UNIVERSITY OF ALBERTA

IMAGING OF THE LITHOSPHERE USING SEISMIC REFLECTION DATA FROM CENTRAL ALBERTA

BY

LEI WEI ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

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FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **IMAGING OF THE LITHOSPHERE USING SEISMIC REFLECTION DATA FROM CENTRAL ALBERTA** submitted by **LEI WEI** in partial fulfillment of the requirements for the degree of **Master of Science** in **GEOPHYSICS**.

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Date January, 1997

To my baby son, Leon Nan Jiang

Abstract

High quality crustal-scale seismic reflection data acquired by Lithoprobe in 1992, including two PRAISE'1994 seismic lines recorded also by Lithoprobe, have been reprocessed and interpreted in this thesis to image the structure of the lithosphere across central Alberta.

Starting with the stacked seismic data, phase-shift migration and coherency filtering was applied in the reprocessing with Second White Speckled shale(2WS) - a consistent stratigraphic marker flattened and shifted in a fixed two-way traveltime to remove errors in static corrections and the effect of the different processing datum elevations for individual seismic lines. Using the 2WS as a datum level tended to diffuse the multiples which was present after the data was migrated. This produced a section in which primary reflected energy dominates. As phase-shift migration can handle the dips of up to 90° accurately and coherency-filtering can enhance the visibility of coherent events, the results of reprocessing produce excellent images of the structure of the lithosphere in the study area.

A second method using depth migration, accurate for dips of up to 70°, further corrections for edge effects, and a display using a trace bias produced even better images.

The seismic data was compared to the gravity and magnetic potential field during interpretation. Some effects of Precambrian basement reactivation were discovered. The Precambrian event shows regional crustal thrust imbrication. The depth crustal depth varied from 36 km to 43 km in central Alberta.

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Finally, I am gratified to have a comprehensive husband who tried his best to help me with my thesis. Also I am grateful to my parents for all their spiritual encouragement and love.

TABLE OF CONTENTS

CHAPTER **PAGE**

LIST OF TABLES

LIST OF FIGURES

FIGURE		PAGE

Imaging of the Lithosphere Using Seismic Reflection Data from Central Alberta

Chapter 1. Introduction

As part of project LITHOPROBE, the work in this thesis involves seismic studies of the lithosphere in central Alberta, where the Western Canadian Sedimentary Basin (WCSB) is located. Eight out of ten reflection seismic lines from the Central Alberta Transect(CAT) 1992 and two Peace River Arch Industry Seismic Experiment(PRAISE)1994 seismic lines have been reprocessed on a SUN workstation in the Seismology Laboratory of University of Alberta using Insight processing software (IT & A, Landmark) supported by the Lithoprobe Seismic Processing Facility (LSPF). Detailed geophysical interpretation has been carried out along all the reprocessed lines and the lithosphere structure underneath has been imaged.

1.1 The LITHOPROBE Project

LITHOPROBE is a national collaborative geoscience project to study the crust and upper mantle, the lithosphere of Canada. A multidisciplinary team was organized from Canadian universities, federal and provincial research agencies and industry. The objective of LITHOPROBE is to investigate the rigid outermost layer of the Earth to construct a geological history of the Canadian Craton during the past 4000 m.y. Seismic techniques are the main methods for deep crustal inspection, but gravity, magnetism and electromagnetism studies are conducted as well. The largest part of the project funding goes to seismic profiling, but there are separate budgets supporting other geoscience studies such as geochemistry, geochronology, geological surface mapping, rock physical properties and so on (Clowes, 1993). Thus, seismic methods are applied in the LITHOPROBE project to form the basis for other geoscience methods to probe the structure of lithosphere.

Ten areas were designated to investigate various geological provinces in Canada. The Alberta Basement Transect (ABT), which includes three phases of seismic reflection data acquisition, the Central Alberta Transect (CAT, 1992), the Peace River Arch Industry Seismic Experiment (PRAISE, 1994) and the Southern Alberta Lithosphere Transect (SALT, 1995), is one of these ten. It was planned to investigate the structure of the crystalline basement and the deep crust under the Western Canadian Sedimentary Basin (WCSB) and their influence on the overlying sedimentary cover (Fig. 1.1). The basin is the major source of the petroleum resources in Canada. The Central Alberta Transect traverses part of the Pembina field, a large Cretaceous oil pool, in addition to a series of SW-NE oriented Devonian reef trends that also host prolific hydrocarbon production. The deep crustal reflection seismic data which were reprocessed in this thesis come from the dataset of the Central Alberta Transect (CAT). It is worthwhile to mention that even though this survey aims to investigate deep crustal structure, the CAT dataset has yielded high quality seismic images of the basin sediments as well.

1.2 Seismic Methods

Seismic methods use artificial sources (explosives, mechanical vibrators, marine airgun, etc.) to generate seismic waves in solids or fluids in order to image the structure and physical properties of the deep Earth. They can be divided into two main techniques - one is the seismic reflection technique (Fig. 1.2) and the other is the seismic refraction technique. The seismic reflection method, also called near vertical incidence seismic profiling, has been applied to deep crustal study for over 30 years. Compared to the older refraction method, the seismic reflection technique has many inherent advantages in producing information about the crust and upper mantle. This is because the wavelengths of the reflected waves are usually many times shorter than those of refracted waves and the source-receiver intervals in the reflection method are smaller than those of the refraction method. Due to these reasons and the high signal frequency combined with a broad bandwidth, the reflected waves yield high resolution and great precision in imaging the structure of the lithosphere.

When applying the seismic reflection technique, structures of the lithosphere, including the crust, upper and lower lithosphere, are imaged by taking the seismic energy recorded near the surface and using the wave equation to downward continue the pulses to their reflecting point. Any changes in the physical properties of rocks (density, rigidity etc.) will affect the seismic energy and its recorded travel time. The path for seismic waves to travel from a source (shot point) to a reflector and back to the (geophone) receiver are shown in Fig. 1.2. By analyzing and interpreting the recorded information in terms of seismic cross-sections, the underground structures can be recognized. Sometimes, the receivers (geophones) are arranged along lines as near to perpendicular to the strike of the geological structure extension in the research area. The collections of seismic lines are called profiles.

From its birth in the 1920's to the present, the seismic reflection technique has always been the most useful petroleum prospecting technique in the oil industry and has been proven to be the most valuable method for investigating deep crustal structures. That is the reason why the Canadian LITHOPROBE project team chose the seismic reflection technique as the main method of approach to lithosphere studies, while integrating with many

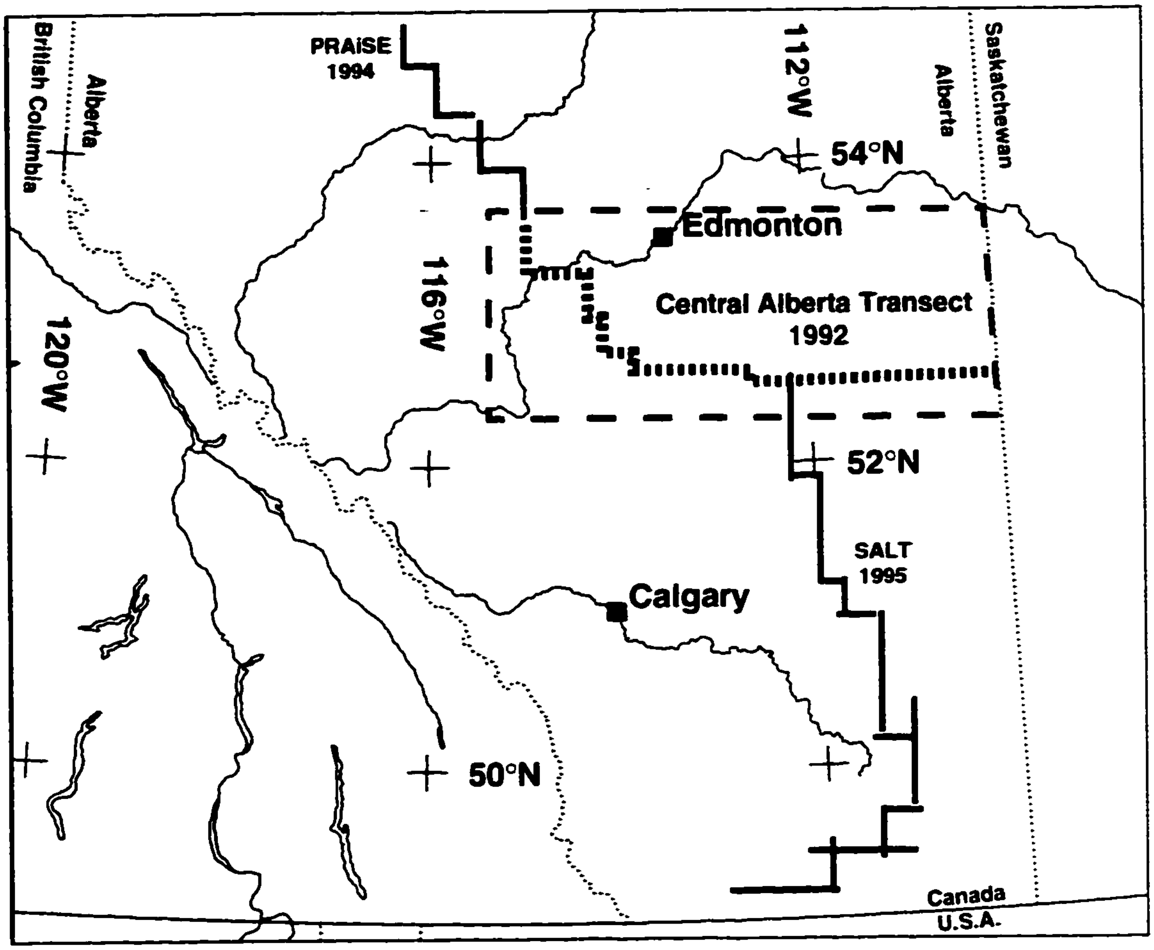

Fig 1.1 Map of Alberta showing the general locations of LITHOPROBE's Alberta Basement Transect (Modified from Burianyk, 1994)

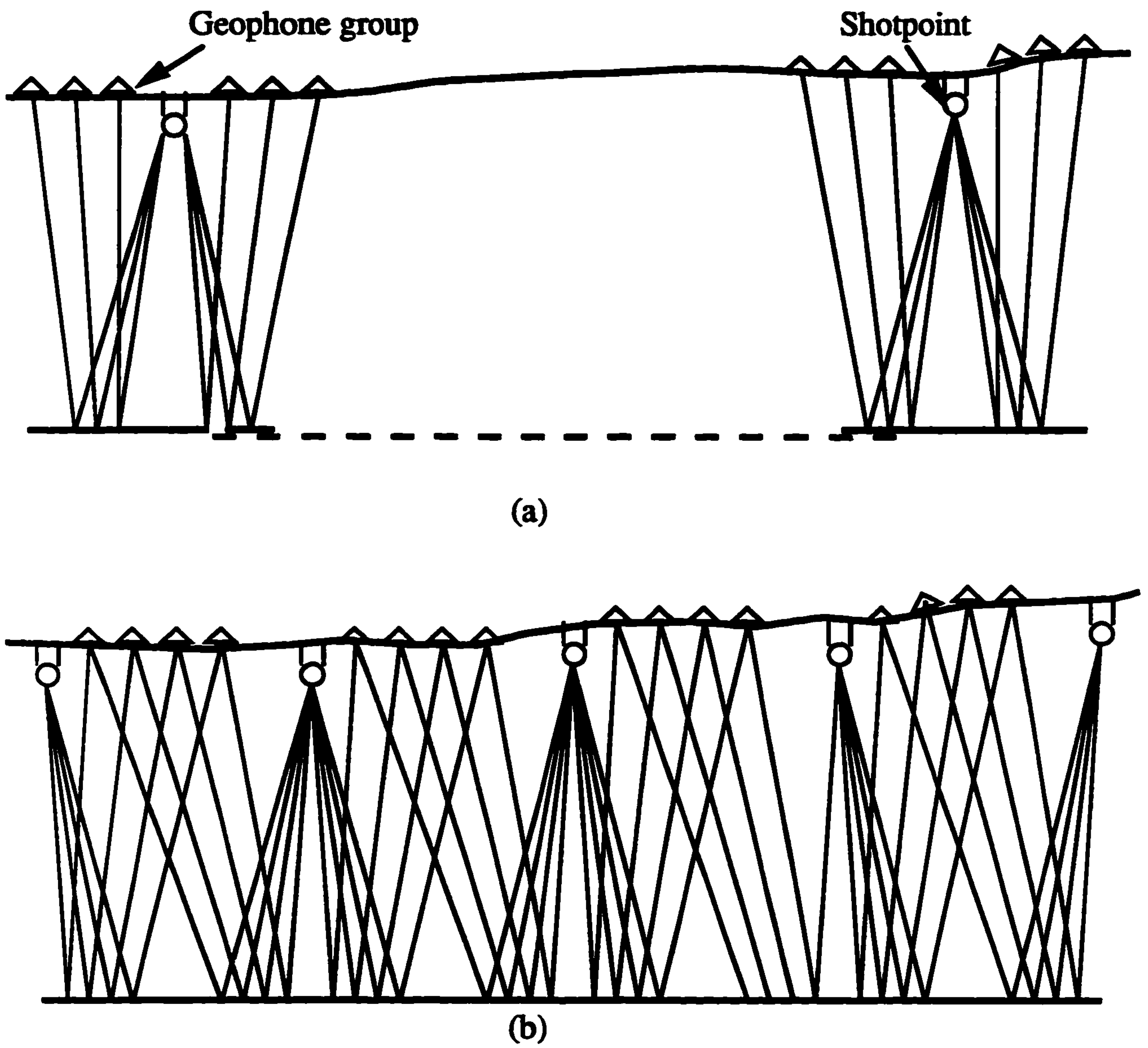

Fig. 1.2 The seismic reflection technique

(a): Reflections are correlated between widely spaced measurements to map an interface

(b): Uniform sampling of the subsurface along lines of seismic profile other geological and geophysical techniques as mentioned before.

As in all seismic exploration methods, the seismic reflection technique consists of three stages: data acquisition, processing and interpretation. Particularly, seismic data processing is a very important stage. Although it is affected by the field acquisition parameters, the computational processing results will directly influence the reliability of the interpretation.

Using digital seismic records and a high speed computer, seismic reflection data may be processed through various signal enhancement techniques to exhibit the very fine detail of the deep structure within the Earth. The techniques include static corrections, a special procedure to correct for near surface velocity anomalies and the difference of elevations used for individual seismic receiver stations. Some auxiliary processes help in the reduction of noise and improve the resolution besides the principal processes.

The three principal processes are deconvolution, stacking and migration(Yilmaz, 1987). By collapsing the seismic wavelet to approximately a spike and suppressing reverberations on some field data, deconvolution quite often improves temporal resolution. Because the common-midpoint (CMP) recording is the most widely used seismic data acquisition technique (Fig. 1.3(a)), common-midpoint stacking is the most important in the three principal processes. As shown in Fig. 1.3(a), geophone groups and source points are used in various combinations so that the reflections are recorded from the same portion of the subsurface a number of times. In the figures, six ray paths involve the same reflecting point and result in 6-fold shooting. After CMP stacking, there is not only a significant suppression of uncorrelated noise to increase the S/N (Signal-to-Noise) ratio, but also attenuation of a large part of coherent noise in the data, such as guided waves and multiples. When the

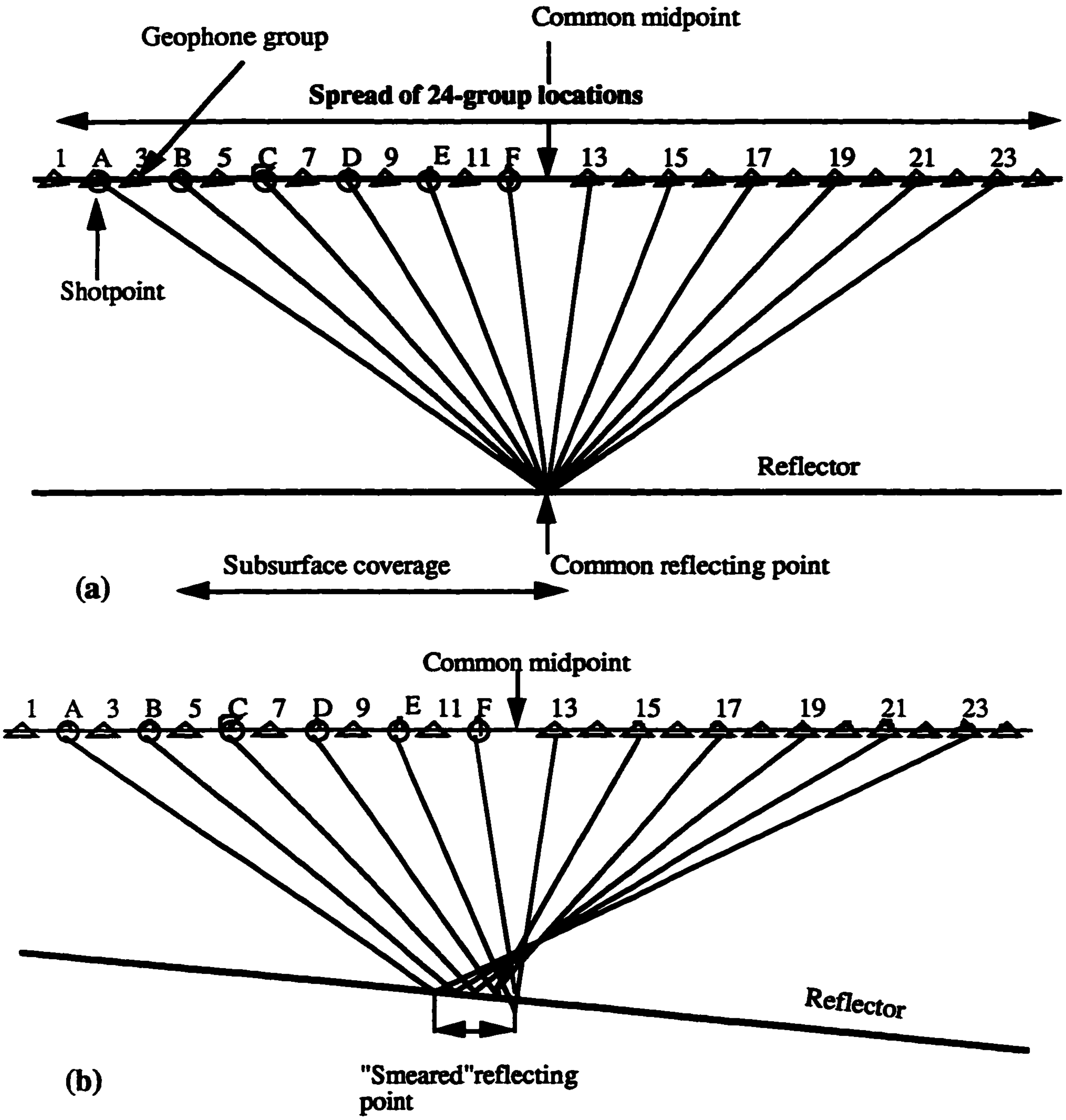

Fig. 1.3. The common-midpoint (CMP) seismic reflection technique.
(a): The common-midpoint (CMP) displayed in horizontal reflector.
(b): The common-midpoint (CMP) displayed in dipping reflector.

reflector is dipping, the reflections will not have a common reflecting point (Fig. 1.3(b)), but a smeared reflecting point which moves updip as the distance between source and geophone increases. This problem can be solved by migration. Migration is an imaging process, which collapses diffraction and moves dipping events to their true subsurface locations. Fig. 1.4 shows three principal seismic data processes along time-offset-midpoint coordinates and their related functions. From this figure, one can visualize the space in which the three processes are applied and the relationships between them.

