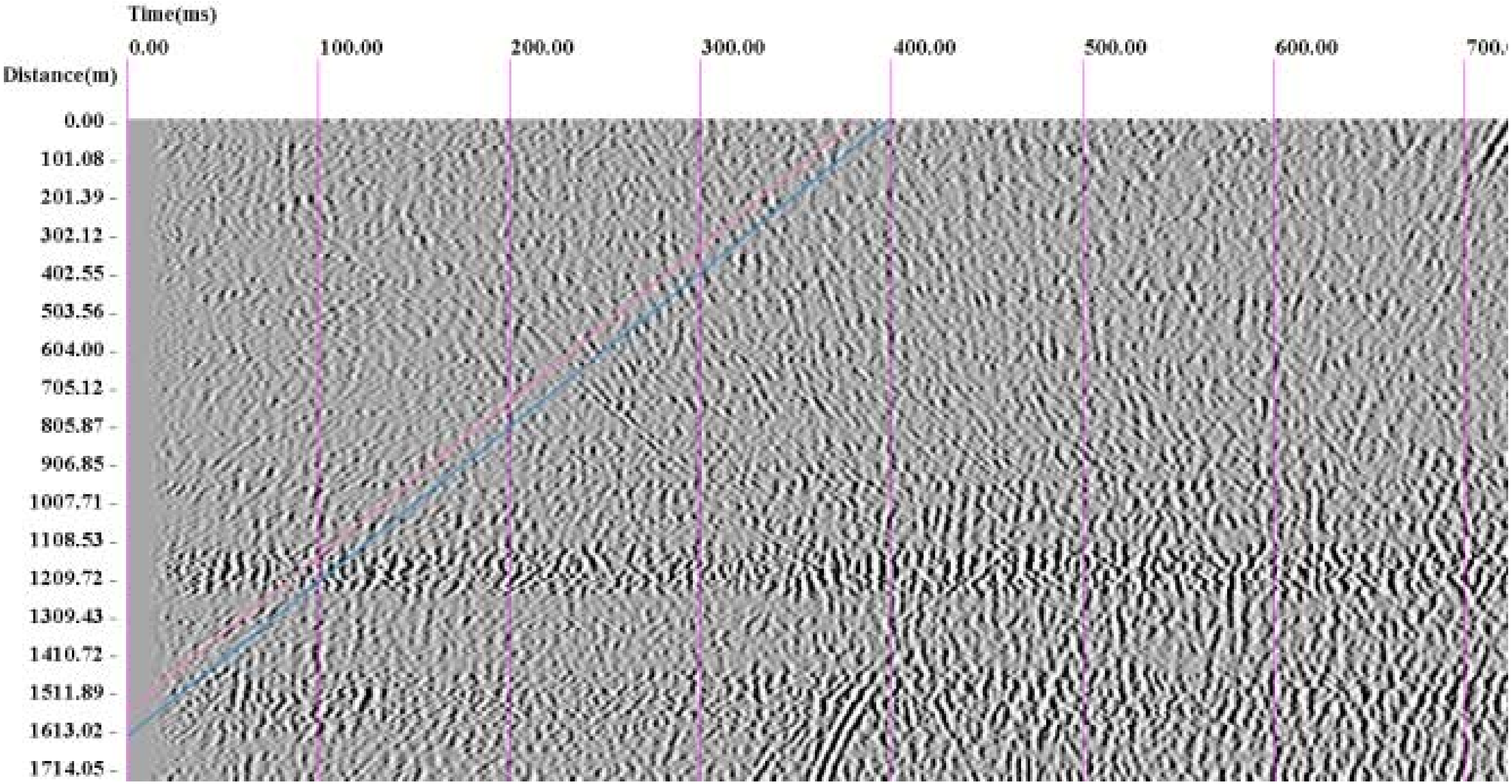

Figure A1-33. *profile 1*
H1, H2 (from left to right) as described in Table 4-1

