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THREE-DIMENSIONAL SEISMIC REFLECTION STUDIES OF THE ALBERTA BASEMENT

E. R. KANASEWICH[1], M. J. A. BURIANYK[1], G. P. DUBUC[2], J. F. LEMIEUX[3] AND F. KALANTZIS[4]

ABSTRACT

The three-dimensional seismic reflection technique, common in the petroleum industry, has seen only intermittent use in crustal studies. In 1992, Lithoprobe conducted a feasibility study to evaluate the technical and scientific viability of using three-dimensional seismic reflection recording for crustal studies in Alberta. The deep crustal three-dimensional seismic reflection experiment was conducted in central Alberta, southwest of Edmonton. The data volume, stacked into 8-fold 100 m x 100 m bins, covered 144 square kilometres and had 18 s record lengths. It was acquired during the course of regular Lithoprobe two-dimensional regional crustal reflection profiling and required very little in the way of extra effort and costs. The recording parameters and field equipment were similar to that used for the concurrent two-dimensional experiments.

A major drawback of the experiment was that the location of the experiment had to be chosen on logistical, rather than scientific, grounds. It was only after the coincident and concurrent regional two-dimensional profiles were recorded and processed that more suitable targets were identified. Nevertheless, the amount of reflectivity visible on the three-dimensional records was encouraging and comparisons between the 60-fold two-dimensional profiles and the corresponding three-dimensional data in-lines and cross-lines confirm that we were able to record reflections from the crust down to the Moho.

Four major reflecting horizons were chosen for initial analysis. Two reflections from the upper crust are correlative with a set of highly coherent, strong-amplitude, flat-lying events found in the two-dimensional records at 5-7 s of traveltime. These horizons are of uncertain origin and significance. The third horizon is from the lower crust while the fourth is at the level of drastically diminished reflectivity corresponding to the Moho. All events were carefully analyzed by a combined procedure of simultaneous in-line and cross-line picking. The resulting traveltimes were compiled into colour time-structure maps and block-perspective diagrams.

The difficulties overcome to obtain the results show us that three-dimensional crustal seismic experiments can suffer from several problems. These include poor data areas, low fold, poor horizontal resolution and small areal coverage. This last aspect, especially, did not allow us to make much structural sense of the analyzed horizons. This experiment, however, was successful in that we were able to record three-dimensional reflectivity from near surface to the Moho and we were able to map four crustal horizons, including the bottom of the crust. This not only justifies the use of the three-dimensional seismic reflection method for crustal studies but also determines the necessary improvements for future work.

INTRODUCTION

An innovative three-dimensional reflection experiment was conducted over central Alberta to study the feasibility of the technique for crustal studies and to complement the first stage of two-dimensional deep crustal seismic reflection profiling of Lithoprobe's Phase III Alberta Basement Transect. The seismic acquisition, undertaken in the summer of 1992, marked the beginning of multidisciplinary probing of the crust beneath the Western Canada Sedimentary Basin to study the origin of the continent (Ross et al., 1995) and the influence of basement structure on the sedimentary section above (Eaton et al., 1995).

The two-dimensional reflection data were recorded in north-south and east-west profiles, numbered 1 to 10 from west to east and totalling 512.8 km. Lines 1, 3, 4, 6 and 8 were north-south while the other profiles were predominantly east-west. The lines followed the grid road system of Alberta, crossing the basement domains as near as possible perpendicular to strike. The three-dimensional recording was conducted in the region of the intersection of lines 2 and 3 (Figure 1).

The use of the three-dimensional seismic reflection recording has been common in the petroleum industry for the last two decades and has seen intermittent use in crustal studies for perhaps only the last five years. The method is used extensively in the petroleum exploration industry primarily for the precise delineation of oil and gas reservoirs (Brown, 1988). Generally, Walton (1971, 1972) gave the first, basic description of the method and French (1974) showed the importance of three-dimensional recording and imaging for the interpretation of seismic reflection data in areas of complex geology.

Three-dimensional methods for crustal studies were first used in wide-angle experiments, initially in limited terms (Milkereit et al., 1986) and then later using full three-dimensional geometry and interpretation (Kanasewich et al., 1987). In near-vertical incidence reflection experiments, Chiu et al.

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[1] Seismology Laboratory, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1

[2] Seismology Laboratory, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1; presently: Norcen Energy Resources Limited, 715 5th Avenue S.W., Calgary, Alberta T2P 4V4

[3] Seismology Laboratory, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1; presently: Université Laval, Québec, P.Q.

[4] Seismology Laboratory, Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1; presently: Anderson Exploration Ltd., 1600 Home Oil Tower, 324 8th Avenue S.W., Calgary, Alberta T2P 2Z5