1.3 Seismic Data Reprocessing And Lithosphere Studies

One fundamental problem in seismic data processing is that differences in the choice of parameters and detailed aspects of implementation of processing algorithms are not always optimal, particularly when they involve massive computing and large amounts of human time for quality control. In this case, data reprocessing is necessary. My data are stacked seismic data processed by Pulsonic Geophysical Ltd., a commercial seismic processor contracted by the LITHOPROBE team. To improve the resolution and the accuracy of the interpretation of the lithospheric structure beneath central Alberta, we undertook the reprocessing using some special techniques.

About the purpose of the lithosphere studies, several questions might be asked. Does knowledge of the deep structure of the lithosphere greatly enhance the understanding of the historical evolution of the research area? What was the role the tectonic evolution of the lithosphere in the formation and distribution of hydrocarbon accumulations? Did reactivation of the deep crustal structures influence the evolution of the overlying sedimentary basin? By reprocessing the crustal-scale seismic reflection data with some effective techniques such as static processing methods, correlation and phase shift migration, a better image of the lithosphere structure in the research area can be provided. After interpreting the reprocessed data in terms of geological sections, new insight into the nature of crustal processes and tectonic assembly

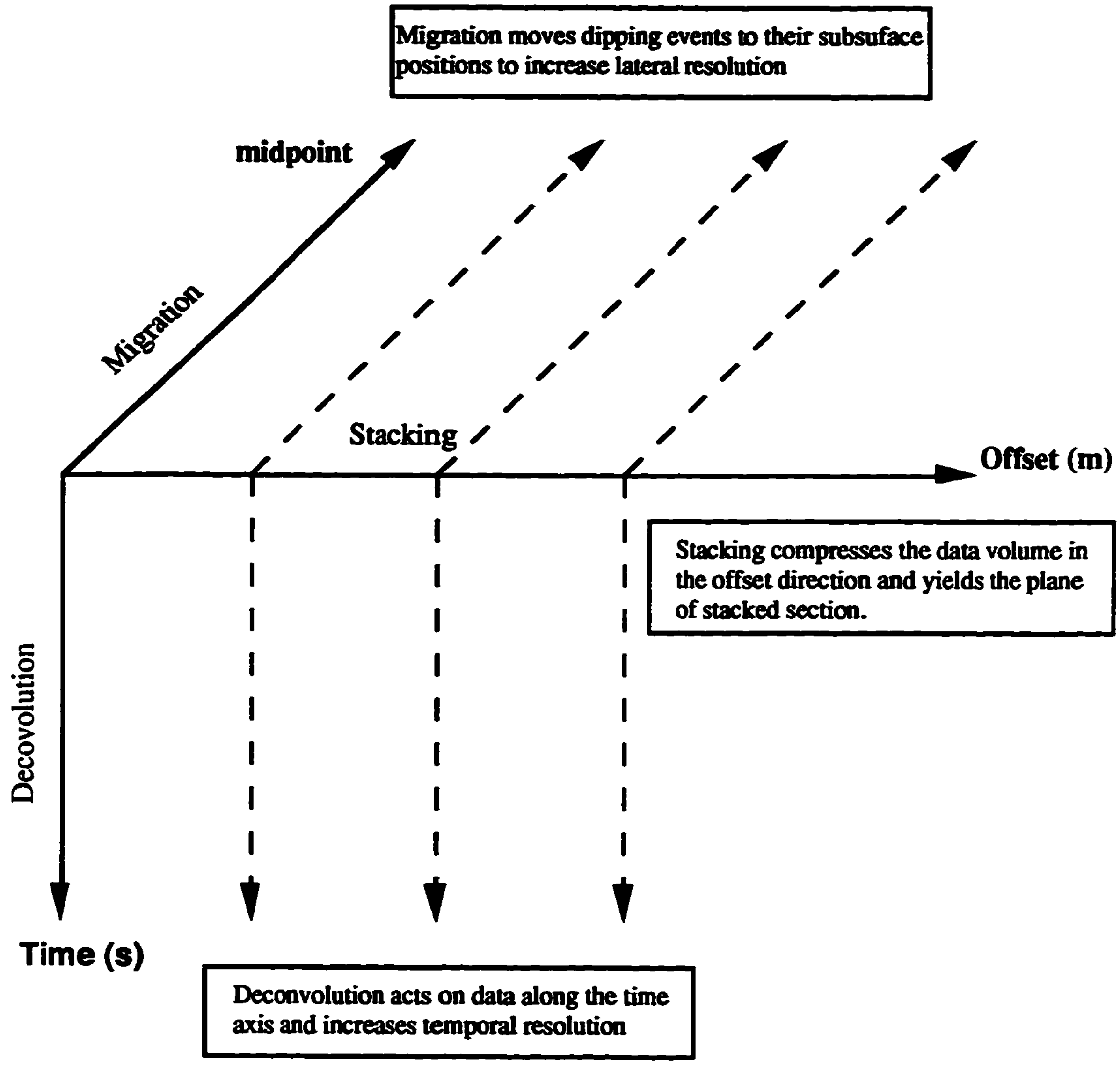

Fig. 1.4 Three principal seismic data processes along time-offset-midpoint coordinates and their related functions. This figure is modified from *Seismic Data Processing*(Yilmaz, 1987).

of the basement in central Alberta may be obtained. This can help answer the questions posed.

1.4 Geological And Geophysical Background

The study area is divided into two geological parts. The shallow part is the Western Canadian Sedimentary Basin (WCSB). The part below the sediments, from east to west, is called the Hearne Craton (of Archaean age) and the Proterozoic Rae Craton. Both cratons extend in a northeast direction. The boundary between these two domains is the Snowbird Tectonic Zone, a structural and potential field discontinuity of controversial origin that can be traced from the Foothills of the Canadian Cordillera eastward to Hudson Bay (Hoffman, 1989; 1990).

The main geographic element of central Alberta (Fig. 1.5) is a plain east of the Rocky mountains which is ideal for seismic data recording. Northwest of the Bow Island Arch and south of Tathlina High (Fig. 1.5), this part of WCSB is called the Alberta Basin. It can be viewed as a simple wedge of Phanerozoic strata above the Precambrain crystalline basement. The Phanerozoic strata have a maximum thickness of about 6000m on the axis of the Alberta Syncline which reduces to zero in the northeast along the Canadian shield. The shadowed region in Fig. 1.5 indicates the thickest area of the Alberta Basin. Fig. 1.6 shows the thickness of the Phanerozoic strata. Having two major high areas inside the basin: the Peace River Arch and the West Alberta Ridge, the Alberta Basin is a northwest-trending trough in front of the Cordilleran fold and Thrust Belt and extends eastward to the Canadian shield (Mossop and Shetsen, 1994). Bounded by the exposed Canadian shield in the northeast and the Rocky Mountain Fold and Thrust Belt (RMFTB) in the southwest, the tectonic and stratigraphic history of Alberta Basin is inextricably related to the origin and evolution of Canadian Cordillera,

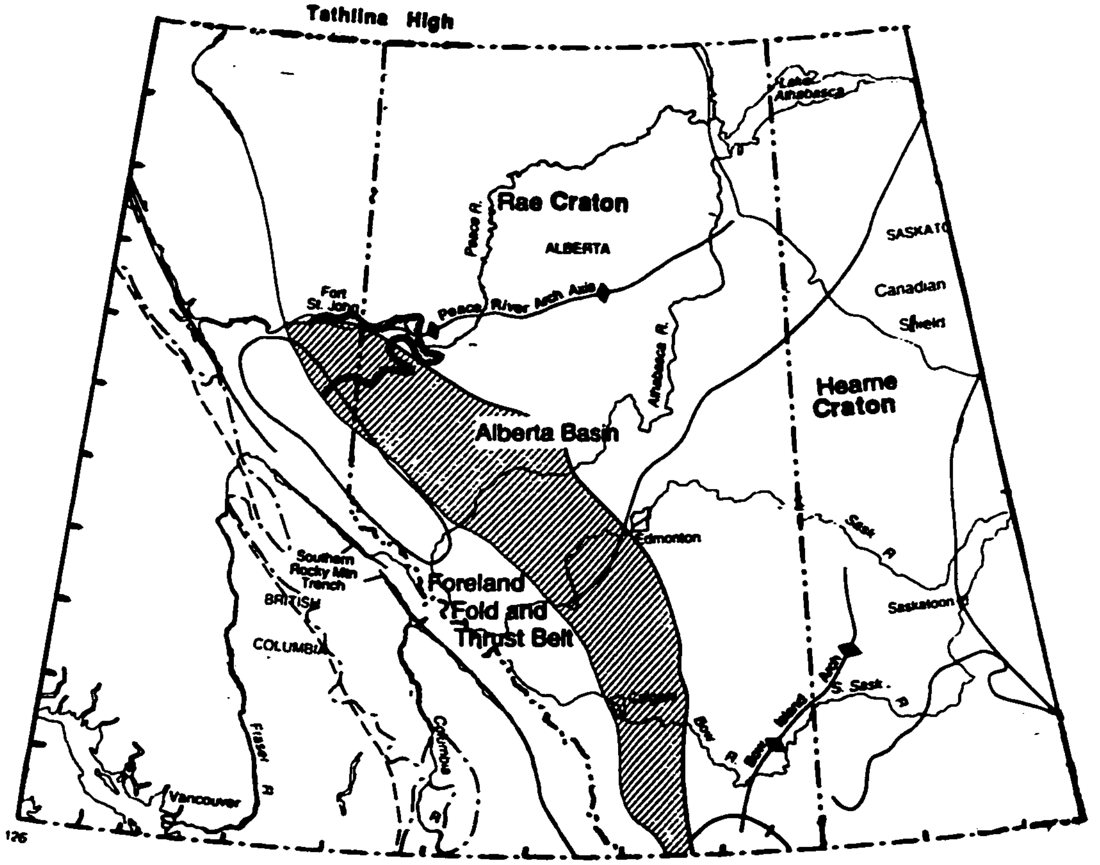

Fig. 1.5 The geological setting of the Alberta Basin. This figure is modified from the Geological Atlas of the Western Canadian Sedimentary Basin.

especially the Canadian Rocky Mountains.

The eastern-most area of the Cordillera is also an integral part of the Western Canadian Sedimentary Basin (WCSB). The Cordillera, including the Rocky Mountains, is a result of collision between the North American and many proto-Pacific plates. Preserved in the Cordillera, the western margin of the WCSB has had a long tectonic history and was dominated by major episodes of extension. The central part of Alberta shows little evidence of significant tectonic activity until Tertiary time (Wright et al., 1994). Table 1.1 is a summary of the geological history in central Alberta (Mccrossan and Glaister 1964). Fig. 1.7 shows the major Mesozoic structural elements of the study area and the sediment distribution along one cross-section.

As a part of the stable craton throughout most of Phanerozoic time, the Alberta Basin has sedimentary rocks from nearshore clastic facies of Cambrian, Ordivician, Silurian, Devonian age through marine environment of Triassic, Jurassic strata and mixed continental-marine facies of Cretaceous to continental Cenozoic rocks. In the stable depositional environment, many marker horizons can be recognized for over 1500 kilometers. Belonging to the Cretaceous Colorado group, the Second White Speckled shale layer (2WS) was deposited in a sea and formed a widespread horizontal sedimentary marker covering almost the whole basin. In the following chapter, the 2WS will be chosen as a marker in the reprocessing to remove structural ambiguity introduced by different processing datum elevations of the individual seismic lines. By picking and flattening the 2WS to a fixed stratigraphic level, all the seismic reflection data below it can be corrected for inaccurate static correction and are all normalized structurally to a time before the latest phase of Cenozoic structural deformation.

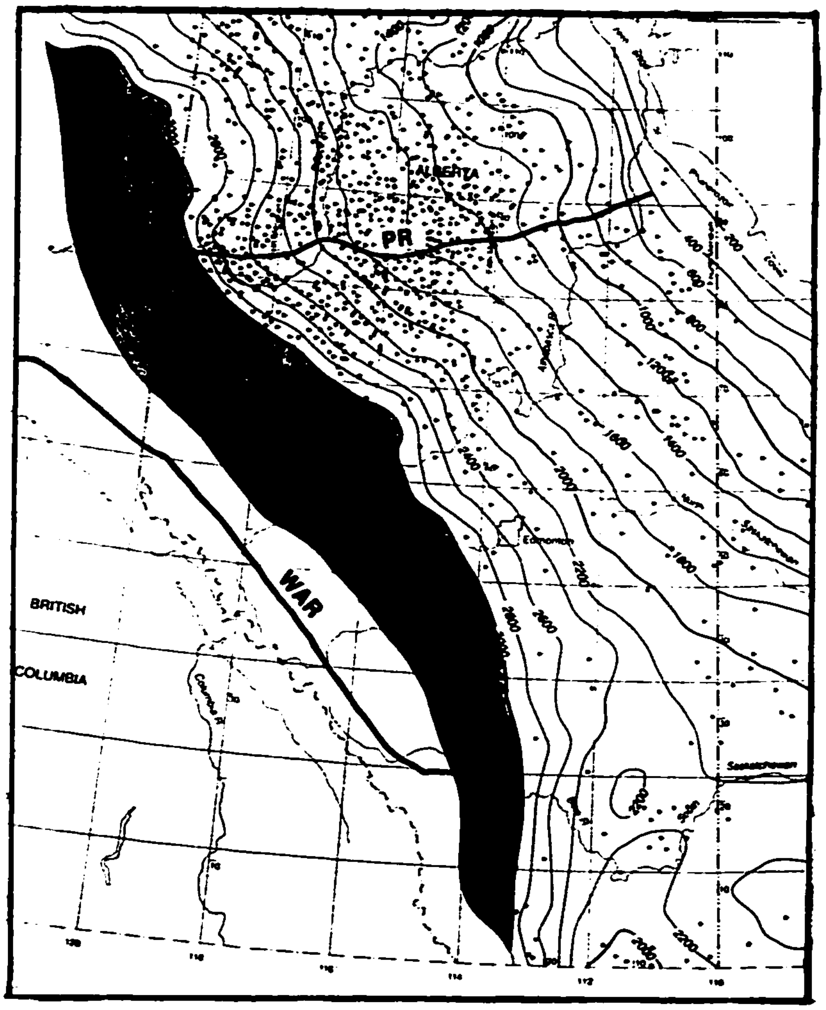

Fig. 1.6 Phanerozoic isopach (KB to Precambrian Basement) of the Alberta Basin. Represents 540 m.y. of deposition.KB - Kelly Bushing of rig. This figure is modified from the Geological Atlas of the Western Canadian Sedimentary Basin. PR - Peace River Arch WAR - West Alberta Ridge

• Control well ■ Thickest parts of the basin

Table 1.1 Summary of the geological history in central Alberta

Time	Main Events
Quaternary	Minor uplift with accompanying degradation. Glaciation.
Tertiary	Rock Mountain orogeny (Laramide) with formation of Rockies by thrusting from the west and up to 100 miles of crustal shortening.
Late Cretaceous	Basin area more negative and marine with eventual filling and terrestrial deposits in western parts.
Early Cretaceous	Deposition continued uninterrupted from Jurassic time in Foothills and Front Range area. Widespread transgression of the sea onto the craton with abundant clastic sediments grading from non-marine in west to marine in east derived from new mountains to the west.
Jurassic	More widespread transgression along west and southern part of craton, erosion continuing in other parts of craton. Depositing terminated by mild uplift. May have been widespread transgression over Palaeozoic rocks in very late Jurassic.
Triassic	Seas narrow, restricted to far west. Erosion in other parts of craton. Deposition terminated by mild uplift.
Permian	Narrow seas and minor deposition in Cordillera and north-western Plains. Erosion continued in other parts. Widespread uplift of craton. Devonian and widespread transgression of craton with resulting Carboniferous thin deposits formed. Sediments mostly "intrabasin" carbonates and ultrafine clastics. Uplift with some erosion. Ordovician and extensive deposition in seaway confined around the Silurian general Trench and western Rockies areas. Restricted deposition in eastern part of craton. Widespread uplift and erosion.
Late Cambrian	Continued deposition of carbonates and fine clastic sediments in Rockies, very restricted deposition on Plains.
Middle Cambrian	Continued deposition of fine clastic sediments and carbonates in Rockies, first transgression of the seas onto the Plains, wide-spread sea left thin deposit-mostly clastic sediments.
Early Cambrian	Deposition of fine clastic sediments and carbonates in Rocky Mountains and non-deposition on Plains.
Late Proterozoic	Some deposition in western Rockies.
Middle Proterozoic	Possibly some deposition in western Rocky Mountains area. Deposition of quartzose sands in intracratonic basins on present Shield but not recognized on surface.
Early Proterozoic	Highly metamorphosed rocks present under Plains. Long and complicated geological history. Hudsonian orogeny closed the Early Proterozoic. This was the last major orogeny involving the western Canada craton.
Archaean	Highly metamorphosed rocks present in eastern end of section. Long and complicated geological history.