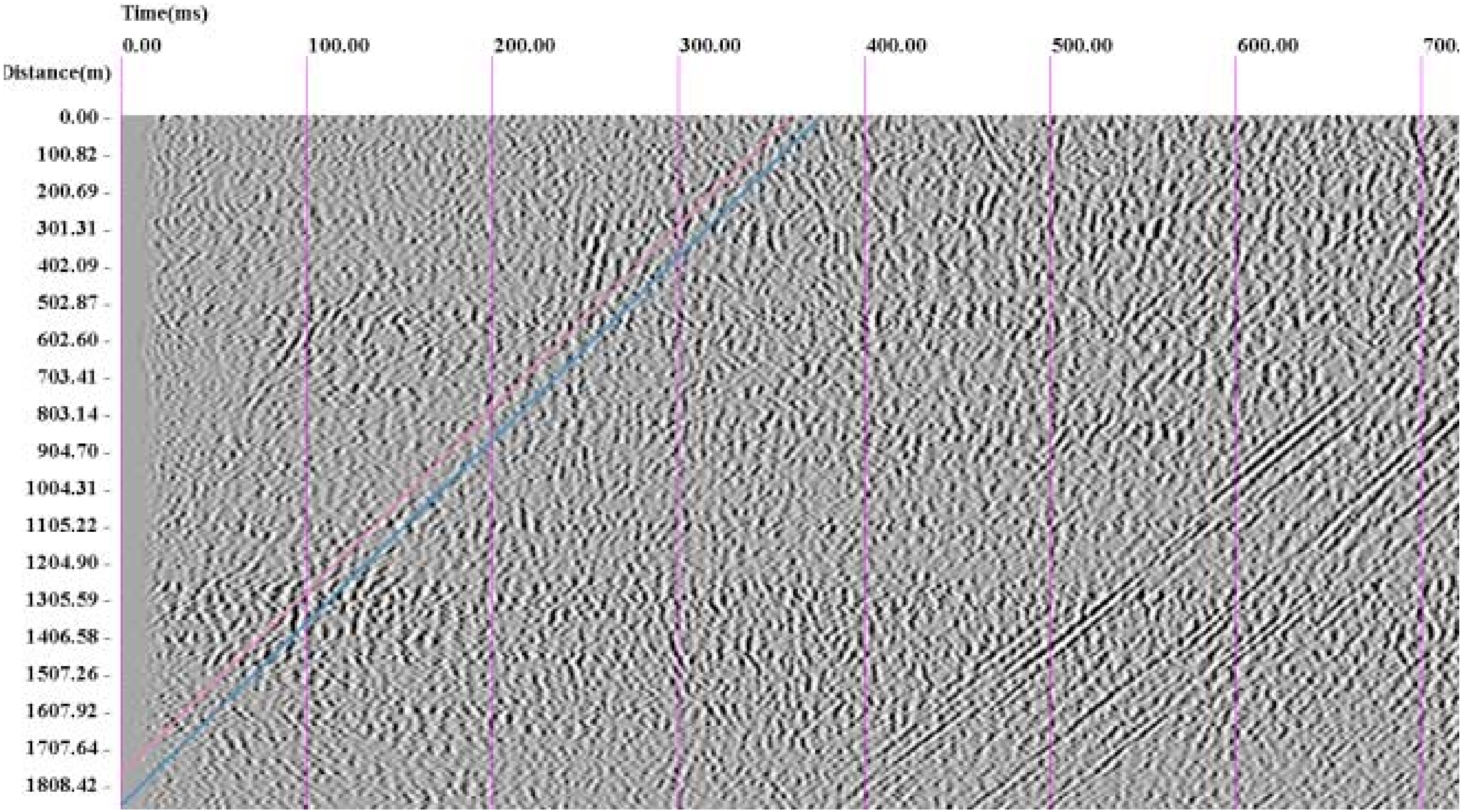

Figure A1-34. *Profile 4*
H1, H2 (from left to right) as described in Table 4-1