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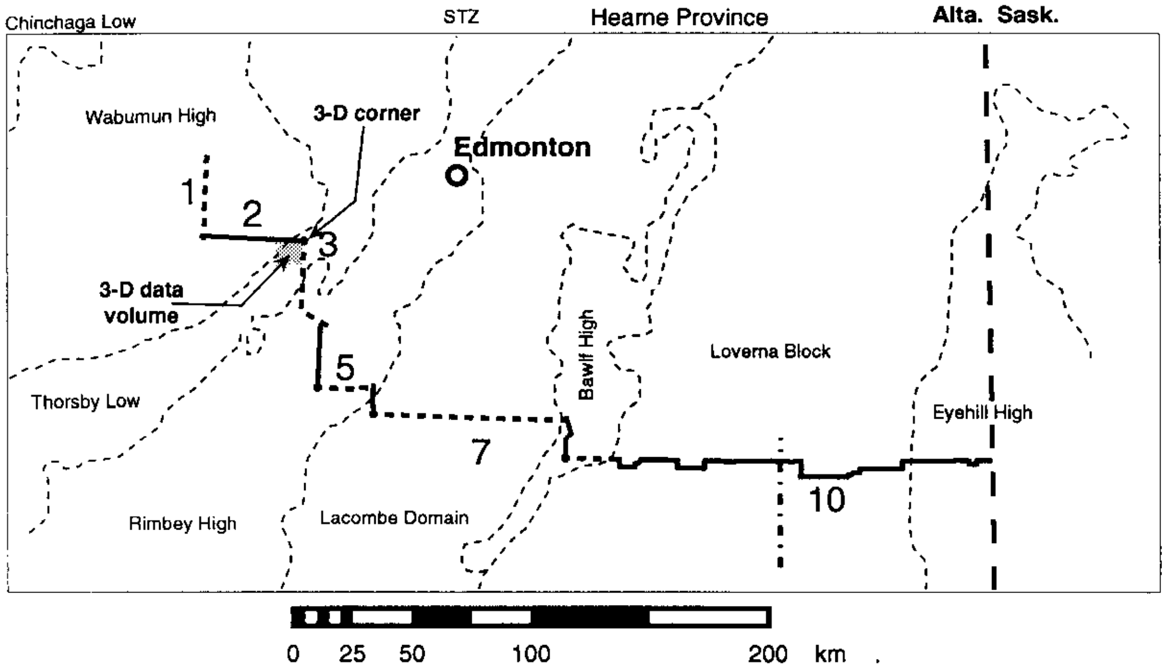

Fig. 1. Map of basement geological domains of central Alberta, interpreted from potential field data, with respect to Alberta Basement seismic reflection lines.

(1986) performed three-dimensional inversion on crooked-line seismic reflection data from Vancouver Island. Since then, fully three-dimensional reflection experiments have taken place as reported by Cook and Coflin (1990), Young et al. (1990), Gebrande et al. (1991), Stiller (1991), Weiderhold (1991), Marthelot et al. (1994) and Smythe et al. (1994). All suffer to various degrees from one or more problems of limited areal extent, low fold and lack of deep reflectors.

THREE-DIMENSIONAL ACQUISITION

In planning the original two-dimensional seismic reflection experiment, the north-south, east-west grid road system of the Prairies had to be taken into account, creating at the same time problems and opportunities. The strike of the basement domains is northeast to southwest. It is most appropriate to profile perpendicular to strike, but the extra costs (involving negotiations for private land access, line clearing, cleanup, etc.) for placing seismic lines across country was prohibitive. As well, Alberta provincial regulations hinder seismic (especially vibrator) operations on paved roads. Therefore, the lines had to be placed alternately on the north-south and east-west gravel roads, making a zigzag line that was as close as possible to a perpendicular crossing of geologic strike (Figure 1).

Besides making it unnecessary to use crooked-line geometry processing, each overlapping, linear segment was processed independently, the perpendicular elements also allowed for innovative, inexpensive acquisition of three-dimensional reflection data. This was done at what was termed ‘three-d corners’. Our only opportunity was at the corner created by the intersection of Lines 2 and 3 (Figure 1). Since planning had to be long term, the location was picked more on logistical than geophysical or geological grounds.

Data acquisition was based on using, as much as possible, the existing field setup. The standard two-dimensional seismic reflection spread consisted of 240 receiver stations with each receiver station made up of nine (9) Oyo 20 DX 14 Hz geophones per 42 m in-line array. The group interval was 50 m. All geophones were buried to reduce ambient noise. The source interval was 100 m (every two receiver stations) resulting in a nominal 6000% CMP coverage. The spread configuration was an asymmetric split spread – 3150 m maximum receiver/source offset on the west/north short end and a maximum 9150 m offset on the east/south long end. The seismic source consisted of four 44 000 lb peak force, buggy mounted vibrators which swept eight times per source point with a 14 s linear sweep from 10 to 56 Hz. The data were recorded on a sophisticated cable telemetry seismograph which included diversity stacking and burst editing along with standard band-pass and notch filtering. Correlated record lengths were 18 s with a 4 ms sampling rate.

The three-dimensional acquisition used the same line geometry, instrumentation and recording system, except that 480 channels were used in place of the standard 240. At the end of the west-east Line 2, after the two-dimensional profiling was completed, the vibrators were placed on the north-south Line 3, leaving the recording spread on Line 2. “Broadside” shots were then recorded, creating an east-west line of CMPs (Figure 2a). This method is exactly that as described in the first three-dimensional seismic reflection work in the petroleum industry (Walton, 1971, 1972). As the vibrators moved northward along the line, the broadside recording created additional lines of CMPs. The basic method was then improved upon by vibrating on the west-east Line 2 and recording on Line 3, after setting up the array for a new two-dimensional profile, obtaining a set of north-south CMP lines perpendicular to the first set. Thus, we acquired a three-dimensional grid of CMPs that could be bin stacked (Figure 2b). With the 480 channels and only 49 extra vibration points (for only a minimal extra cost) on each perpendicular segment (the source interval was 500 m), we achieved a 49 x 49 grid of 2000% bins (250 m x 250 m), or a 121 x 121 grid of 800% bins (100 m x 100 m), in a 12 km x 12 km area (Figure 2b). The larger bins, of course, have a higher signal-to-noise ratio, but at the same time if there is any appreciable geological dip a certain amount of "smearing" can be expected during summation. Smaller bins mitigate against that, at the expense of a smaller theoretical signal-to-noise ratio.