Along the Central Alberta Transect (CAT) line, there are nine wells used as control points for seismic-stratigraphic correlations (Dietrich, 1996). Of these wells, some are drilled to the middle Devonian and some to the Precambrian. Table 1.2 givess the location of the nine wells along the seismic lines from west to east. Fig. 1.8. shows the position of these wells along the Central Alberta Transect (CAT). It is shown that all tnine wells are very near to the seismic line and well Amoco Wroses is just on Line 4. The well information is very useful in seismic correlation, especially in identifying the depth of some important reflectors.

Making use of drilling core information acquired during 50 years of exploration, the Alberta Basin is found to have basement crystalline rocks in a complex mosaic of Archean and early Proterozoic crystalline terranes. Some of the structural elements of the Alberta Basin are associated with movements of the underlying basement and these different domains. The relation between the pre-existing terrane boundaries, the zones of weak crust and the patterns of the deposition and mechanisms of the basin formation is what we are trying to find out.

Through the interpretation of aeromagnetic signatures and U-Pb geochronology of drill core recovered by the petroleum industry, it was interpreted that the crystalline basement buried beneath the Western Canadian Sedimentary Basin (WCSB) corresponds to distinct crustal domains(Ross et al., 1994, Villeneuve et al., 1993). In 1992, Lithoprobe began a five-year program to systematically examine the deep crust of the region and its possible influence on the evolution of the sedimentary cover.

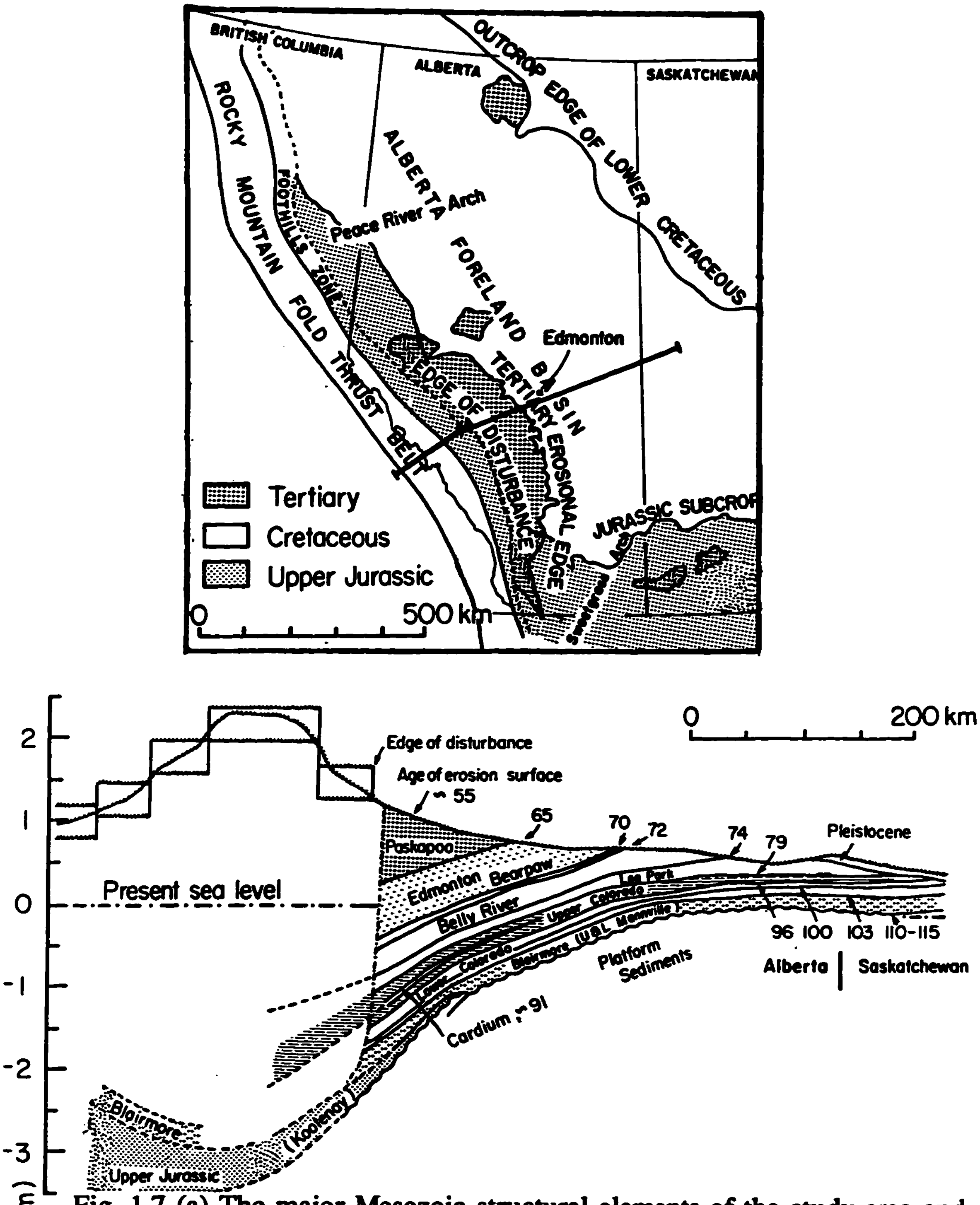

Fig. 1.7 (a) The major Mesozoic structural elements of the study area and the location of one section. (b) Sediment distribution along the section. Numbers are the approximate ages of the boundary between the stratigraphic units. (Modified from Beaumont et al.,1993)

Table 1.2 Location of the nine wells along CAT

Well Name	Location
• Mobil Pembina	11 - 27 - 49 - 08W5
• Home Brightbank	10 - 05 - 52 - 02W5
Amoco Wroses	15 - 35 - 44 - 02W5
Canterra Bashaw	16 - 36 - 41 - 23W4
Atapco Buffalo	06 - 11 - 40 - 21W4
• CPOG Oberlin	10 - 15 - 38 - 21W4
Tricent Forestburg	16 - 36 - 41 - 15W4
• PCP Killam	15 - 34 - 43 - 10W4
• BP Chauvin	06 - 28 - 42 - 02W4

Wells with • are those drilled to the Precambrian.

On the eastern part of this central Alberta study area, Line 10 crossed a strong positive aeromagnetic anomaly trending north, named the Eyehill High. Basement intersections in the Eyehill High consist of Archean metaplutonic and gneissic rocks, suggesting that the Eyehill High is an extension of the high-grade rocks of the Archean Cree Lake Zone in western Saskatchewan (Collerson et al., 1988). With a broadly trapezoidal outline bounded to the east by the Eyehill High, the Loverna Block is characterized by a negative to neutral aeromagnetic signature with local moderately positive anomalies. The Lacombe Domain is a north-east trending belt with moderate negative aeromagnetic character west of the Loverna Block. It is bounded to the northwest by the Rimbey High. The Rimbey High is a prominent northeast-trending curvilinear domain that extends from exposed rocks of the Virgin River Shear Zone (a strand of the Snowbird Zone) in Western

Saskatchewan (MacDonald, 1987) southwestward beneath the Rocky Mountain Foothills (Ross and Parrish, 1991). With a positive aeromagnetic signature, the Rimbey High is interpreted as a possible magnetic belt consisting of biotite granite.

The Thorsby Low, a narrow north northeast-trending curvilinear aeromagnetic and gravity low zone, merges with the Snowbird tectonic zone to the northeast and appears to head unbroken into the Cordillera to the southwest. Coinciding with the edge of a gravity high to the northwest, the Thorsby Low seems to mark a pronounced crustal discontinuity that may represent the ductile southern extension of the Snowbird Tectonic Zone (Ross et al., 1993).

The Wabamum High, interpreted as a large area of magmatic rocks, is a broad wedge-shaped domain with a dominantly positive aeromagnetic and gravity signature at the northwest end of the seismic lines. According to the interpretation of potential field data and U-Pb geochronology of selected samples of basement, the Eyehill High and Loverna Block both are Archean Cratons, the Lacombe domain consists of metavolcanic-metasedimentary rocks, the Rimbey and Wabamun Highs are continental margin magmatic arcs. Actually, these Precambrian tectonic domains mentioned above have provided a critical geophysical framework for further study of the interaction between the crystalline basement, the deep crust with the sediment cover.

Fig. 1.9. shows the aeromagnetic potential field with the seismic lines plotted. From the cross-section shown in Fig. 1.10. and comparing it with Fig. 1.9., one can find that Line 8 is just over the anomaly named "Bawlf high". Line 6 and Line 7 belong to the area "Lacombe Domain" with three wells drilled along Line 7. Line 4 and Line 5 are located in the anomaly of "Rimbey High" with one well located on Line 4. Line 3 and part of Line 2 are in the

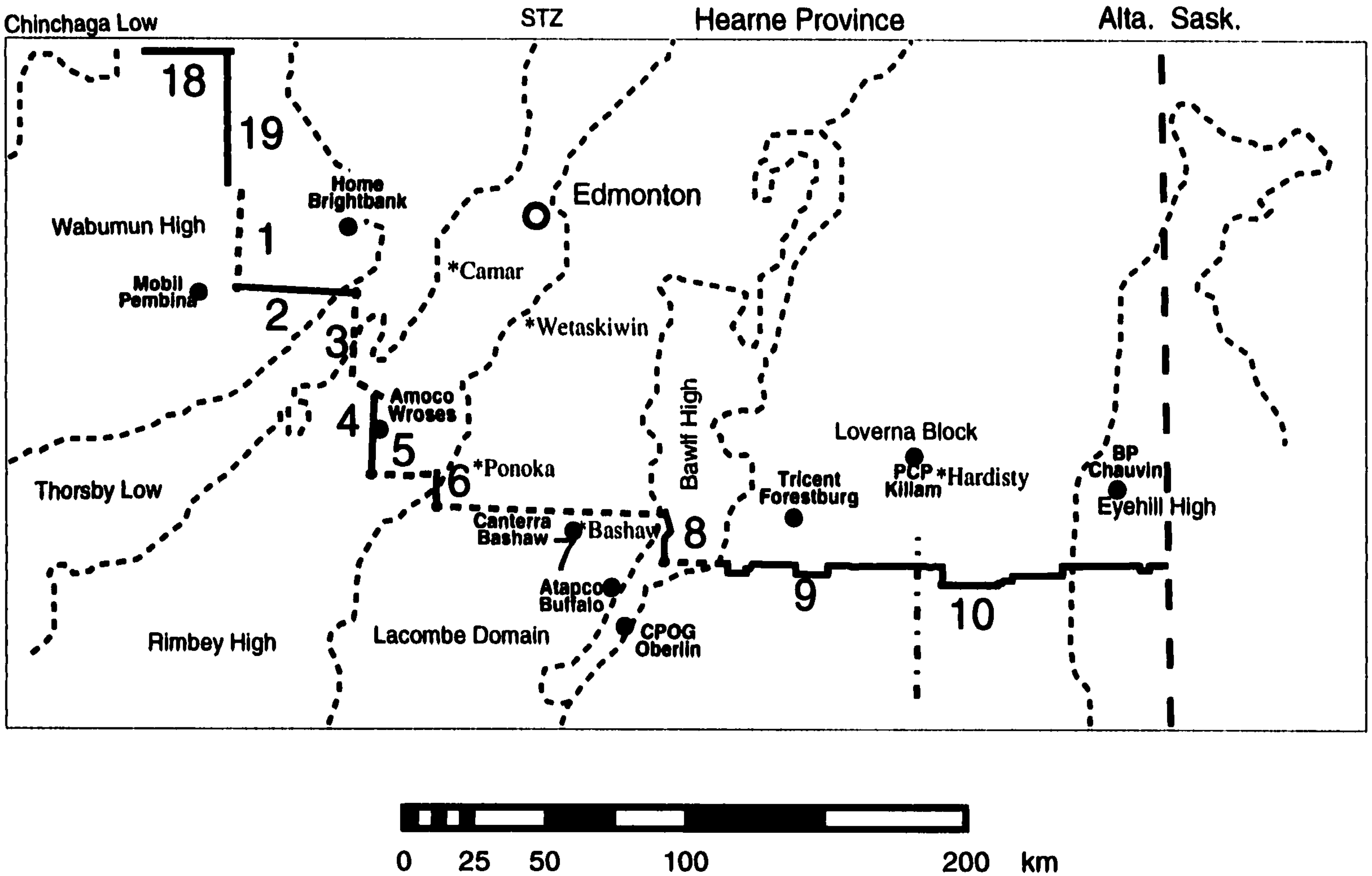

Fig. 1.8 The location map of wells along the Central Alberta Transect (CAT).

anomaly of "Thorsby Low" with one well drilled nearby. Line 1 and part of Line 2 are just in the centre of the anomaly called "Wabamun High" with one well drilled near the boundary between Line 1 and Line 2. Seismic lines crossing distinct domains may have different reflection characters. This need to be noticed during interpreting the reprocessed profiles.

In the Bouguer gravity anomaly map of the research area, there is a prominent curvilinear low in the western part of the transect at the subsurface extension of the Snowbird Tectonic Zone. Particularly, the Bouguer gravity anomaly map is dominated by a long-wavelength gravity anomaly, which is related to the properties of the lithosphere such as variations in thickness, thermal structure and average density. This information can be useful for inferring the structure of the lithosphere from a new perspective. Therefore, integrating the aeromagnetic, gravitivative potential fields and well data-based geological studies with the deep crustal seismic reflection data should elucidate the structures of the crust underlying the basin more reasonably.

1.5 Seismic Data Acquisition and Current Research

In the summer of 1992, the first modern ten lines of crustal-scale seismic reflection data in Alberta were recorded. Designed by G.M. Ross and E.R. Kanasewich, these lines were placed across central Alberta and yielded a continuous seismic cross section across many conspicuous magnetic anomalous trends (Ross, Broome, and Miles, 1994).

Using a cable telemetry recording system with a mechanical vibrator source, Veritas Geophysical Limited acquired the data, including ten 2-dimensional seismic lines, a 3-dimensional survey and a wide angle expanding spread reflection (ESP) profile (Pulsonic, 1993). These central Alberta

Transect lines cover over 500 kilometers extending from the far west line 1 at Township 53 - Range 7W5, 80 km west of Edmonton to the far east line 10 at the Alberta - Saskatchewan border Township 40 - Range 1W4(Eaton, et al., 1995). As shown in Fig. 1.8, Lines 1, 3, 4, 6 and 8 were north-south while Lines 2, 5, 7 were predominantly east-west. The lines followed the grid road system of Alberta, crossing the basement domains as near as possible perpendicular to the strike (G.M. Ross, et al., 1993). The seismic lines were designed to over-lap at corners to eliminate the need for subsequent crooked-line processing.

The object of acquiring these seismic lines is to image the deep crustal structure. In this case, four large vibroseis units were needed to obtain reflected energy from a depth of least 50 km. The large truck-mounted mechanical vibrators used in the reflection work had sweep frequencies (10 - 56 Hz) that are slightly lower than the average value for industrial acquisition. The group spacing for the sources was 50 m with 240 channel recorder resulting in 6000% CMP (Common-midpoint) coverage, which greatly improves the signal quality.The parameters for the recording and acquisition are shown in Table 1.3.

Besides these special recording and acquisition parameters, high quality data recovery was ensured with real-time noise elimination processing and sophisticated vibrator synchronization monitoring. According to Eaton et al. (1995), the data quality for this survey is consistently good across the transect, as demonstrated by the lateral continuity and consistent character of reflections from the sedimentary section. This should be an advantage for processing, reprocessing and interpreting.