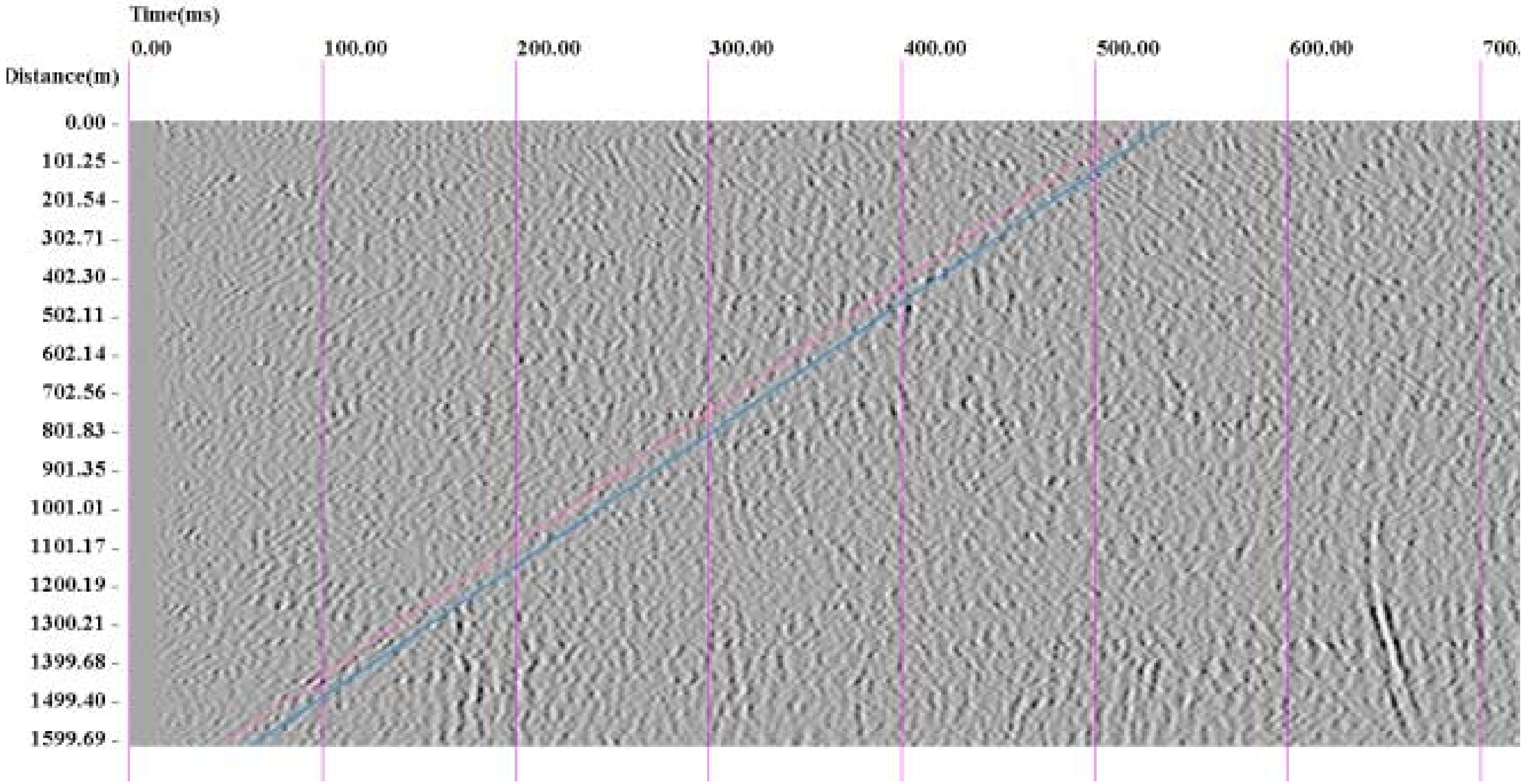

Figure A1-35. *Profile 2.1*
H1, H2 (from left to right) as described in Table 4-1