This special experiment required VHF radio transmission (for control of vibrators) over distances much longer than required in the usual seismic reflection recording. During testing the seismic contractors, Veritas Geophysical Limited of Calgary, discovered that the vibrator sweep start triggering tone was not regularly received by all vibrators at maximum vibrator/recorder distances. They solved this problem by mounting a large telescoping mast with a 6 db gain directional antenna on the recording truck, increasing reception to acceptable levels. With technical difficulties solved, acquisition proceeded normally.

During commercial processing both bin sizes, 250 x 250 m and 100 x 100 m, were used. The smaller bins were considered to image reflections better, despite their smaller fold, due to the smaller spatial spread – that is, dip effects were less pronounced over a smaller area. Since the actual sites of VPs and recording stations are identical to the regular profiles, the same refraction derived and residual static corrections could be applied to the three-dimensional data. A process of residual trim statics was also used to remove random static variations still in the data. Random noise attenuation, band-pass filtering and scaling, and a finite-difference migration were run after stack. The processed data volume was about 120 cross-lines by 120 in-lines of 8-fold traces.

TWO-DIMENSIONAL DATA

Figure 3 shows the migrated and coherency-filtered (a method of simplifying the reflection profiles, leaving only the stronger reflected energy) plots of the regular, two-dimensional Lines 2 and 3, in whose east/north intersection corner lies the three-dimensional data set. In general, the data quality is very good for Lines 2 and 3. Line 2, especially, is very reflective throughout the whole section to the Moho. This indicates that this same reflectivity might be visible in the corresponding three-dimensional data set. However, the data quality of the profiles does deteriorate as it enters the region sampled by the three-dimensional experiment.

The Moho (the bottom of the crust) is interpreted to be at 12-14 s (approximately 35-45 km depth) at the base of the zone of strong reflectivity. That is, the Moho is at a region of abruptly diminished reflection amplitudes. In relation to the entire 500 km of the Central Alberta Transect, there is no sharp Moho visible on the west end of Line 2. However, on the east side of Line 2 and the north end of Line 3, where the three-dimensional data volume is situated, the Moho is clearly imaged at 14 s, shallowing almost to 13 s at the south end of Line 3.

Between 5-7 s (15-20 km depth) on Line 2, there is a set of horizontal high-amplitude arrivals of uncertain origin and significance (Ross et al., 1995). These reflections continue into the three-dimensional sampled area on the east end of Line 2, but are greatly diminished on Line 3.

THREE-DIMENSIONAL DATA

When we look at the three-dimensional data (Figures 4 and 5), we have to keep two things in mind. One is that the three-dimensional data volume has a much lower signal-to-noise ratio than the corresponding two-dimensional profiles as a consequence of the difference in redundancy. We have 8-fold for the three-dimensional data as opposed to 60-fold for the two-dimensional data. Secondly, we have only one stacked three-dimensional trace for every four traces of the two-dimensional regional lines over the same profile length. In comparison with the regional data, data quality is sacrificed with the lower fold, as is continuity and spatial correlation of reflections with the lower lateral resolution.What is rather encouraging, however, despite this, is the large amount of reflectivity that is visible in the data volume (Figures 4, 5).

The 5-7 s reflective structure seen on the east end of Line 2, for instance, was easily recognized and a top (labelled 'C0') and bottom (labeled 'C1') of a structure has been mapped (Dubuc, 1994). In-lines close to Line 2 show the reflecting event C1 with similar two-way traveltime and synformal geometry as the bottom horizon of the 5-7 s set evident on the two-dimensional data. As well, there are antiformal horizons corresponding to the top of that set. Figure 4 shows representative cross-lines (north-south) and in-lines (east-west) with these reflectors present. On these figures, picks from a certain line are shown as solid lines while those picks from intersecting perpendicular lines are presented as circles.

These two horizons were picked by first defining the reflections in a high-reflectivity area in the middle of the data volume and following the reflection trajectories outward along the in-lines and cross-lines. It was found that the in-lines defined the bottom horizon (C1) much better than the cross-lines. On the other hand, the top horizon (C0) was much better imaged on the cross-lines. This resulted in a procedure of combined in-line and cross-line picking.

The Moho (labelled 'MOHO') reflector was interpreted (at about 14 s) as well as a shallower deep crustal horizon (about 13 s depth – labelled as 'R1') (see Figure 5). Again, comparisons with the two-dimensional profiles (Figure 3) initially helped identify the reflectors on the north and east edges of the data volume. The highly reflective region at about 14 s, followed by a transparent zone, was identified as the Moho. Slightly dipping reflector segments at 13 s (more prominent in three-dimensional than in the two-dimensional profiles)