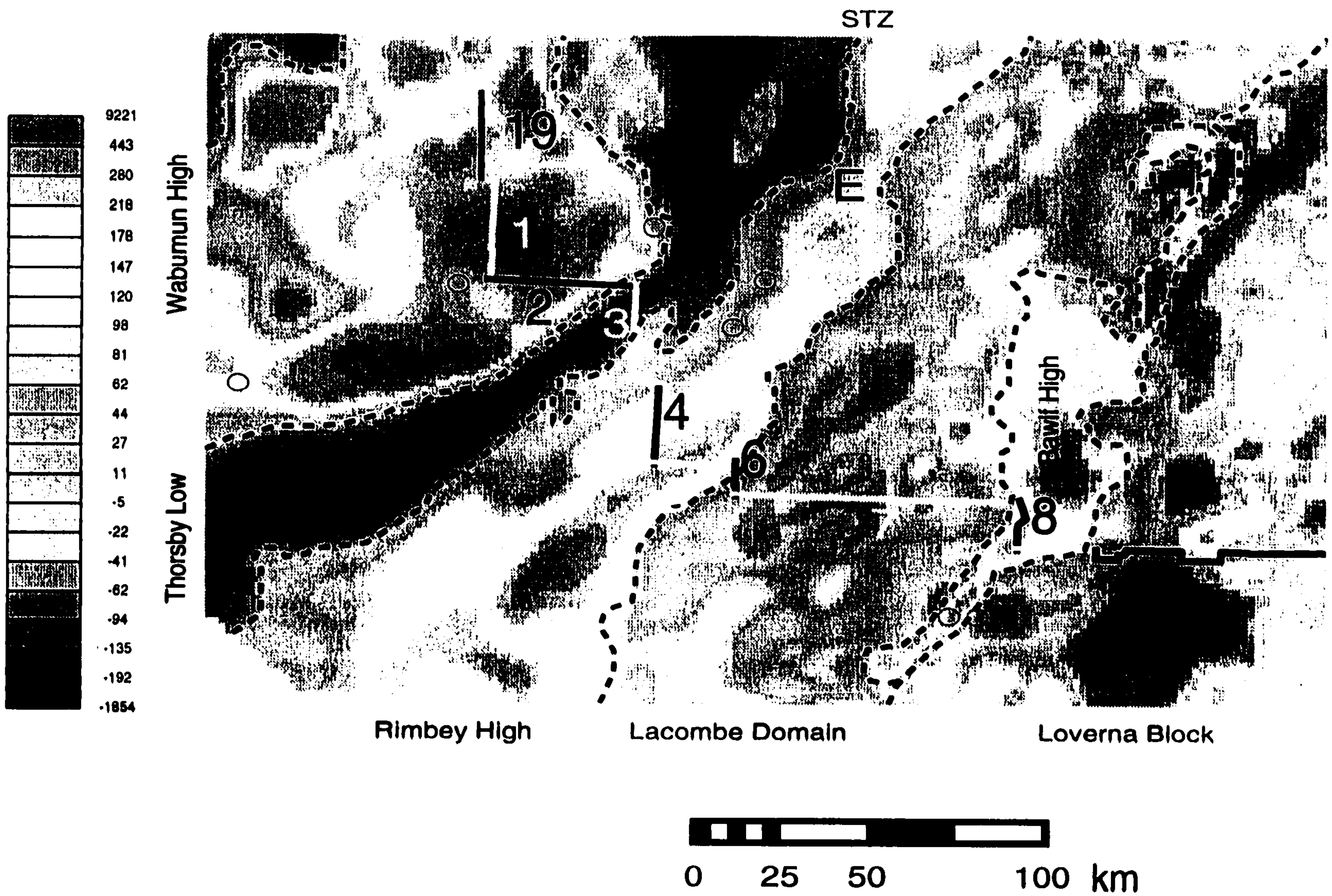

Fig. 1.9 Aeromagnetic anomaly map of central Alberta with the location of the LITHOPROBE seismic lines plotted. (Index unit nT)

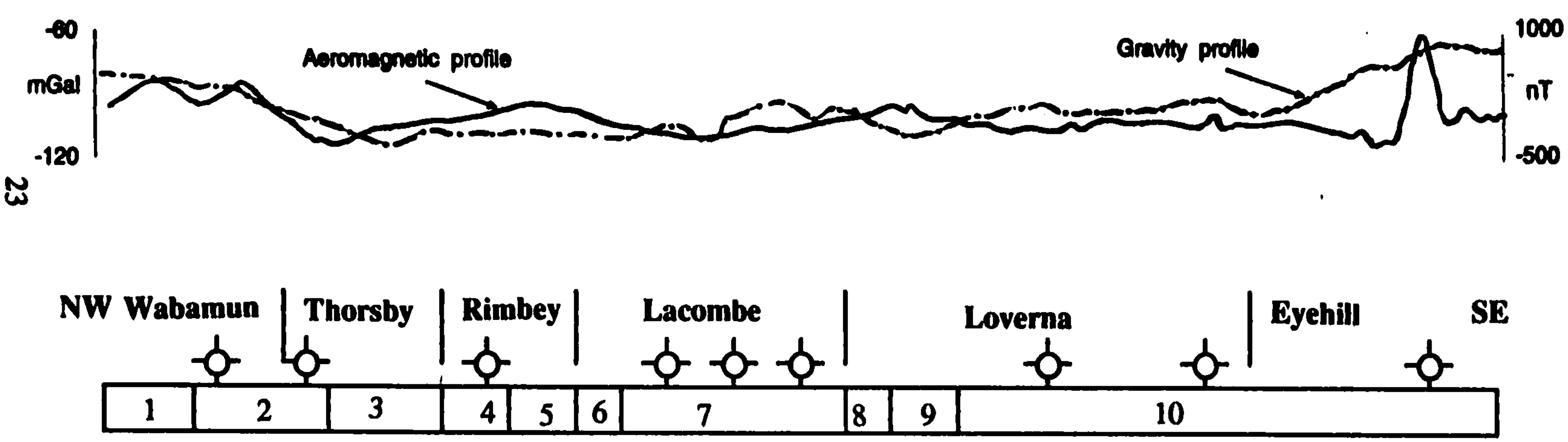

Fig. 1.10 Cross-section of the Line 1 - 10 with gravity and aeromagnetic anomaly curve plotted along the top and the section of tectonic domains with location of wells in the middle.

Table 1.3 Recording and acquisition parameters of the seismic data

Recorded by:	Veritas Geophysical Ltd.
Data of Survey:	July, 1992
Recording System:	I/O system one, 16 bit digital + 4 bit gain control
Recording filter:	3 - 90 Hz
Format:	SEGD
Sweep Frequency:	10 - 56 Hz
Notch Filter :	out
Resonant Frequency:	14 Hz
Record Length:	18.0 seconds
Sample Rate:	4.0 ms
Sample Type:	Vibroseis
Source pattern:	4 Vibs/50 meters
Receiver Pattern:	9 over 72 meters
Number of Sweep:	8
Source Interval:	100 meters(for 2-D data)
Group Interval:	50 meters
Nominal Fold(2-D data):	6000%

There are eight lines (plus Line 2a) out of ten which have been reprocessed as a part of this research. They are shown in Table 1.4. The last two lines (Line 9 and Line 10) were reprocessed and interpreted in 1994 (Rong Lu, 1994). These deep crustal seismic profiles not only can provide the structures of basement domains and lower crust in cross section, but also can indicate in detail the relationship between crystalline basement and sedimentary cover, the lower crust and upper crust, the crust-mantle boundary.

Table 1.4 Shooting information of 2-D production data

Line #	CDP#	Source Point Range	# of Shots/line	Line Length(km)
1	208-1625	102-823	362	36.1
2	205-1800	104-1010	457	45.5
2a	1542-1996	815-1011	99	11.4
3	208-1948	101-993	445	44.6
4	206-1331	102-662	286	28.4
5	209-1196	101-603	258	25.8
6	205-761	101-389	145	14.4
7	238-3591	119-1797	837	84.8
8	208-974	107-495	198	19.7
Total			3,087	310.7

By comparing the 2-D and 3-D seismic dataset of line 2 and line 3, Kanasewich et al. (1995) found that the two-way traveltime to the Moho varies from 14.1s to 14.3s and there is a tendency toward deeper Moho to the east. Based on the 2-D seismic data reprocessed by Rong Lu, Kanasewich (1994) interpreted line 9 and line 10. One conclusion they made was that "The seismic section shows a steeply dipping basement fault which also effects lower Cambrian sediments. The basement topography shows the effects of a long period of erosion and several faults that were generated or reactivated during lower Palaeozoic sedimentation. Faults extending into the upper Devonian may be present but there are very few of these." Rong Lu (1994) recognized several zones where the Precambrian rock may have been reactivated in the reprocessed Line 9 and Line 10. She also found that the Precambrian unconformity is crossed by some faults which extend into the sedimentary zone.

Eaton et al. (1995) analyzed the nature and extent of Alberta basement controls over Phanerozoic depositional and diagenetic processes. They have established three styles of basement influence in distinct seismic expressions: Type 1. Sediment onlap, drape and infill over underlying basement topography. Type 2. b Intersection of basement faults with the basement-cover contact. Type 3. Sedimentary facies change above a basement tectonic boundary. In detail, they gave a description and interpretation of the different interactions, also some examples.

From the crustal seismic reflection data, Ross et al. (1993) imaged the paleoproterozoic collisional orogen beneath the sedimentary cover of central Alberta. They concluded that the major crustal shortening processes because of the formation of a large region crustal thrust belt with opposite vergence in eastern Alberta has affected the basement of Alberta.

1.6 Outline of this Thesis

Besides the introduction to the Canadian national project LITHOPROBE, the seismic reflection techniques involved and background information, the geological and geophysical background in central Alberta seismic data acquisition parameters and its current research, the purpose of this thesis and the problem need to be solved are mentioned in this chapter.

Chapter 2 is a key chapter of this thesis. It describes the detailed reprocessing methodology and procedure for Line 1 to 8 and also Line 18 and

19. A processing stream diagram is used to review the processing history of the seismic data processed by Pulsoinc Geophysical Ltd. It is the stacked seismic data that the reprocessing begins with. The effective reprocessing techniques are explained and carried out to obtain the migrated seismic sections with 2WS flattened to a fixed stratigraphic level. Besides the Second White Speckled (2WS) Shale layer picking and flattening, the reprocessing techniques include padding empty traces on each edge of the seismic line, velocity profile editing and shifting and coherency filtering of the migrated seismic data. The comparison between the pre-reprocessed and after-reprocessed seismic data is also presented. Two different migration methods were used, one a commercial package software and one developed at the University of Alberta. Lines 18 and 19 from the 1994 Peace River Arch Industry Seismic Experiment (PRAISE) were added to this study because they clarified the structure of the Wabamun domain which was encountered on Lines 1 and 2.

In Chapter 3, the geophysical interpretation of these ten lines is given one by one. Many interesting results such as faults and thrusts near the basement and the crust-mantle boundary, the interactions between different reflection layers and some important strong reflections traced are shown. Some discussion is given on their formation mechanism. Integrating with aeromagnetic and gravitational potential fields, the tectonic evolution of the lithosphere in central Alberta and its role in the formation and distribution of hydrocarbon accumulations are discussed to get a better understanding of the historical evolution and economic potential of the area.

Chapter 4 summarizes the conclusion of this research. It discusses the application of LITHOPROBE's seismic deep crustal reflection data acquired across the central Alberta. The excellent reprocessed data quality allows clear imaging of the lithosphere structure below the Alberta Basin. Finally, by analyzing the reprocessing procedure, the reprocessed seismic data and their geophysical interpretations, the general conclusions and important results are put forward.

Chapter 2 Reprocessing Methodology and Procedure

2.1 Introduction

In seismic exploration, processing is the bridge connecting data acquisition and interpretation. The most common objective of data processing is to increase the signal-to-noise (S/N) ratio. In seismic interpretation, the signal consists of primary reflections, i.e., the seismic waves that have been reflected only once by bedding underneath the seismic line (R. E. Sheriff, 1989). But in field experiments, different types of events such as surface waves, shallow refracted energy, multiple reflections and diffracted waves may arrive at the same time as primary reflections, as shown in Fig. 2.1. These, in addition to background ambient noise, are usually superimposed on the seismic record. Only by seismic data processing can the primary events be enhanced at the expense of extraneous waves and noises.

Preprocessing includes demultiplexing, trace editing, static correction, geometric spreading correction, deconvolution and stacking. Deconvolution is used in the recording of the data to remove the distortion produced by many convolving operations. Seismic data processing includes frequency and wavenumber filtering, additional deconvolution to enhance high frequencies and migration. In the first stage, the seismic data are demultiplexed to correct for instrument response and to arrange the digital signals in a convenient format for further processing. Trace editing involves deletion of very noisy traces or noisy sections of data. Static corrections are the important factor in the preprocessing and involve correction for differences in elevation and near surface velocity variations. Velocity analysis and static corrections are necessary to obtain good subsurface velocities which are required for stacking and migration.

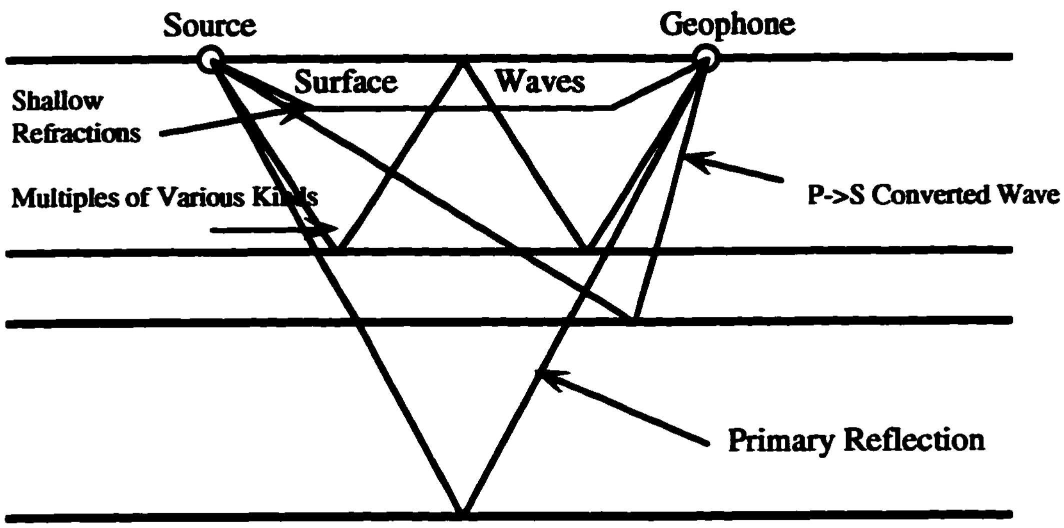

Fig. 2.1 Various kinds of waves may have the same traveltime. (After R. E. Sheriff, 1989)

Stacking can reinforce reflected energy that is in phase and minimize the effects of respective types of noise. Seismic data is recorded so that it may be stacked according to the common midpoints (CMP) of the reflected events. The number of seismograms stacked at any typical location is called the stacking fold. A normal moveout (NMO) correction is applied in a conventional seismic data processing flow chart (Fig. 2.2) to data with different source to receiver paths so that the seismic waves appear to be reflected at vertical incidence. Residual static corrections are performed on the moveout-corrected CMP (common midpoint) gathers to improve stacking quality. Migration is the complex procedure used to image each reflecting event at its appropriate subsurface location and produce a display of the seismic data from which the structural subsurface horizons can be inferred.

The seismic data acquisition for the Central Alberta Transect (CAT) - LITHOROBE's project was performed by Veritas Geophysical Limited in July of 1992. The acquisition and recording parameters are mentioned in Chapter 1. Contracted by LITHOPROBE, Pulsonic Geophysical Ltd. processed all the CAT data according to the general processing sequence in the same year. This included data format transformation, gain compensation, zero to minimum phase conversion, deconvolution, surface consistent residual static, velocity analysis, NMO correction, stacking, random noise attenuation and migration (Hepburn et al., 1993). Because the budget was limited for the commercial processing sequence and processing procedures need to be iterated several times to optimize the results, data reprocessing is necessary. By using the Insight 5 processing software package of Inverse Theory and Application (IT&A, Landmark) through the Lithoprobe Seismic Processing Facility (LSPF), CAT seismic data were reprocessed in the Seismology Laboratory, University of Alberta. The procedure was begun with the stacked seismic data provided by Pulsonic Geophysical Ltd. and followed four main steps. They are summarized as follows:

Step 1. Correction of original static processing
- Picking and flattening the geological marker
- Padding empty traces on each side of the seismic section
- Editing and shifting the velocity profile

Step 2. Migration
- Phase-shift migration (Industry Algorithm)
- Depth Migration with Optimized Coefficients (U. of A. Seismology Laboratory Algorithm)

Step 3. Coherency filtering

Step 4. Plotting
- Compressing the long seismic section
- Displaying

Static corrections obtained by computerized commercial packages are imperfect because the procedure is nonlinear and good results can take an enormous amount of computing time. To improve these, we have taken advantage of the simple stratigraphic nature of a shallow Cretaceous bed, the Second White Speckled Shale. This marker horizon, which has produced a clear seismic reflection over much of Alberta, was deposited in a shallow marine basin with a very gentle dip. Assuming uniform tectonic conditions, one can use this bed as a marker horizon to correct the near random fluctuations introduced into the seismic data by computer processing. One can also remove the effect of subsequent tectonic warping by flattening the horizon to its condition when the sediments were deposited. The procedure works well over distance of 50 to 100 km but needs adjustment for longer lines, so different reference levels are used along an extended profile. One must also correct for seismic velocity changes as the horizon deepens when approaching the foothills and the mountains. The procedure is very labour intensive, involving human identification of the Second White Speckled Shale reflector and correcting it for the depth errors introduced.

One fixed time level was chosen to flatten the Second White Speckled shale(2WS) marker. This was set arbitrarily to 1.0 second in two-way traveltime. To make a consistent correction, the velocity profile at the special CDP number is shifted by the same amount as the corresponding marker.