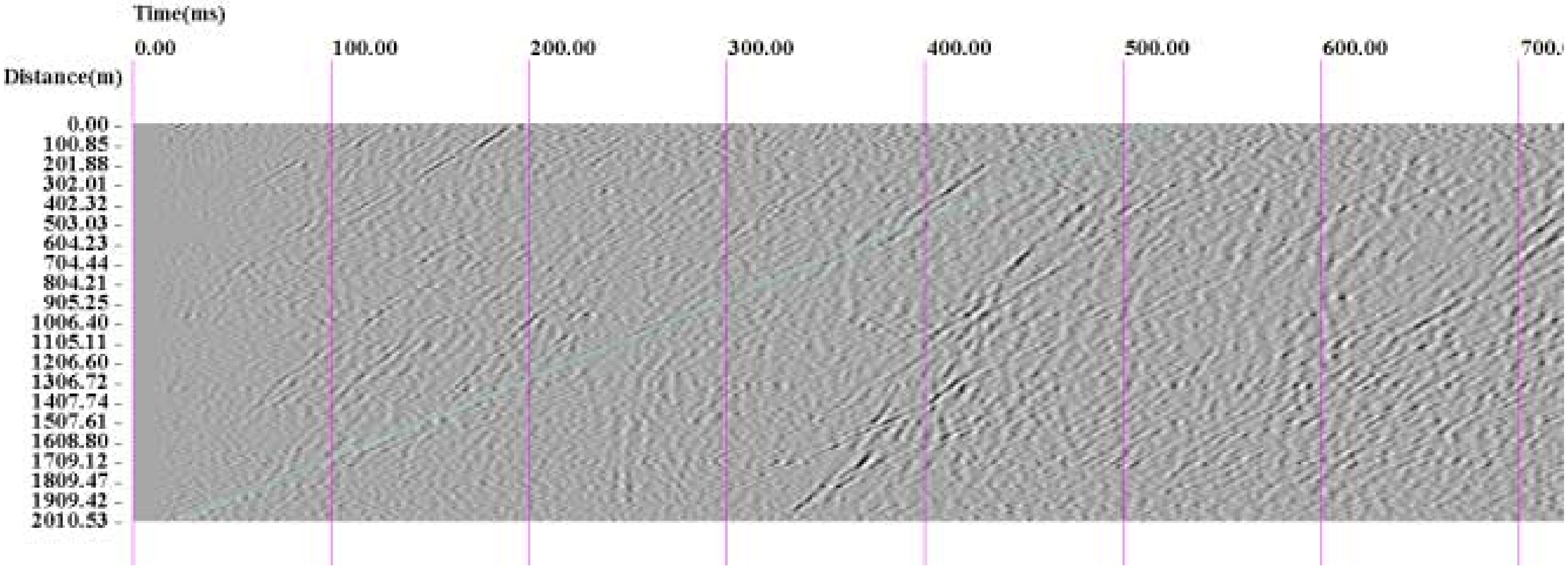

Figure A1-36. *Profile 3*
I1 dip 70, strike30

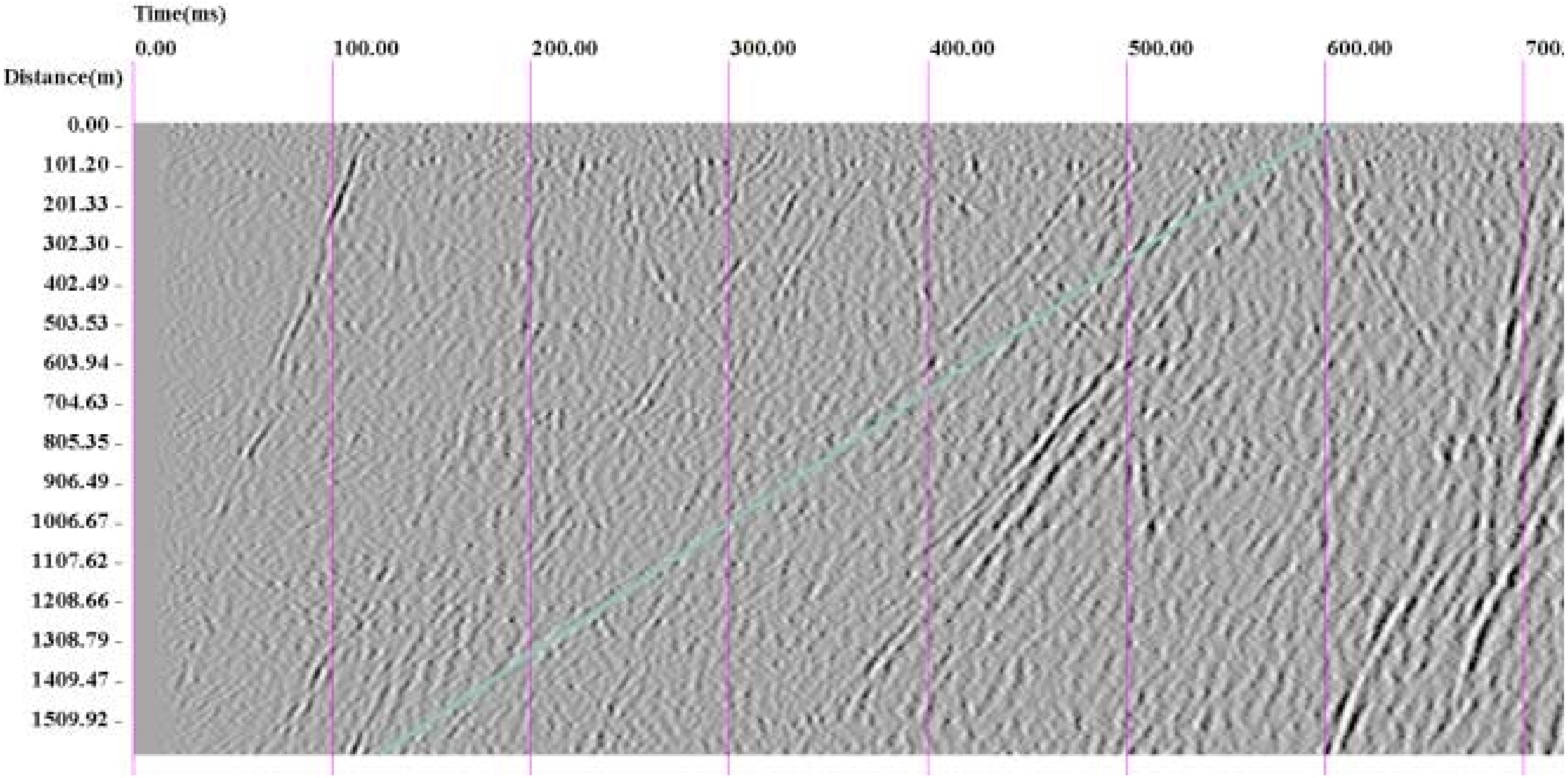