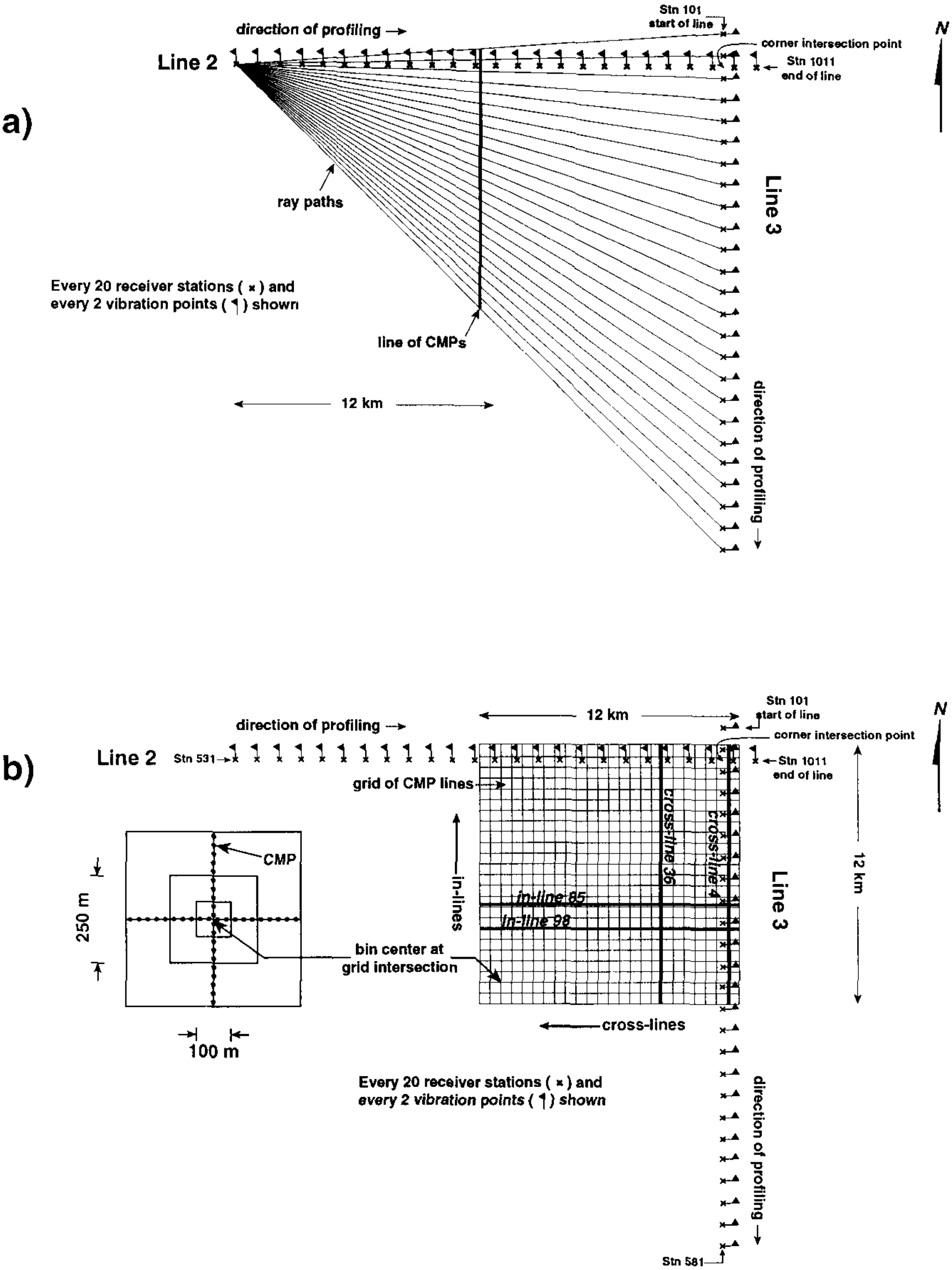

Fig. 2. Three-dimensional field acquisition procedure. **a)** A set of vibrators on Line 2 recorded at the beginning of Line 3 (fan, or broadside geometry) resulted in a line of common midpoints (CMPs) parallel to the receiver line. Vibrators on Line 3 with recording on Line 2 gave a perpendicular line of CMPs. **b)** With 480 receiver stations and 50 vibrator points along 24 km of line, we got a 12 km x 12 km grid of CMPs. Three-dimensional stacking bins of 250 m x 250 m have 2000% redundancy while 100 m x 100 m bins have 800% fold, but with less smearing due to geological dip. Also shown are the locations of cross-lines 4 and 36 and in-lines 85 and 98, the data for which is shown in Figures 4 and 5.