Before migration the data is padded with zero amplitude traces along each edge of the seismic section to avoid creating false edge diffraction. Phase-shift migration was carried out in the frequency - wavenumber domain to image the stacked section so that it resembles a geological cross section along the seismic line. An alternate depth migration method, the final version being created by Dr. S. Phadke at the U. of A. was used to good effect as a comparison. After migration, coherency filtering is

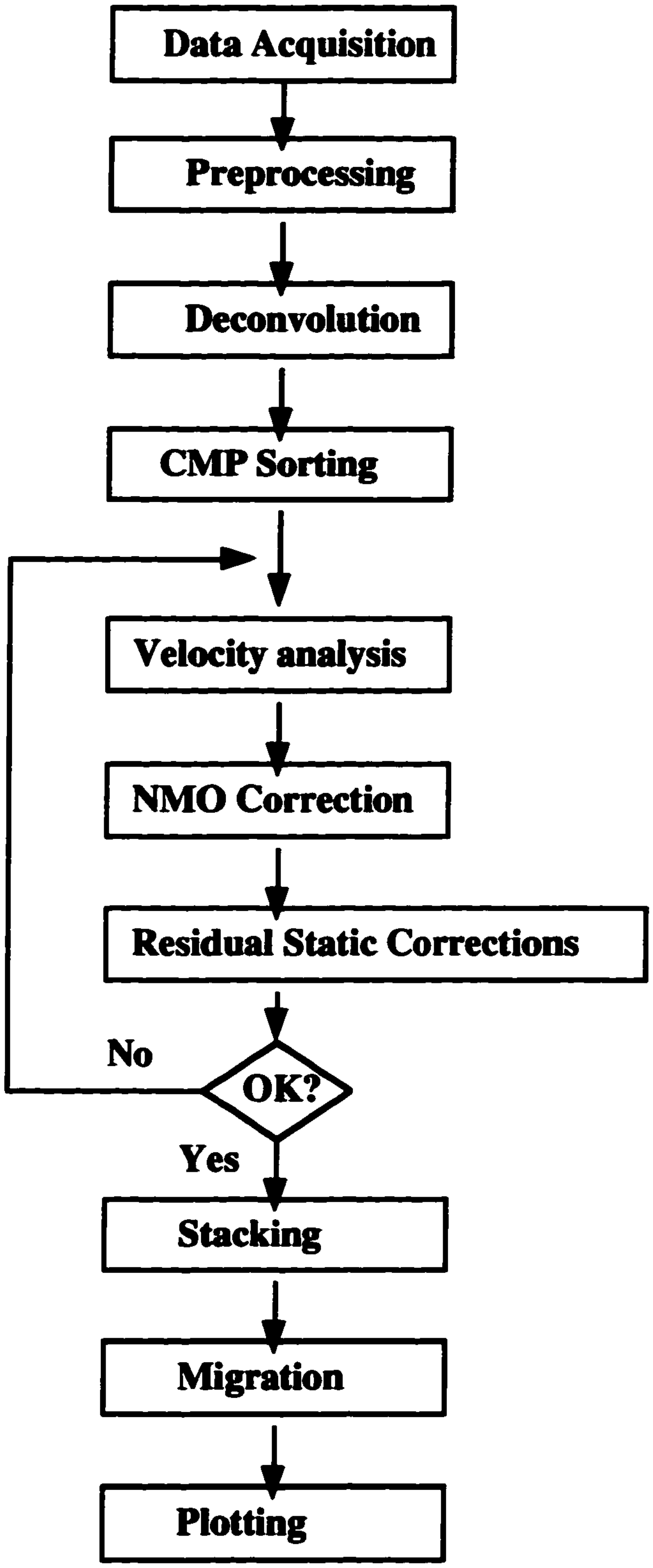

Fig. 2.2 A Conventional seismic data processing flow chart.

applied to the migrated data to emphasize the continuous horizontal reflectors and decrease the visibility of background noise. Seismic sections now display clear geological structures with superior imaging of faults and dipping reflectors, which provide a ideal basis for interpretation. In the following sections of Chapter 2, the reprocessing methodology and procedure will be discussed in detail.

2.2 Previous Processing Stream

Contracted by LITHOPROBE, Pulsonic Geophysical Ltd. in Calgary carried out the initial processing of the Central Alberta Transect (CAT) seismic data in 1992. The field data was output to 9 track tape in SEG D format. Pulsonic designed a processing stream for the entire dataset. Fig. 2.3 shows the pre-migration processing stream. The processing sequence was similar to that applied to seismic data in petroleum exploration.

First, the field data was demultiplexed and converted from the digital recording standard SEG D to Pulsonic's internal format. After 2D Geometric correction, an AGC (Automatic Gain Control) and a zero-to-minimum phase conversion were applied over the new format data. Deconvolution was implemented over specific design windows in two passes. The first was Pulsonic's convolution program (shot-averaged deconvolution). This program designs an operator in the frequency domain with a supplied amplitude spectrum and the wavelet was assumed to be minimum phase. The second one was DECON Z program, which designs and applies inverse filters in the frequency domain and performs whitening with spectral shaping capabilities. This can be useful in handling frequency and noise variations as a function of traveltime(Hepburn et al., 1993). A multigate (four-window) deconvolution was applied to maintain the power level for each window.

Since over 500 kilometers of seismic data was recorded, the surface elevation changed considerably. Appropriate changes in datum selection and replacement velocity for each line were required. Weathering corrections were performed to correct for near surface velocity variation. Also, surface consistent residual static corrections were applied because weathering corrections rarely compensate completely for the effects of near-surface lateral velocity variations.

Velocity analysis for the CAT data was performed over two time windows. The first window involved data throughout the sedimentary basin or the top three seconds. The second time window involved data from 3.0 - 14.0 seconds. This represented data below the sedimentary basin down to the upper mantle. The Constant Velocity Stack (CVS) method was employed to estimate the stacking velocities for the deep seismic events. The stacking velocities obtained were applied to correct for normal moveout (NMO). Then, traces within each common depth point (CDP) gather were summed together and the output trace was divided by the number of traces within the gather. The nominal stacking fold obtained for the production lines was 6000%. This high stacking fold helped to attenuate coherent noise such as multiples, guided waves and ground roll.

Finally, frequency-wavenumber (FX) deconvolution was applied to all lines to enhance linear events and eliminate noise. Before plotting, a multigate automatic gain control (AGC) scaling was used to prevent the amplitude of closely spaced traces from overlapping or becoming too weak for display purpose. The design windows used here are shown in Table 2.1.

Dip moveout (DMO), also named prestack partial migration (PSPM), is usually used to suppress the mispositioning caused by dipping reflected events and to enlarge the dip band-width. During the processing, dip moveout was tested over production Line 2, but proved to be ineffective in bringing out the steeply dipping events. This problem was solved by applying a high stacking velocity from 2.2 to 18.0 seconds. At last, DMO was rejected in the processing stream. This creates problems during migration and will be discussed in the following sections of Chapter 2.

More precise data processing and velocity testing was beyond the budget of the commercial processing sequence. To image the lithosphere structure along CAT seismic lines with clear migrated sections, data reprocessing is carried out in Universities under close supervision of experts.

Table 2.1 Design Windows used in multiple gate AGC scaling by Pulsonic

Time (s)	Window (s)
0.0 - 3.0	0.5
3.0 - 6.0	1.0
6.0 - 18.0	5.0

2.3 Reprocessing Methodology

Usually, static corrections in preprocessing are made in three phases:

1. Elevation variations.
2. Variations in low-velocity layer thickness or velocity.
3. Reference to a datum.

These were carried out by Pulsonic Geophysical Ltd. on the CAT seismic data.

Fig. 2.4 shows the static corrections and static corrected seismic reflection record. As the figure shows, static corrections reduce the effects of near-surface variations on the reflection record and make all the geophones (receivers) along the seismic line appear to be on a reference plane called a datum surface. Since nine lines (Line 1 to Line 8, including Line 2A) of CAT seismic data cover 310.7 kilometers, every seismic line has its own datum surface and reference velocity because the traverses are in different geographic areas with different near-surface conditions. Table 2.2 shows the datum elevation of Line 1 - Line 8.

Generally, a different datum elevation was used on each individual seismic line so the zero second (0s) is changed with each line. In this case, the eight seismic lines do not have the same start levels in recording the travel-time. The travel-time and the depth of certain reflectors can not be compared directly along these seismic lines. Therefore, it is hard to follow the structural changes along the Central Alberta Transect (CAT). By selecting a consistent stratigraphic marker - Second White Speckled shale (2WS), this problem can be solved. As discussed in chapter 1, the Second

Table 2.2 The datum elevation of Line 1 - Line 8

Line #	**1**	**2(2a)**	**3**	**4**	**5**	**6**	**7**	**8**
Datum level (ASL, m)	**900**	**850**	**940**	**1050**	**970**	**900**	**920**	**840**

* **ASL:** Above sea level.

White Speckled shale layer is a widespread horizontal sedimentary layer covering almost the whole Western Canadian Sedimentary Basin (WCSB). This stable continuous layer extends along the CAT. By picking and flattening the 2WS to a fixed travel-time level, all the seismic reflectors

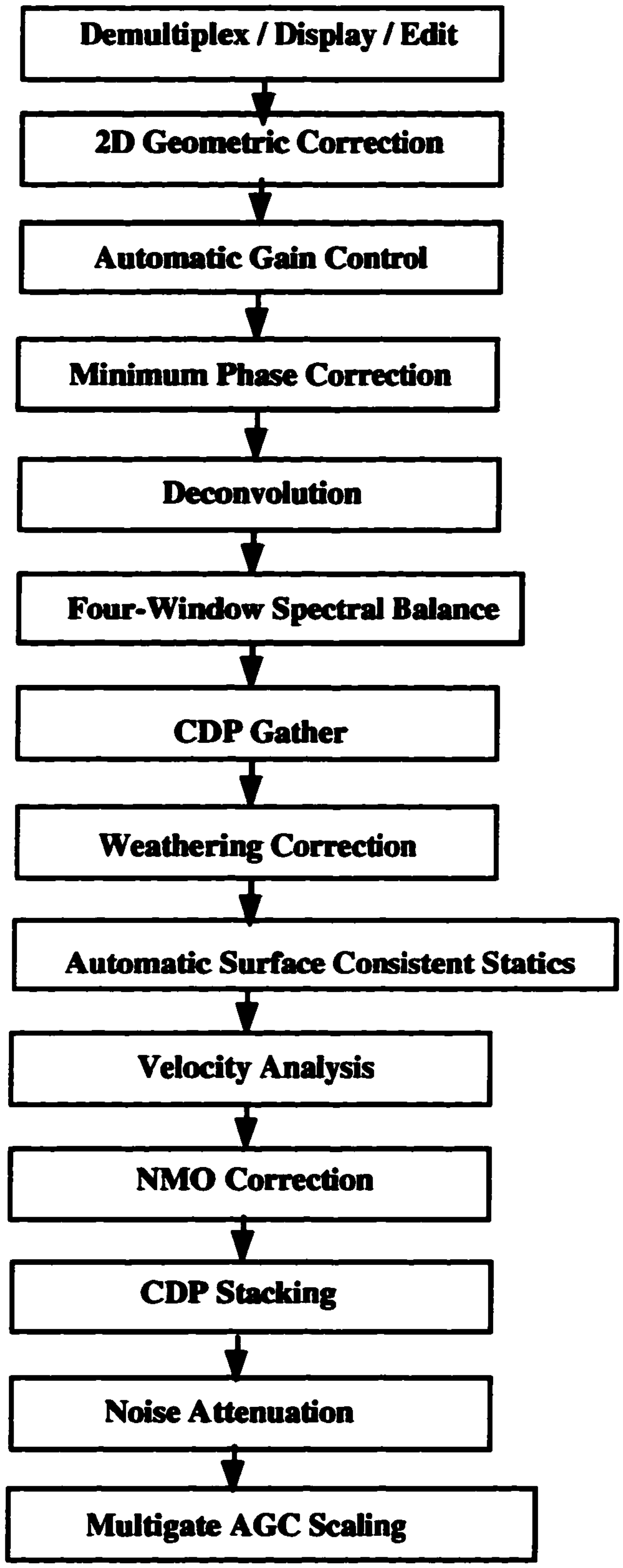

Fig. 2.3 Pre-migration processing stream designed by Pulsonic.

below it can be corrected and all the structures formed after 2WS deposition can be eliminated.

Before migration, additional zero amplitude traces (about 200) are placed on each edge of the stacked section. Migrated events can be imaged into these zero traces at the edges and are not reflected back into the section. This process is called padding, which allows the dipping events to move freely into the padding region (zero - amplitude trace area) during migration, resulting in a clear migrated seismic section.

Unfortunately, the padding process is ineffective if no DMO (Dip moveout) is carried out during the preprocessing.

The velocity profile used in migration is based on the velocity function estimated from the field data along the seismic line. Table 2.3 gives an example of the velocity profile at CDP (common-depth point) 308 on CAT Line 1. Since velocity estimation from seismic data is affected in accuracy and resolution by many things such as stacking fold, signal-to-noise (S/N) ratio, velocity sampling, bandwidth of data etc., some of the time-velocity pairs in the velocity profile are not physically realistic. Using the reference velocity columns shown in Fig. 2.5, the unreliable time-velocity pairs are corrected by editing.

A program is designed in FORTRAN to complete the velocity editing. The velocity changing boundaries within the Canadian Craton and Foreland Belt in Fig. 2.5 are used for the control conditions in the program. The other velocity accuracy guide is the sonic velocity curve obtained from the well-logs. Six wells were selected along Line 1 - Line 8 to calculate the sonic velocity function on different seismic lines. The detailed procedures will be given in chapter 3.

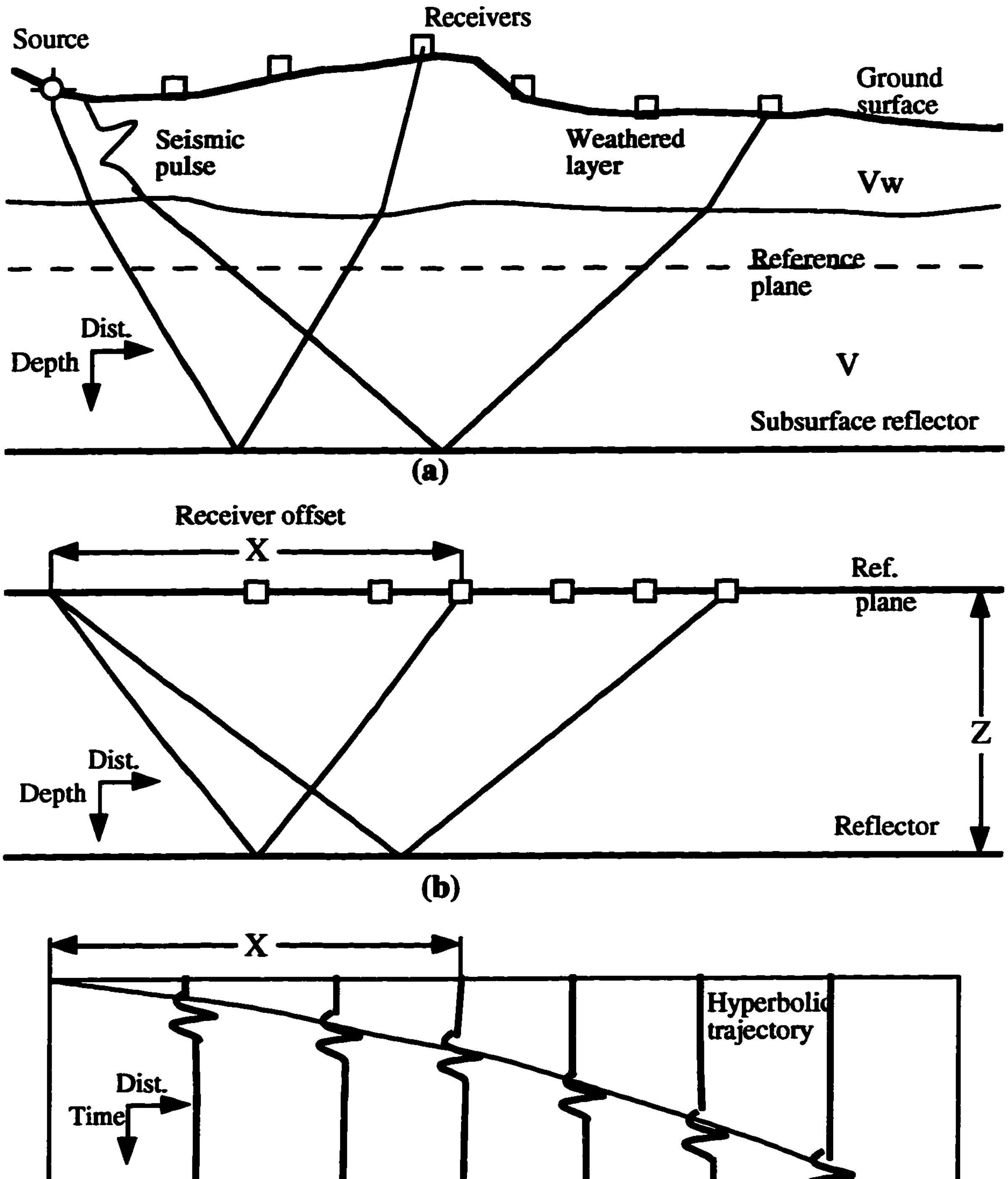

Fig. 2.4 The static corrections and the static corrected seismic reflection record. (a): Depth model with Low-velocity layer.
(b): Depth model after static corrections.
(c): Static corrected reflection record.