Figure A1-37. *Profile 5.1*
I1 dip 70, strike30

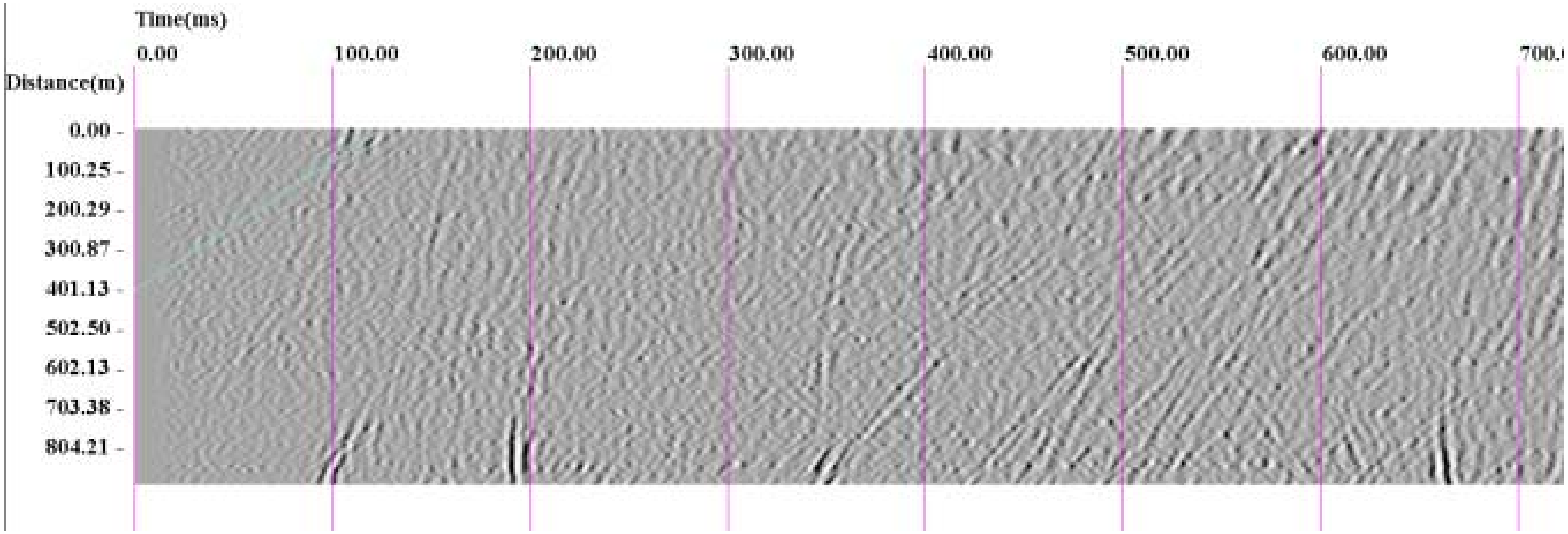

Figure A1-38. *Profile 5.2*
I1 as described in Table 4-1