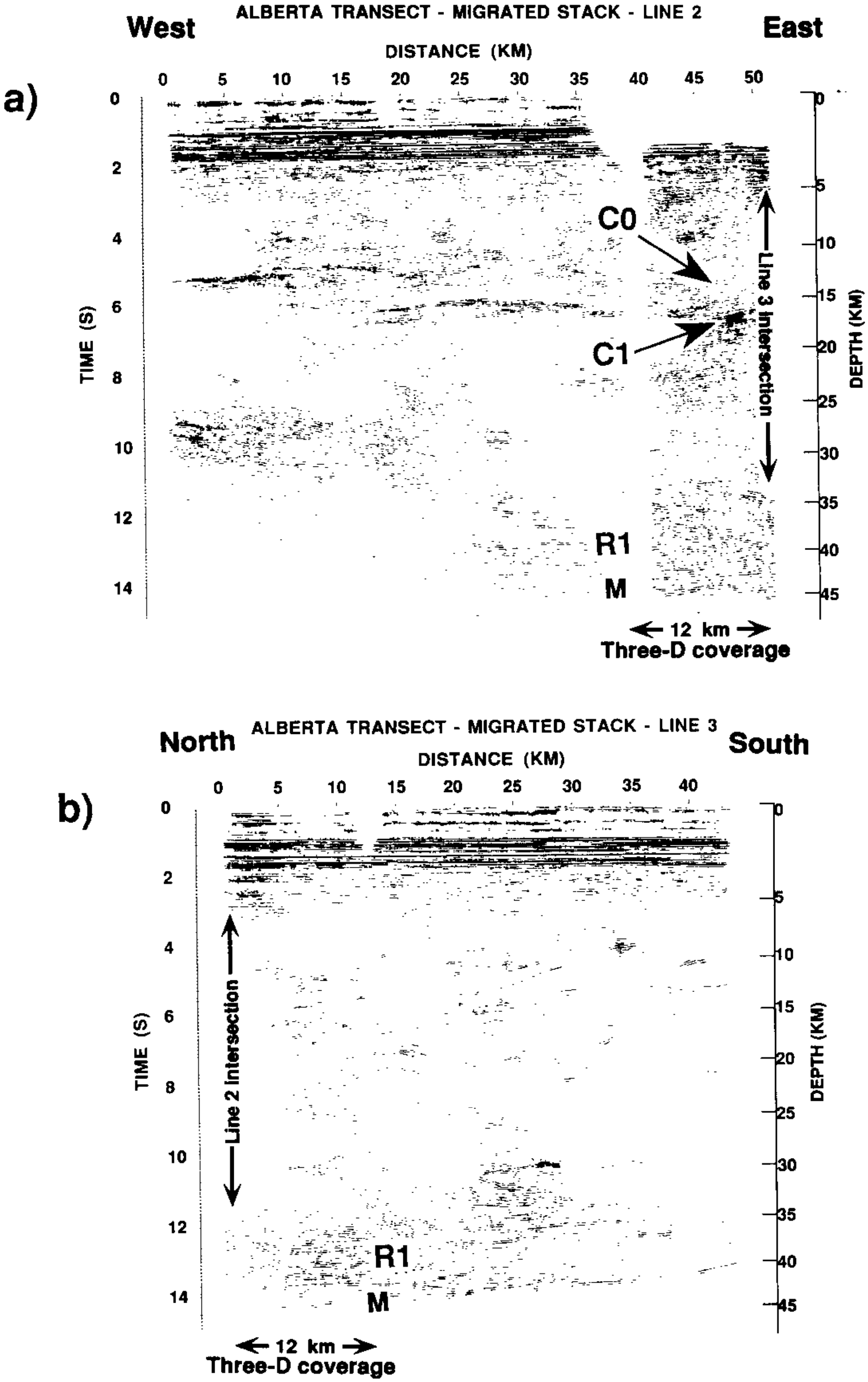

Fig. 3. Line 2 **(a)** and 3 **(b)** of the regional two-dimensional reflection profiling. The three-dimensional coverage is in the easternmost 12 km of Line 2 and the northernmost 12 km of Line 3. The corresponding reflectors that are analyzed in the three-dimensional data set are identified (see Figures 4 and 5).

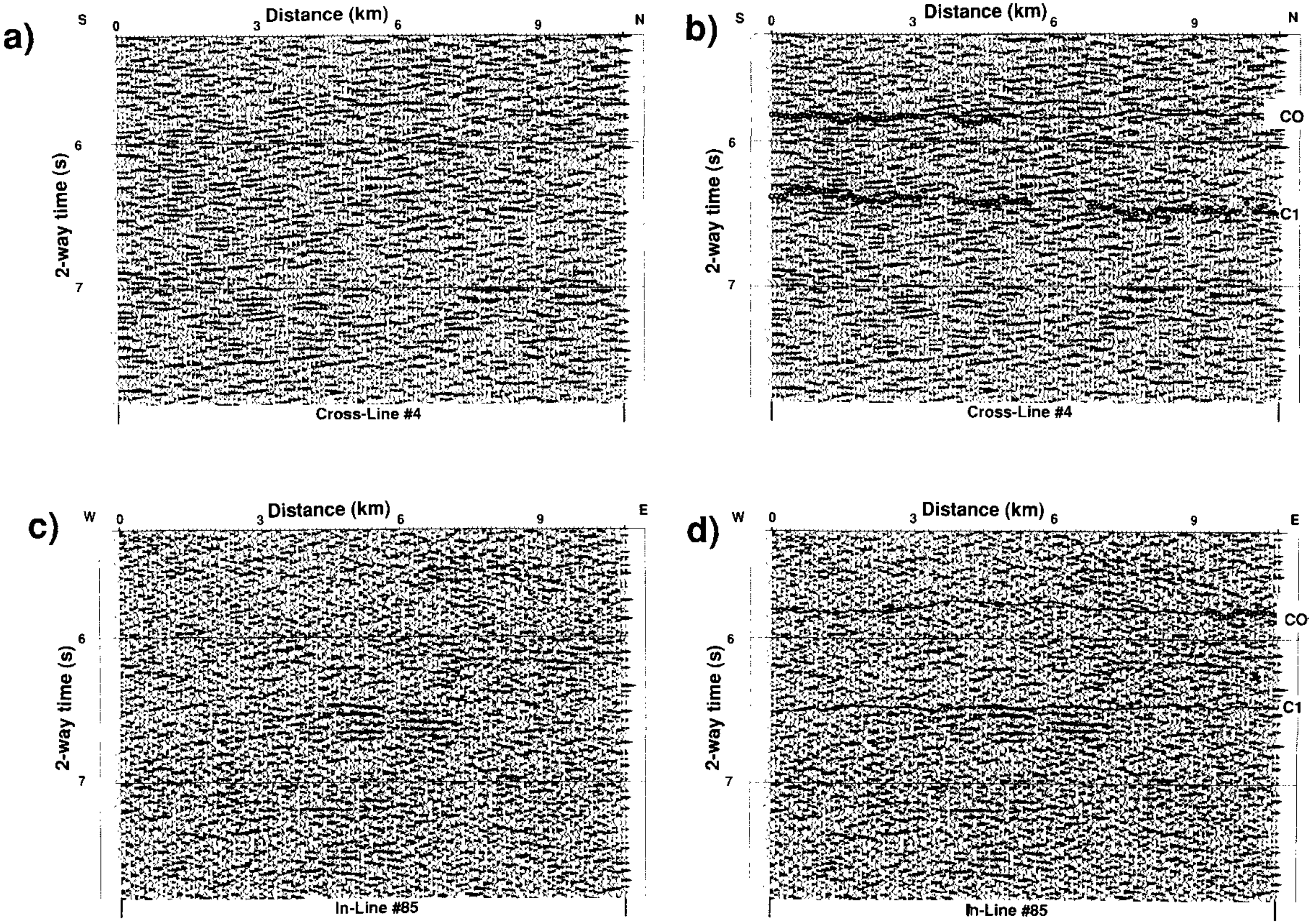

Fig. 4. Representative cross-lines (north-south) and in-lines (east-west) from the three-dimensional data volume for the two shallowest crustal horizons (at 5-8 s – labelled C0 and C1): **a)** cross-line 4; **b)** cross-line 4 with picks (solid lines) and picks from intersecting in-lines (circles); **c)** in-line 85; and **d)** in-line 85 with picks (solid lines) and picks from intersecting cross-lines (circles). Locations of cross-line 4 and in-line 85 are shown in Figure 2.