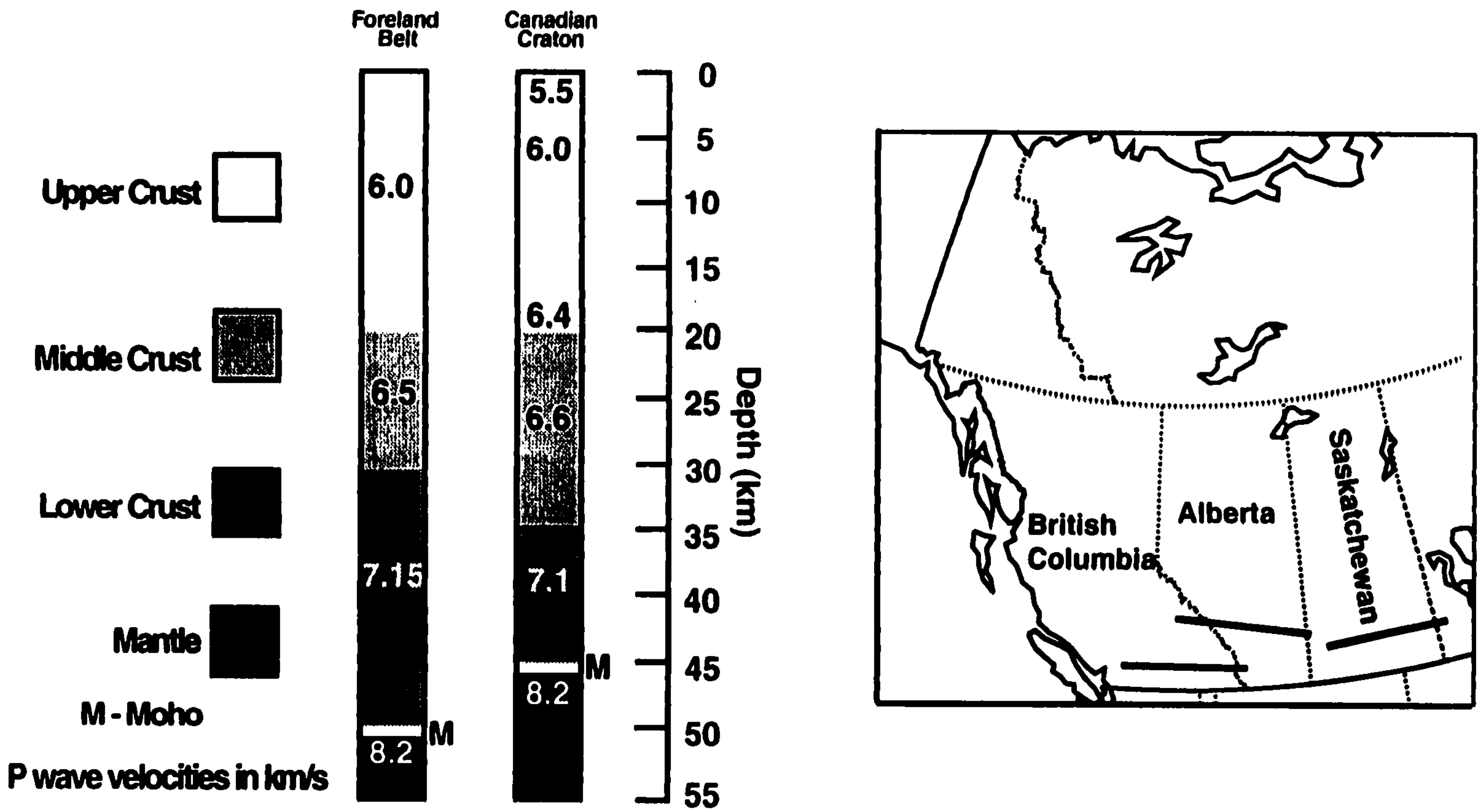

Fig. 2.5 Reference velocity depth columns in western Canada. The inset map shows the approximate locations and orientations of the velocity studies(Modified from Burianyk, 1994).

Velocity shifting is to maintain a consistent velocity profile despite the flattening of the Second White Speckled Shale(2WS) layer. Because 2WS along the seismic line is not at the same time level, the shift at each CDP is slightly different. The velocity function at individual CDP number is

Table 2.3 Velocity profile at CDP# 308 on Line 1

TIME(ms)	VRMS(m/s)	VAVG(m/s)	VINT(m/s)	DEPTH(m)
0	2082	2082	2082	0
298	2135	2135	2135	318
564	2514	2486	2879	701
767	2758	2713	3343	1040
989	3028	2960	3816	1464
1063	3081	3013	3717	1601
1168	3081	3019	3080	1763
1257	3392	3241	6158	2037
1369	3719	3493	6318	2391
1478	3722	3513	3759	2596
1574	3740	3543	4006	2788
1710	3849	3654	4938	3124
1821	3887	3701	4431	3370
1947	3940	3762	4638	3662
2299	4155	3980	5185	4575
3000	4476	4311	5396	6466
4000	5400	5113	7519	10226
5000	6000	5682	7959	14206
7000	6000	5773	6000	20206
14000	7000	6823	7874	47765

* VRMS is the root mean square velocity, VAVG is the average velocity, VINT is the interval velocity.

adjusted so there is a smooth transition between control points. This process is completed by running the FORTRAN program after making the 2WS horizon a flat datum.

Migration is an imaging process which moves dipping events into their true subsurface positions and collapses diffraction. From the migrated section, the position and character of the faults are interpreted to derive a reliable structure map. The migration process that produces a migrated time section is called time migration. If the output of the migration is a depth section, it is named depth migration (Yilmaz, 1987). No matter what kind of migration, all are based on a similar wave equation. Migration steepens and shortens the reflectors and moves the dipping events in the updip direction. Fig. 2.6 illustrates the general principles of migration. In Fig. 2.6, the dipping reflector CD is migrated upward to a steeper and shorter true position EF after migration.

In general, there are three widely used migration techniques which are applied in seismic data processing. The Kirchhoff summation technique is a straightforward summation of amplitude along the hyperbolic trajectory, which handles the lateral velocity variations very well. The second technique called finite-difference migration (Claerbout, 1985) is implemented by downward continuation of the wave fields. Both of these two techniques are based on the scalar wave equation; the first one with the integral solution and the second one having a differential solution. Stolt (1978) introduced the Fourier transform methods in migration, which is also called frequency - wavenumber migration. As a type of frequency - wavenumber migration, phase-shift method was developed by Gazdag (1978). Fig. 2.7 is the flow chart of the phase-shift migration. The mathematical development of this migration starts with the 2-D scalar wave equation(2.1), where P(x,z,t) is the compressional wave fields propagating in the medium with constant material density and compressional wave velocity v(x, z):

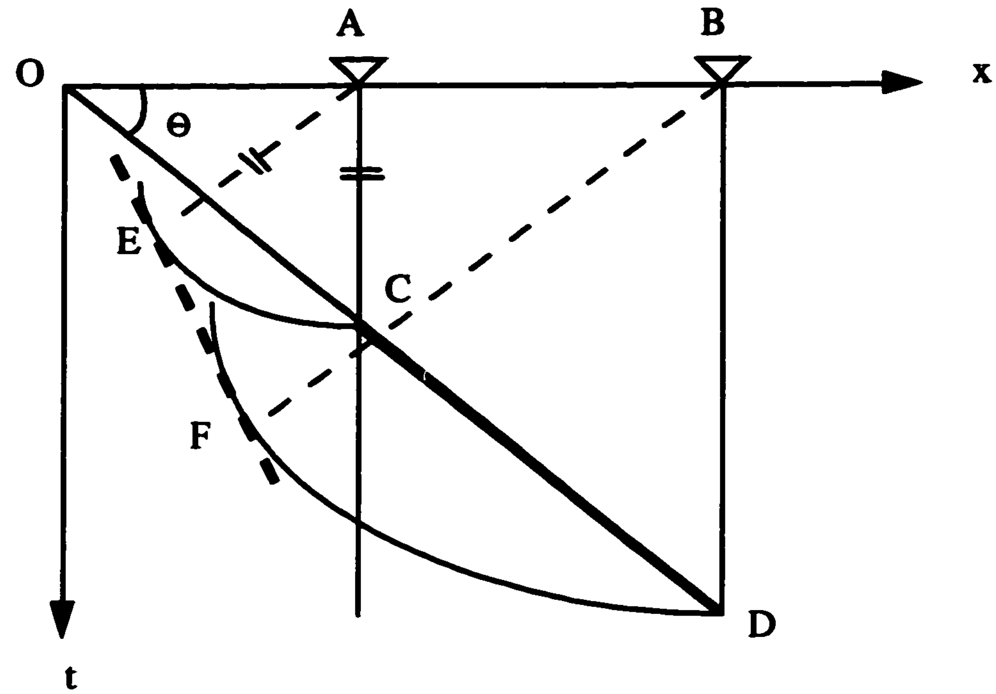

Fig. 2.6 Migration effects to the dipping reflection CD in time section.

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} - \frac{1}{v^2}\frac{\partial^2}{\partial t^2}\right)P(x,z,t) = 0 \qquad (2.1)$$

x is the horizontal spatial axis, z is the depth axis(positive downward) and t is the time. Under the condition that there is no lateral velocity variation, the wave field in equation(2.1) can be Fourier transformed over the horizontal axis x. So,

$$P(k_x, z, \omega) = \int \int P(x, z, t) \exp(ik_x x - i\omega t)\, dx\, dt \qquad (2.2a)$$

and inversely,

$$P(x, z, t) = \int \int P(k_x, z, \omega) \exp(-ik_x x + i\omega t)\, dk_x\, d\omega \qquad (2.2b)$$

Applying the differential operator in equation(2.1) to equation(2.2b), the result is

$$\frac{\partial^2}{\partial z^2} P(k_x, z, \omega) + (\frac{\omega^2}{v^2} - k_x^2)P(k_x, z, \omega) = 0 \qquad (2.3)$$

The solution for upcoming waves to equation(2.3) is

$$P(k_x, z, \omega) = P(k_x, 0, \omega) \exp [-i(\frac{\omega^2}{v^2} - k_x^2)^{1/2} z] \qquad (2.4)$$

By defining the vertical wavenumber as

$$k_z = \frac{\omega}{v} [1 - (\frac{vk_x}{\omega})^2]^{\frac{1}{2}} \qquad (2.5)$$

The equation(2.4) takes the simple form as

$$P(k_x, z, \omega) = P(k_x, 0, \omega) \exp (-ik_z z) \qquad (2.6)$$

This is the solution of the scalar wave equation for the zero-offset wave field. Assuming a horizontally layered earth model v(z) and by inverse Fourier transforming equation(2.6), where k_x is replaced with k_y, we have

$$P(y, z, t) = \int \int P(k_y, 0, \omega) \exp (-ik_z z) \exp (-ik_y y + i\omega t)\, dk_y\, d\omega \qquad (2.7)$$

Since the CMP (common mid-point) stack section is migrated as if it were the zero-offset wave field generated by tiny explosions at the reflecting point, the equation used for the downward extrapolation portion of migration is the one-way wave equation. To account for the one-way traveltime, the velocity should be taken as half the medium velocity. Thus, the vertical wavenumber is expressed from equation (2.5) as

$$k_z = \frac{2\omega}{v}\left[1 - \left(\frac{vk_y}{2\omega}\right)^2\right]^{\frac{1}{2}} \tag{2.8}$$

When t=0, equation(2.7) becomes

$$P(y, z, t = 0) = \int\int P(k_y, 0, \omega) \exp\,(-ik_y y - ik_z z)\, dk_y\, d\omega \tag{2.9}$$

This is the equation for phase-shift method (Gazdag,1978), which involves an integration over frequency domain and inverse Fourier transformation along midpoint axis y. The downward continuation has a pure phase-shifting operation $\exp(-ik_z z)$. At each z step, a new extrapolation operator with the velocity defined for that z value is computed. The procedure of downward continuation and imaging is repeated until the entire wave field is migrated (Yilmaz, 1987).

Regardless of the three different migration algorithms used, the interpretability of the final migrated section is dependent on the quality of the stacked section, the signal-to-noise (S/N) ratio and the velocities used in migration. The reason for choosing the phase-shift algorithm in Central Alberta Transect (CAT) seismic data reprocessing is that this method handles dips of up to 90 degrees accurately and allows for vertical velocity changes.

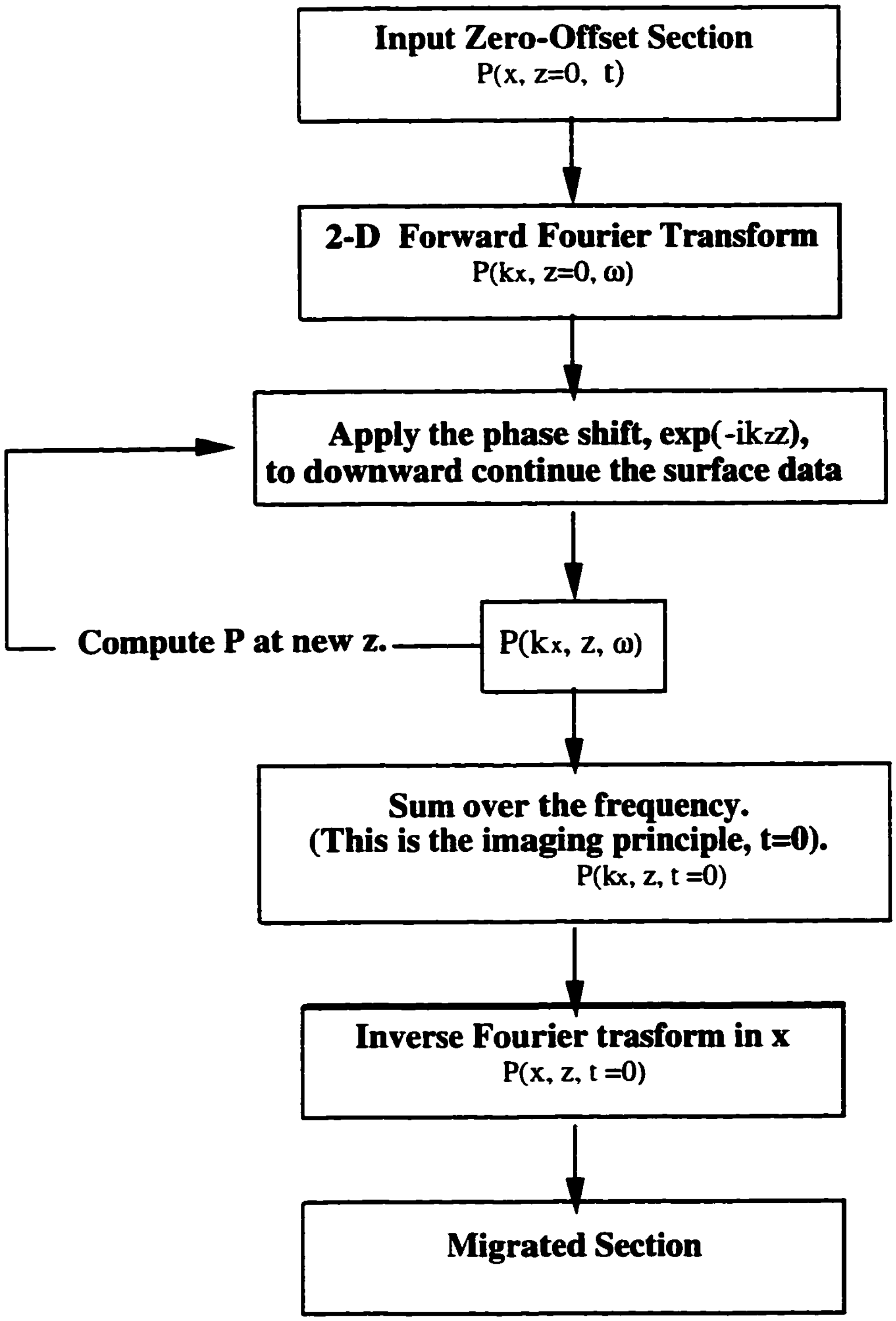

Fig. 2.7 The flow chart for Gazdag's phase-shift method of migration.

A second set of migrated sections are presented in this thesis using a depth migration technique as developed by Dr. Suhas Phadke at the University of Alberta. It handles dips up to 70° and produces a section with superior images because of the way the partial differential equations are approximated.

The identification of the coherent events from a noise background is one of the main objectives of seismic data processing, especially for deep crustal seismic data reprocessing. By enhancing the visibility of coherent events, coherency filtering is an effective method to realize this object. At the Lithoprobe Seismic Processing Facility (LSPF), a coherency filtering algorithm has been developed to enhance the crustal seismic data and meet the needs of interpretation. Based on a measure of coherence in quantitative form and the similarity of adjacent seismic data, this program uses a sliding window to compute the semblance of seismic traces along dipping straight lines with a lateral window and smooths the seismic data in the direction of maximum semblance. Semblance here is the ratio of signal energy of migrated trace to the total energy within the window. The basic steps of the coherency filtering algorithm are:

Step1. Compute semblance over a lateral window of traces.
Step2. Compute coherencies from these semblances.
Step3. Smooth the data in the direction of the maximum semblance.
Step4. Filtered the smoothed data using the coherency.

The result of the first step is a semblance value for each dip at each input data point and the maximum semblance over all dips is the output. The effect of the second step is to press low semblances lower while minimally decreasing high semblances and reduce the incoherent noise. In the third step, the seismic data are smoothed by taking the average value in the direction of maximum semblance over lateral window. At last, the filter is applied by scalar multiplication of the smoothed data with coherency point by point.

The program module includes eight parameters, which are:

Numtr, the number of traces to process.
TrSpac, the trace spacing in meters.
WinSze, the number of traces in the sliding window.
MaxSl, the absolute maximum value of the dip limits expressed as slowness in millisecond/meter (ms/m).
NumSl, the number of slowness (dips) to be used.
SemExp, the semblance exponent.
Bias, trace bias in percent.
PrFlag, the degree of message printing controller.

To avoid spatial aliasing, the value of parameter MaxSl must satisfy

$$\text{MaxSl} \leq \frac{1000}{2 * F * \text{TrSpac}}$$

where F is the maximum frequency of the seismic data in Hz.