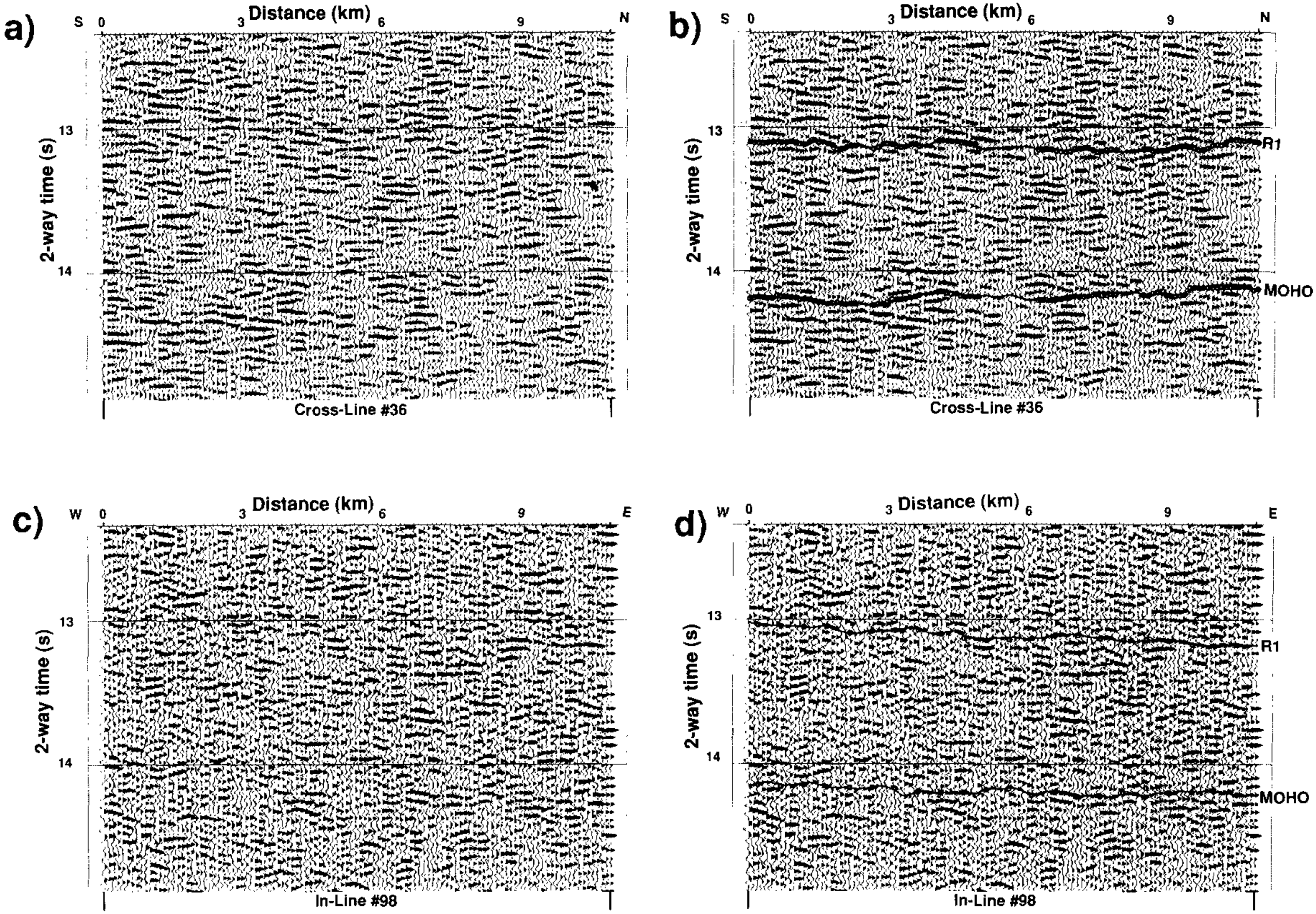

Fig. 5. Representative cross-lines (north-south) and in-lines (east-west) from the three-dimensional data volume for the two deepest crustal horizons (12-15 s – labelled R1 and MOHO): **a)** *cross-line 36*; **b)** *Cross-line 36 with picks (solid lines)* and picks from intersecting in-lines (circles); **c)** in-line 98; and **d)** in-line 98 with picks (solid lines) and picks from intersecting cross-lines (circles). Locations of cross-line 36 and in-line 98 are shown in Figure 2.

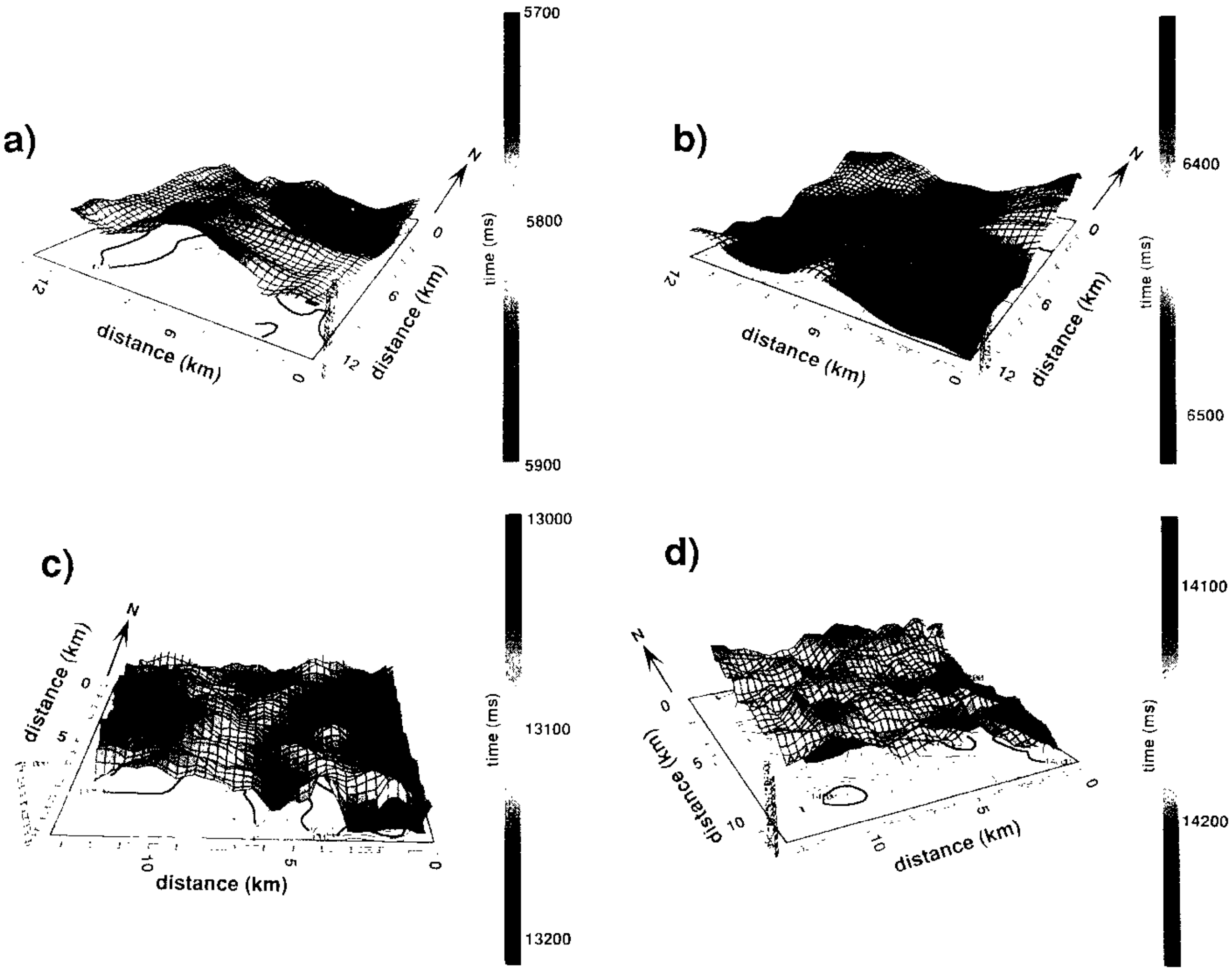

Fig. 6. Perspective block diagrams of each of the four interpreted crustal horizons **a)** C0; **b)** C1; **c)** R1; and **d)** MOHO.

constitute the shallower pick. Picking criteria were based on following the most continuous reflectors and on consistency of in-line and cross-line correlations. Neither of these two reflections were of the same amplitude nor were as continuous as the 5-7 s reflections. However, the control from picking simultaneous in-lines and cross-lines insured that a reasonable structure was interpreted.

The four horizon structures defined are shown as either perspective block diagrams (Figure 6) or time-structure contour maps (Figure 7). These diagrams are presented with colour coding, corresponding to the two-way traveltime of the reflector. That is, they are time-depth structure maps.

The C0 and C1 reflectors are presumed to be, respectively, the top and bottom of a distinct geological structure, whose nature is as yet speculative. On the west side of Line 2 C0 is a high-amplitude reflection coincident with a strong positive magnetic anomaly characteristic of the Wabamun domain (Figure 1). This horizon deepens on the eastern half of Line 2 and the magnetic field decreases by 2 or 3 orders of magnitude. These reflections are not visible on any part of Line 3 where reflectivity above both C0 and C1 have a different dip. The crosscutting nature of C0 and C1 along with their magnetic signature within the Wabamun magnetic high may indicate that they are part of a group of sills. As these reflectors dip to the west and ultimately disappear, they may approach temperatures above the Curie point, resulting in a lack of a positive magnetic signature associated with Line 3, within the Thorsby magnetic low (Figure 1). The C0 horizon (Figures 6a, 7a) has a depth differential (assuming 6000 m/s average crustal velocity) of 600 m and a northwest-southeast trend. The bottom (C1) of the structure (Figures 6b, 7b) has a 550-m variation in depth and a synformal structure.

The R1 horizon (Figures 6c, 7c) varies from 13.0 s to 13.2 s. There is an obvious west to east dip, as seen on the in-lines (Figure 5). Assuming an average crustal velocity of 6.2 km/s, the depth would range from 40.3 to 41.0 km, corresponding to a depth differential of 700 m.