The guideline of selecting parameter NumSl to avoid time aliasing at the far traces is that

$$\text{NumSl} \geq \frac{2 * F * \text{MaxSl} * \text{TrSpac} * (\text{WinSze} - 1)}{1000} + 1$$

Besides, the value of parameter NumSl must be an odd integers between 3 and 201.

Choosing proper parameters is very important for obtaining the ideal filtering output. This needs many tests and correct calculations. Only when the coherency filtering program has proper parameters can the optimal filtered seismic section be obtained. The relevant examples will be given in the following section.

2.4 Reprocessing Procedure

According to the reprocessing methodology mentioned before, the reprocessing procedure follows a sequence as follows: picking and flattening the Second White Speckled layer, padding, editing and shifting velocity profile, phase-shift migration, coherency filtering and plotting the final seismic section.

2.4.1 Picking and Flattening the Second White Speckled Shale Layer

Static corrections here have small errors because a statistical method is used to correct for near surface velocity irregularities. Each different seismic line has also been corrected to their own datum surface by making the deeper section an isopach in time relative to the 2WS horizon. Picking horizon 2WS correctly is a time consuming human operation and one must recognize the reflection character of this geological marker properly.

As the 2WS sedimentary layer was deposited under the uniform marine conditions in a very stable environment, the reflector should also be stable without phase shifts, faults or folds. The amplitude of the reflection is also comparatively constant. Since the difference in density and velocity between 2WS and the overlying and underlying sediments is nearly constant, the reflector is not complex and it can be distinguished clearly in most cases.

Due to the wedge of Phanerozoic strata in the Alberta Basin (Fig. 1.6), the buried depth of 2WS along the seismic line in the eastern edge of the basin is different than that along seismic lines in the central basin. For instance, the two-way travel-time to the 2WS along Line 8 is between 0.75 ~ 0.76 s, while along Line 4 the two-way travel-time to the 2WS is 1.05 ~ 1.07 s. Table 2.4 gives the two-way travel-time range to the 2WS along the seismic lines and the time level to which the 2WS is shifted. A two-way travel-time of 1.0s was selected to be the fixed time level for the 2WS. The 2WS along all the seismic lines was shifted to the fixed time level of 1.0 s.

Table 2.4 Two-way travel-time to the 2WS and the shifting time level

Line #	1	2(2a)	3	4	5	6	7	8
Two-way traveltime to 2WS (S)	0.98 ~1.03	0.95(0.93±) ~0.85	0.95 ~0.98	1.05 ~1.07	1.04 ~0.98	0.92 ~0.93	0.90 ~0.79	0.75 ~0.76
Shifted time level (S)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Starting from the most eastern Line 8, the 2WS was picked and the two-way travel-time, T_{2WS}, was recorded by the CDP number. Then the shifted amount for different CDP is calculated from $\Delta T_{CDP} = T_{SHT} - T_{2WS}$, where T_{SHT} is the fixed time level for 2WS to be shifted to. For Line 8, T_{SHT} = 1.0 s. ΔT_{CDP} calculated from the formula is used to shift the time-velocity pairs by CDP number. Note that shifted amount ΔT_{CDP} here can be negative, which means that the reflectors including 2WS are shifted up to the smaller times compared to their original two-way travel-time. After picking 2WS trace by trace, an Insight 5 program, flat.in5, was run to shift and flatten the 2WS to the fixed time level. The exact same procedure was used from Line 1 to Line 8. As an example, Fig. 2.8 shows an example of the seismic section of Line 6 with 2WS picked before and after flattening,but the fixed sifting time level is 0.8 s not 1.0 s.

2.4.2 Padding

Before migration, two hundred traces of zero amplitude are appended to each edge of the stacked section from Line 1 to Line 8. This padding procedure was completed by running the Insight 5 program named "pad.com". This allows steeply dipping events to move up dip and be visible.

After padding, the range of CDP number from Line 1 to Line 8 is enlarged with four hundred zero amplitude traces. When plotting, these extra traces can be removed from the final section if desired. In this case, the beginning and last CDP number of these extra traces must be recorded. Table 2.5 gives the CDP number from Line 1 to Line 8 before and after padding.

Table 2.5 The range of CDP number before and after padding

Line #	1	2	3	4	5	6	7	8
CDP # pre-padding	208 - 1625	205 - 1800	208 - 1948	206 - 1331	209 - 1196	205 - 761	238 - 3591	208 - 974
CDP # post-padding	8 - 1825	5 - 2000	8 - 2148	6 - 1531	9 - 1396	5 - 961	38 - 3791	8 - 1174

The migrated section with and without padding is shown in Fig. 2.9, which is the migrated part of Line 6 with and without padding before migration. Boundary effects are less evident in the padded section. Since no DMO was carried out in the stacked seismic section, some edge effects are present. These can be reduced by using a cosine taper as was done in the final depth migrated sections.

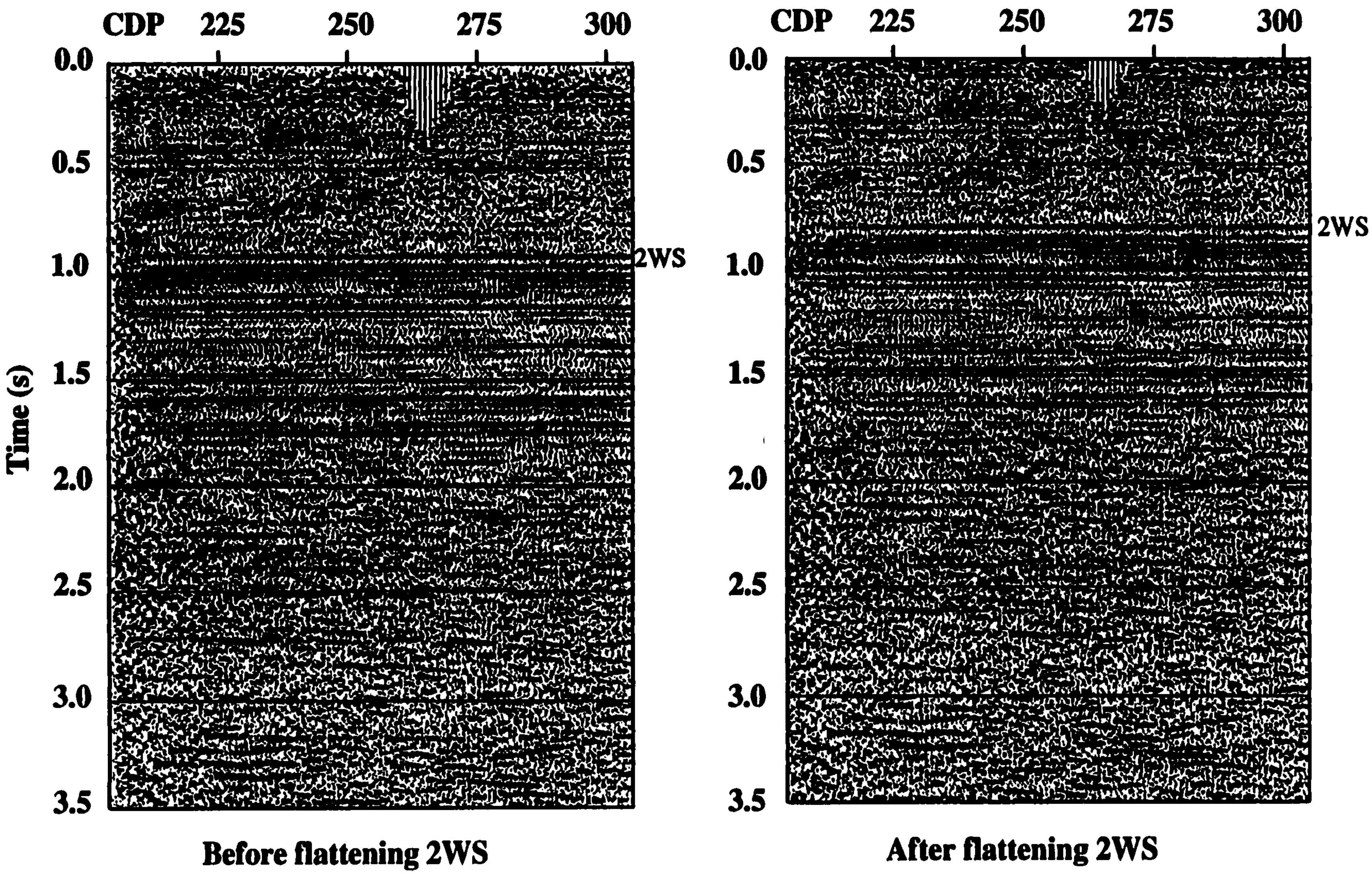

Fig. 2.8 Part of stack seismic section of Line 6 with 2WS picked before and after flattening.

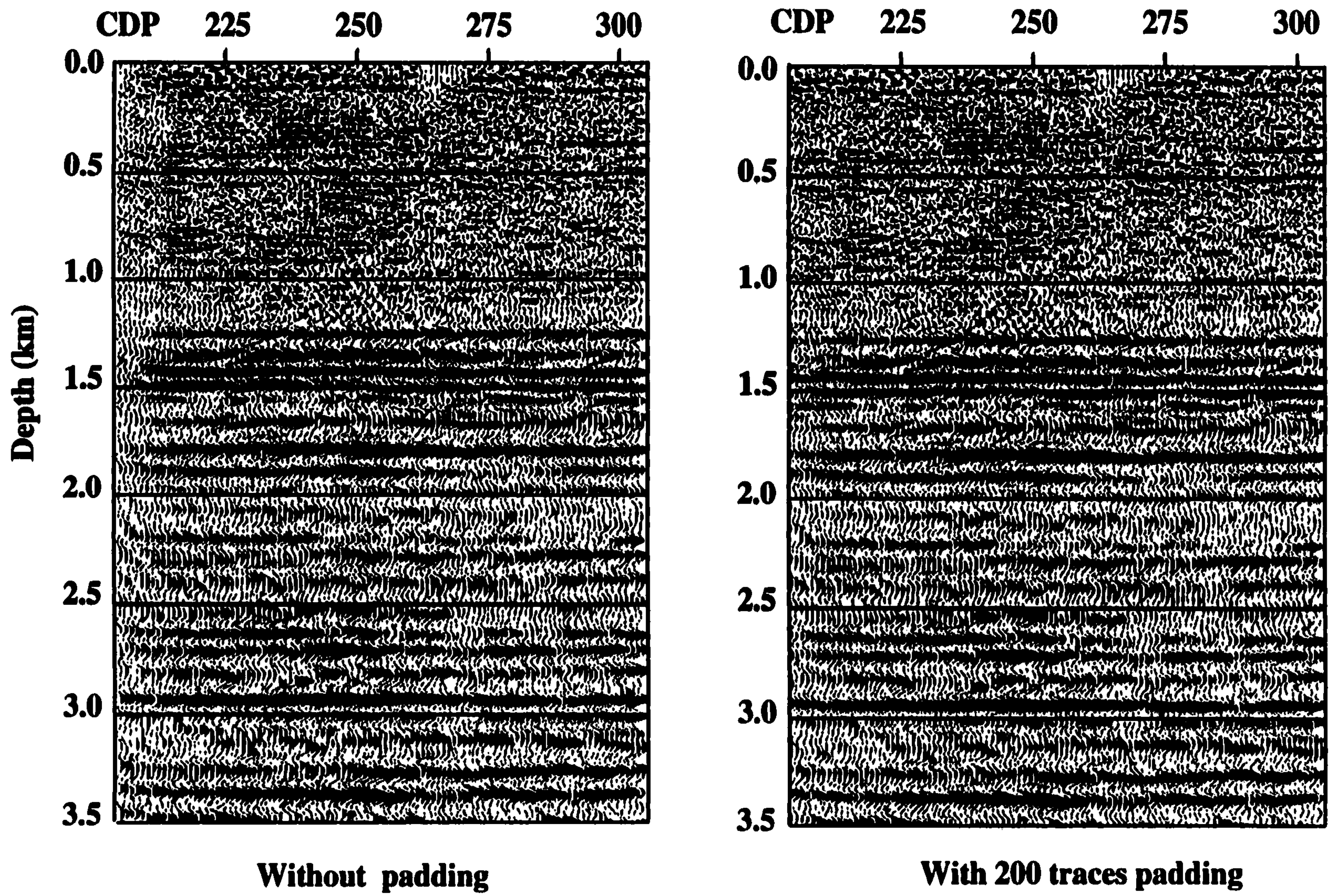

Fig. 2.9 Left boundary of migrated seismic section of Line 6 without and with padding before migration.

2.4.3 Editing and Shifting the Velocity Profile

A velocity profile of every seismic line was determined from the data of well logs in time-velocity pairs according to CDP number. So the editing and shifting of these velocity profiles are processed by CDP number for one line. The reference velocity in Fig. 2.5 was used to be the general guide to edit the time-velocity pairs. The unphysical interval velocity values are corrected in the editing. A time-velocity change at two-way traveltime 13 s was added to the whole velocity profile, since the boundary of crust and mantle - Moho is between two-way traveltime 13 s and 14 s.

When picking the 2WS, the time shift for different CDP was recorded as ΔT_{CDP}. These values were used to shift the various CDP number. For instance, the ΔT_{CDP} of CDP# 308 in Line 2 is 0.073 with the shifted time level 1.0 s. The shifted time-velocity pair at this CDP number of Line 2 is shown in Table 2.6. While the time-velocity pair after shifting is the velocity function for migration at this CDP # 308. The same processing was undertaken for the other CDP numbers of Line 2 before migration.

Even with velocity spectral analysis one can never be certain the velocity function used for migration is the correct velocity. Because the velocity of the rock changes laterally and vertically at the same time, one can only have an approximation.

2.4.4 Migration

The computational procedure for migration is described as follows:

Step1 Pick the 2WS and shift it to 1.0 second(two-way traveltime).
Program used: “flat.in5”. Data processed: stacked seismic data.

Step2 Pad two hundred empty traces on each edge of the seismic line.

Table 2.6 Shifted velocity profile at CDP# 308 on Line 2

Time-velocity before shifting		ΔT_{CDP} =0.073	Time-velocity after shifting	
TIME(s)	VINT(m/s)		TIME(s)	VINT(m/s)
0.000	2142.00		0.073	2142.0
0.300	2397.00		0.373	2397.00
0.511	2685.00		0.584	2685.00
0.724	3626.00		0.797	3626.00
0.920	3775.00		0.993	3775.00
1.061	3424.00		1.134	3424.00
1.162	4061.00		1.235	4061.00
1.245	4562.00		1.318	4562.00
1.346	5137.00		1.419	5137.00
1.449	5709.00		1.522	5709.00
1.525	4704.00		1.598	4704.00
1.675	4824.00		1.748	4824.00
1.836	5054.00		1.909	5054.00
1.968	5251.00		2.041	5251.00
2.314	5264.00		2.387	5264.00
3.000	5137.00		3.073	5137.00
4.000	6150.00		4.073	6150.00
5.000	6300.00		5.073	6300.00
7.000	6450.00		7.073	6450.00
13.000	7150.00		13.073	7150.00
14.000	7874.00		14.073	7874.00

Program used: "pad.com". Data processed: flattened, shifted stack seismic data.

Step3 Edit the velocity profile along CDP and shift the same amount as

2WS. Program used: "vedit.f" and "vshift.f". Data processed: Time-velocity function.

Step4 Migration. Program used: "psmig_fast.in5". Data processed: padded seismic data and shifted velocity profile.

The procedure mentioned above is applied to every seismic line (Line 1 - Line 8 - Line 18 & Line 19) to obtain the migrated section. A flow chart showing this procedure is given in Fig. 2.10.

2.4.5 Coherency Filtering

Before coherency filtering, calculations and tests need to be undertaken to obtain the proper parameters to be used in the processing. First, select several dipping events in the migrated seismic section to calculate the slowness (ms/m) and find the maximum value as the input parameter MaxSl. Secondly, calculate from the MaxSl to choose the parameter NumSl. Thirdly, change the parameter WinSze and Bias to test the coherency-filtering program and find the optimal value of these two parameters. The final coherency-filtered seismic section should be a better image reflecting the subsurface structure.

To make the final coherency-filtered seismic section comparable, all the parameters used in the coherency-filtering are kept constant except the parameter MaxSl, which depends on the dipping events of every seismic line. They are given in Table 2.7. The input data of the filtering is migrated

Table 2.7 Parameters and their values used in coherency-filtering

Parameter	Numtr	TrSpac(m)	WinSze	MaxSl	NumSl	SemExp	Bias	PrFlag
Value	0	25	21	Variable	21	1	-300	1

seismic data and the program used is "smb_smooth.in5" of IT&A.