The time structure of the Moho (Figures 6d, 7d) varies from 14.1 to 14.3 s over the 144 square km area, and there is

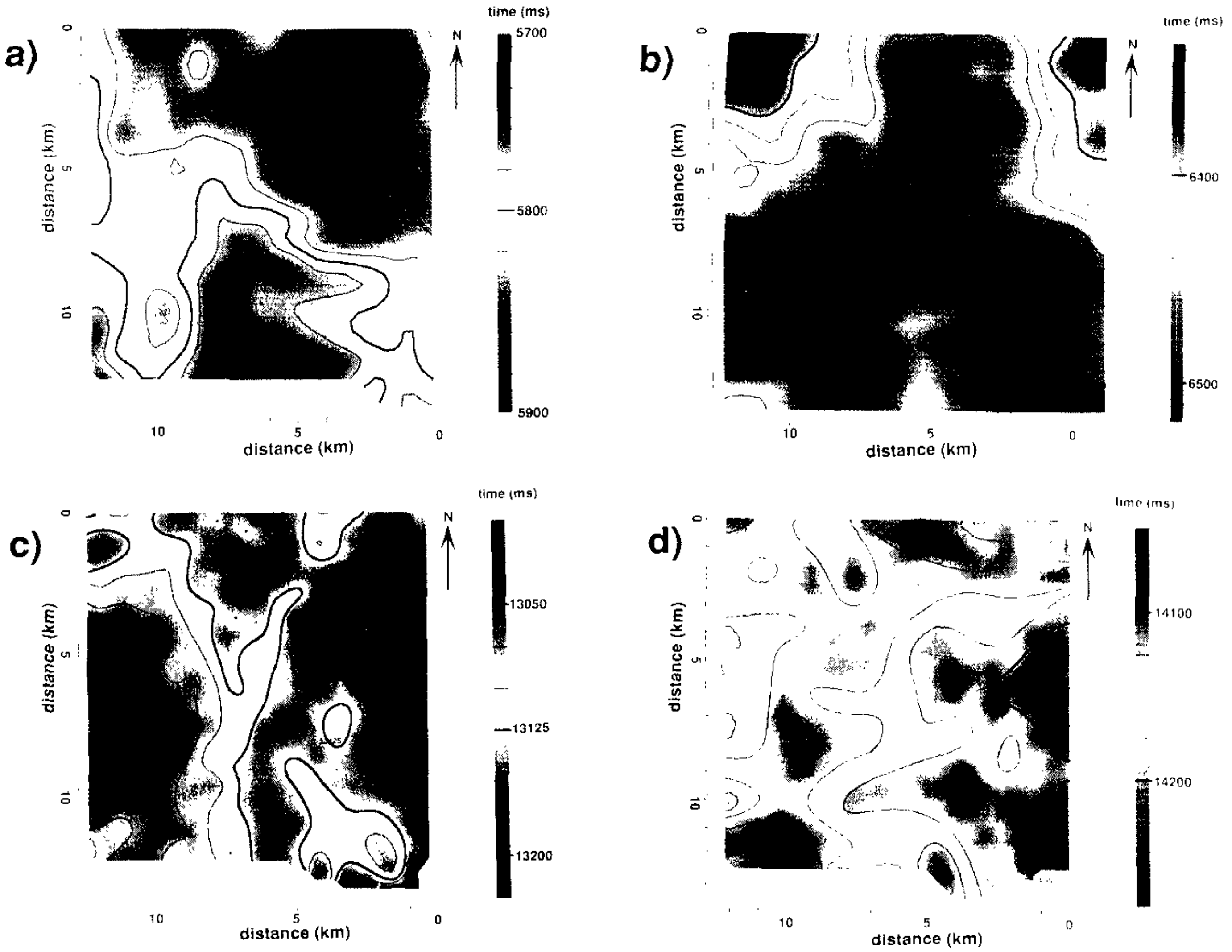

Fig. 7. Contour depth maps of each of the four interpreted crustal horizons: **a)** C0; **b)** C1; **c)** R1; and **d)** MOHO.

a tendency towards deeper Moho to the east. There is also a tendency for this layer to be less uniform, as is especially evident on the block perspective diagram (Figure 6d). With the same 6.2 km/s average velocity, the depth varies from 43.6 to 44.2 km, a 600-m differential. Most of this increase in depth takes place at the eastern edge of the data volume (Figure 7d).

CONCLUSION

During the 1992 Central Alberta seismic reflection acquisition of Lithoprobe's Alberta Basement Transect a three-dimensional data volume was recorded to study the viability of three-dimensional methods for crustal studies. The three-dimensional grid was located in the corner of the intersection of Lines 2 and 3. Acquisition was accomplished by using vibrators on one line and recording the reflected energy on the perpendicular line, then reversing the source and receiver lines. The data volume consisted of 144 square km with 800% fold. The position of the survey was chosen on logistical rather than scientific grounds since the regional lines were being acquired simultaneously. Four reflecting horizons were identified and picked to produce time-structure contour and perspective maps.

This experiment suffered from four fundamental problems. First, it was located in a geologically nonoptimum area. That is, it covered a portion of the crust that was seismically nonreflective, with respect to other areas covered by the regional data set. Second, the data was low fold, resulting in a low signal-to-noise ratio, again relative to the regional profiles. Third, the three-dimensional data had lower lateral resolution with one stacked trace every 100 m (the separation between bin centres) as opposed to CMP separations of 25 m on the two-dimensional surveys. Finally, the data volume covered a comparatively small area. This aspect especially was important since it didn't allow us to make much structural and tectonic sense of the recognizable horizons.

The experiment was a success, however, in that we were able to record three-dimensional reflectivity from the shallow upper crust to the Moho. With this data we were able to map four separate deep horizons, including the base of the crust. This experiment very readily proved the viability of the three-dimensional seismic reflection method for crustal exploration. We have shown that three-dimensional crustal reflection data can be acquired cheaply and that the resulting crustal reflectivity can be interpreted. In addition, we have been able to determine the important and necessary improvements in experimental design for future work.

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