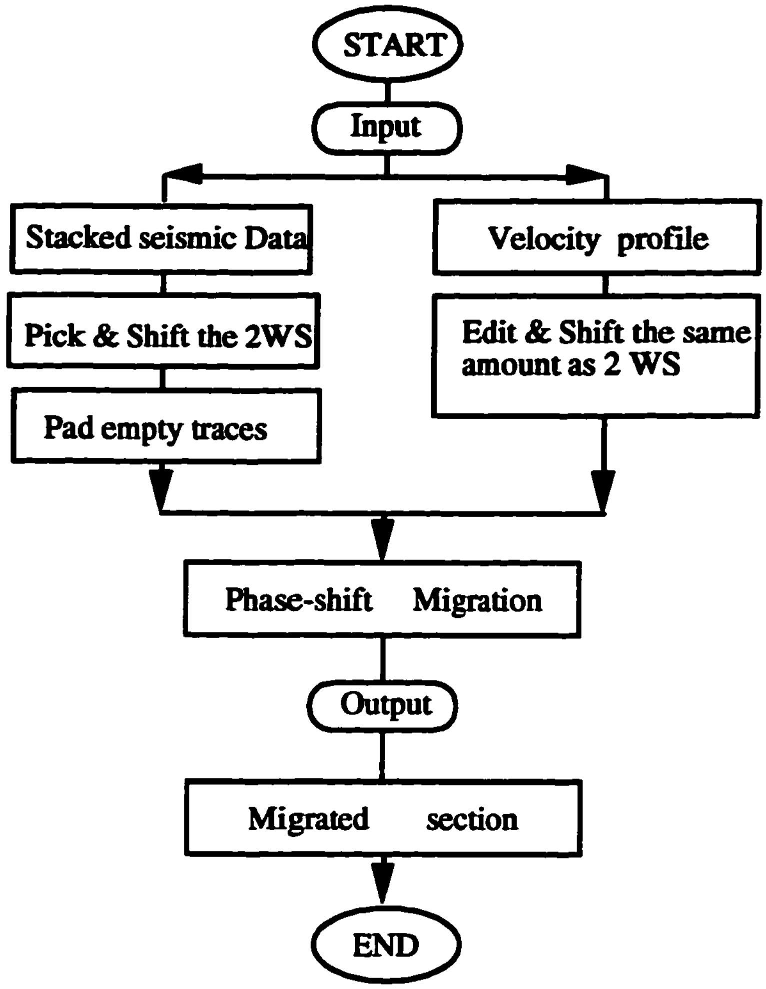

Fig 2.10 The flow chart of the migration applied to CAT seimic lines.

2.4.6 Plotting

All the migrated and filtered seismic data need to be transferred to a rasterfile and then plotted at the Lithoprobe Seismic Processing Facility (LSPF) on the Versatec 7236 plotter at the University of Calgary. The program used is "vaplot.in5" to get the rasterfile and "vadump.in5" to dump the rasterfile to the plotter. Some key cards in the program "vaplot.in5" control the effect of the plots. Tests are needed to obtain a satisfactory output.

Some extra long seismic sections need to be compressed before plotting. This can be completed by either mixing or deleting two or four traces before plotting the output.

2.5 Reprocessing Results

The reprocessing results are the migrated and filtered seismic sections plotted at LSPF. Choosing Line 5 as an example, the preprocessing seismic section - stacked section of Line 5 is shown in Fig. 2.11. The migrated section of Line 5 is shown in Fig. 2.12, while the coherency-filtered section of Line 5 is illustrated in Fig. 3.21. Being the reprocessing results, Fig. 2.12 and Fig. 3.21 provide the clearer structure than that of Fig. 2.11. Further interpretation is based on the reprocessing results, which display the clear geological structure of the lithosphere.

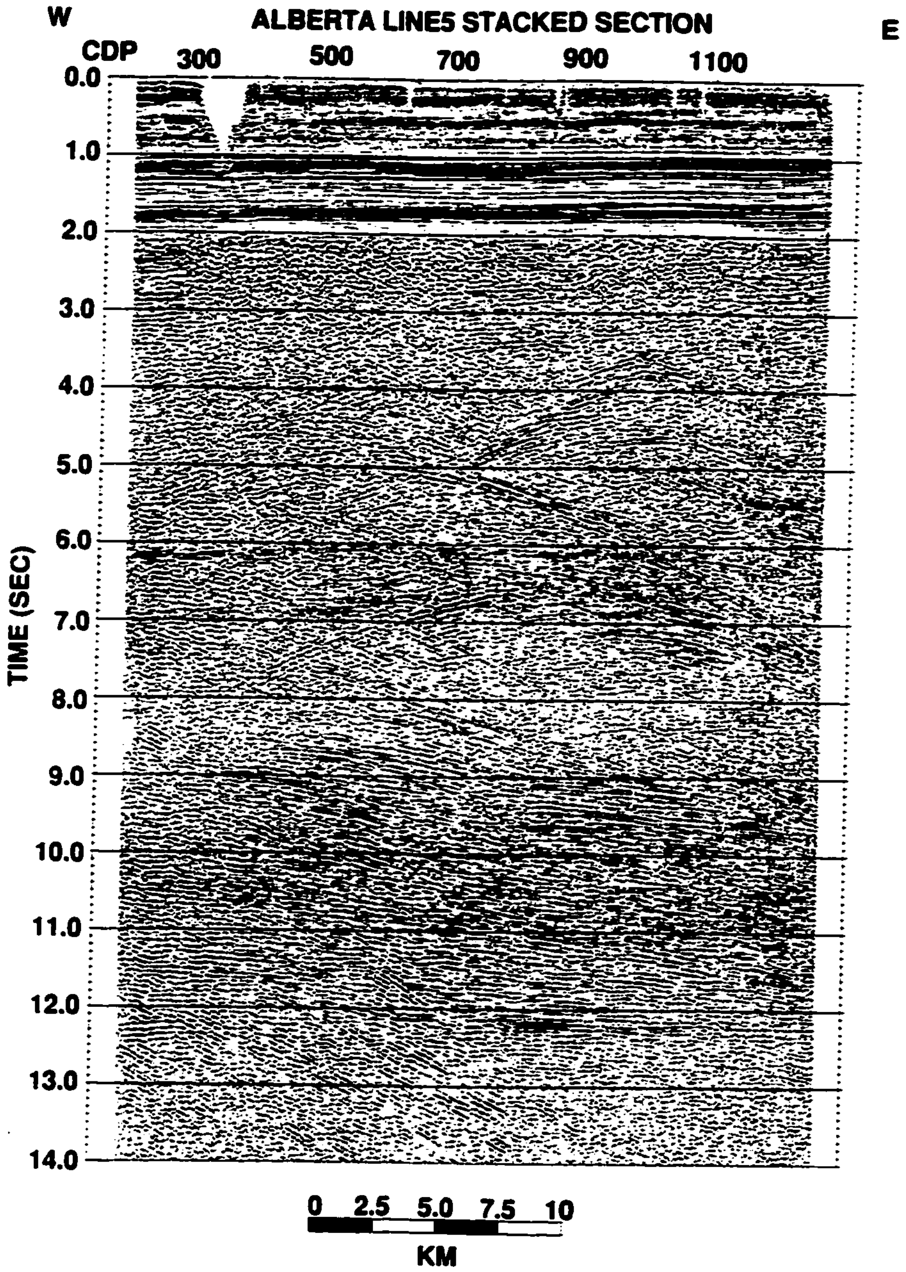

Fig. 2.11 Stacked section of Line 5 before migration.

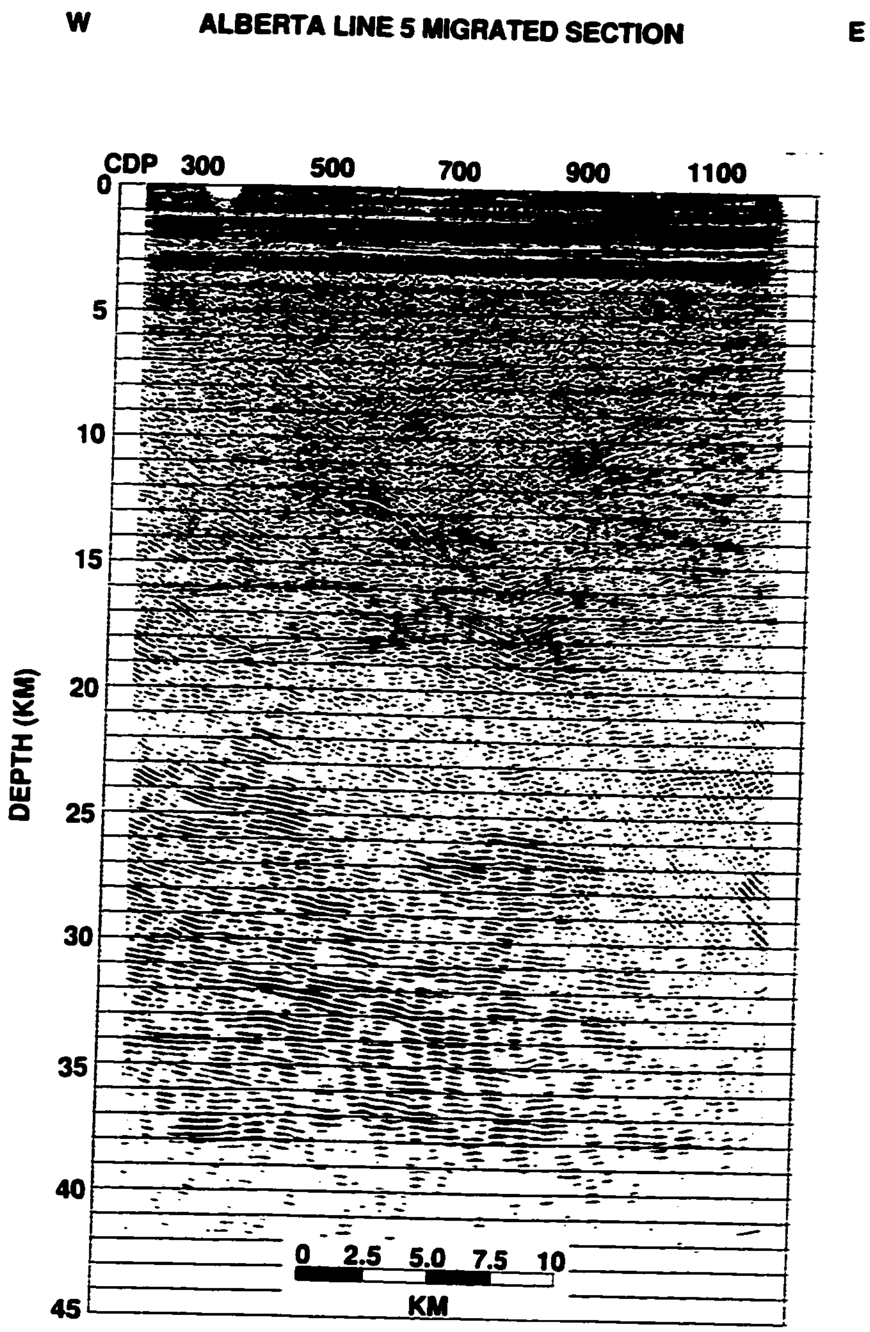

Fig. 2.12 Migration section of Line 5

Chapter 3 Interpretation of The Reprocessed Data

3.1 Introduction

The purpose of seismic data reprocessing is to obtain the best possible seismic images for further geophysical and geological interpretation to investigate the stratigraphical and structural features of the earth. In general, interpretation must incorporate geophysical (gravity, magnetic, seismic, heat flow and electrical conductivity) data with borehole logging information and projections of geologic outcrop information. By interpretation of reflection seismic data, the reflections, the correlation of them at line intersections, their relations to interfaces in drilled wells and even the geologic history are to be determined.

To test the quality of an interpretation of seismic data, all the information, including gravity, magnetic, well and surface data with geological concepts are needed. Usually, an interpretation requires additional field work to test and modify and ultimately leads to a more complete image of the subsurface.

Assuming the coherent events in seismic data are reflections associated with bedding or unconformities, the geologic structure can be inferred from these coherent events. In this chapter, the interpretation of the seismic section along Line 1 to 8 is carried out, taking into account the sonic well logs, gravity and aeromagnetic data. Fold and fault structures with dipping reflections are usually exhibited clearly on the migrated and coherency-filtered seismic sections. From the reflection data from the Precambrian crystalline basement, at a depth of 2 to 3 km, to the Moho, at a depth near 45 km, one can obtain information on the deformational history of Precambrian rocks under central Alberta. The Peace River Arch Industry Seismic Experiment (PRAISE) Line 18 and Line 19 are included to make the northern region crustal structures more complete. As these two lines are in the same tectonic domain - Wabumun High - on the Central Alberta Transect (CAT) Lines 1 and 2, the structure and the reflection characteristic of the four lines can be interpreted as a single unit.

3.2 Geophysical Interpretation

An interpretation of the reflection seismic data should be consistent with sonic log data, as well as aeromagnetic and gravity results. The geophysical interpretation based on the reflection seismic data is given in the following sections. The total number of seismic lines interpreted is ten, including the PRAISE 1994 Line 18 and Line 19.

3.2.1 Identification of Geological Layers from Well Log

Generally speaking, well logs have two main uses: correlation for stratigraphic studies and the evaluation of the physical properties of formation lithology. There are different kinds of well logs and their choice depends on what kind of geophysical data need to be correlated. Well data such as Spontaneous - Potential (SP) log, sonic log and density log, in the area where seismic lines cross through, often provide geological information such as formation tops, lithology and the location of faults and unconformities. By well-to-well log-correlation studies one can identify the seismic reflections associated with the formation tops of the geological layers. Therefore, the structure information such as the location of faults and unconformities can be obtained from the well log data. With this information, the geological evolution of the study area may be inferred.

As mentioned in Chapter 1, there are nine wells, some of them drilled to the basement, near the Central Alberta Transect (Fig. 1.8). Six wells out of nine can be used for the interpretation of seismic data of Line 1 to Line 8, including PRAISE Line 18 and Line 19. They are Well#1 Mobil et al Pembina 11-27, which is located 10 km west of Line 1 and Line 2; Well#2 Home CPOG Brightbank No. 10-5, which is located 20 km north-east of Line 2 and Line 1; Well#3 Dome et al Wroses 15-35, which is located 1 km east of Line 4; Well#4 Canterra Bashaw 16-36, which is located 8 km south of Line 7; Well#5 Atapco Buffalo Lake 6-11, which is located 26 km south-east of Line 7 and south-west of Line 8; Well#6 CPOG Oberlin 10-15, which is located 45 km south-east of Line 7 and south-west of Line 8. From the distance between each well and the seismic line, Well#3 is the ideal well to be consistent with seismic reflection data, next should be Well#4 and Well#1. The poorest one may be Well#6. After modeling the synthetic seismogram, these conclusions should be confirmed. As an example, Table 3.1 gives the formation tops for Well#1 at 11-27-49-08W5. The depth of every formation top here is related to the depth reference KB (Kelly Bushing).

The well log curves for the six wells used here are spontaneous potential (SP), sonic interval transit time (sonic log) and bulk density (density log). The spontaneous - potential (SP) curve is a recording versus depth of the difference between the potential of a movable electrode in the borehole and the fixed potential of a surface electrode. It is useful for locating permeable bed boundaries and permits the correlation of such beds. The sonic log is a recording versus depth of the time required for a compressional sound wave to traverse one foot of formation. The interval transit time is the reciprocal of the velocity of the compressional sound wave. So integrated sonic transit times are helpful in interpreting seismic records. The density curve which is dependent on lithology and porosity is useful for identification of lithological markers and together with the sonic log is used for computing synthetic seismograms.

One problem in relating well data and seismic data is that these two kinds of data have different datum or depth references. As a matter of fact,

Table 3.1 Formation tops information of Well#1 at 11-27-49-08W5

WELL NAME :	MOBIL ET AL
PEMBINA 11-27	
Ground Level Elevation(m):	869.6(ASL)
Depth Reference:	KB
Elevation of Depth Reference(m):	875
TOPS NAME	**DEPTH(m)**
Lea Park	1159.
Second White Speckled Shale	1564.
Viking	1754.
Mannville Group	1799.
Lower Mannville	1943.
Fernie Group	1963.
Banff	2023.
Exshaw	2204.
Beaver Hill Lake Group	2843.
Elk Point Group	3015.
Dead Wood	3204.
Precambrian	3573.

*ASL: above sea level

the well data here have KB (Kelly Bushing) as the depth reference, while every seismic line has its own datum elevation(Table 2.2). Table 3.2 shows the elevation for Well#1 to Well#6. In order to integrate the seismic data with the well data, they must be normalized to the same datum, usually sea level. For Line 1 which has a datum of 900 m ASL, the adjustment is 900 - 875 = 25 m, for Line 2 it is 850 - 875 = -25 m.

Table 3.2 Elevation of depth reference from Well#1 to Well#6

Well number	Well name	Depth reference(KB) (m ASL)
Well#1	Mobil Pembina	874.75
Well#2	Home Brightbank	745.94
Well#3	Amoco Wroses	914.60
Well#4	Canterra Bashaw	852.87
Well#5	Atapco Buffalo	821.35
Well#6	CPOG Oberlin	820.08

ASL: above sea level

The normalizing procedure is used for every well according to the datum of its correlating seismic line.

After normalizing to seismic line datum, some important geological markers such as the Second White Speckled Shale (2WS), Cambrian top and Precambrian top can be interpreted from the well-logs. Table 3.3 -Table 3.8

Table 3.3 Depth of 2WS and Precambrian in Well#1 to Line 1 and line 2

Layers Depth (m)\Seismic line	Line 1	Line 2
2WS	1589	1539
Precambrian	3598	3548

are the well depths of these three geological layers normalized to a specific seismic line.

Because of the wedge-shape of Phanerozoic strata in the Alberta Basin(Fig. 1.6), the sedimentary depth near the location of Well#2 is

Table 3.4 Depth of 2WS and Precambrian in Well#2 to Line 1 and line 2

Layers Depth (m)\Seismic line	Line 1	Line 2
2WS	1231	1181
Precambrian	3063	3013

Table 3.5 Depth of 2WS in Well#3 normalized to Line 4

Layers Depth (m)\Seismic line	Line 4
2WS	1583.4

Table 3.6 Depth of 2WS in Well#4 normalized to Line 7

Layers Depth (m)\Seismic line	Line 7
2WS	1194.1

shallower than that of Well#1. Since Line 1 and Line 2 extend between these two wells, the depth of 2WS and Precambrian along these two lines should be in the normalized depth range of Well#1 and Well#2. One thing needed to be mentioned here is that the 2WS of the reprocessed seismic lines from Central Alberta in this thesis is shifted to a fixed two-way traveltime level 1.0s, which means that all the geological layers below 2WS are all shifted the same amount. Fig. 3.1 shows the shifting amount by time from Line 8 -

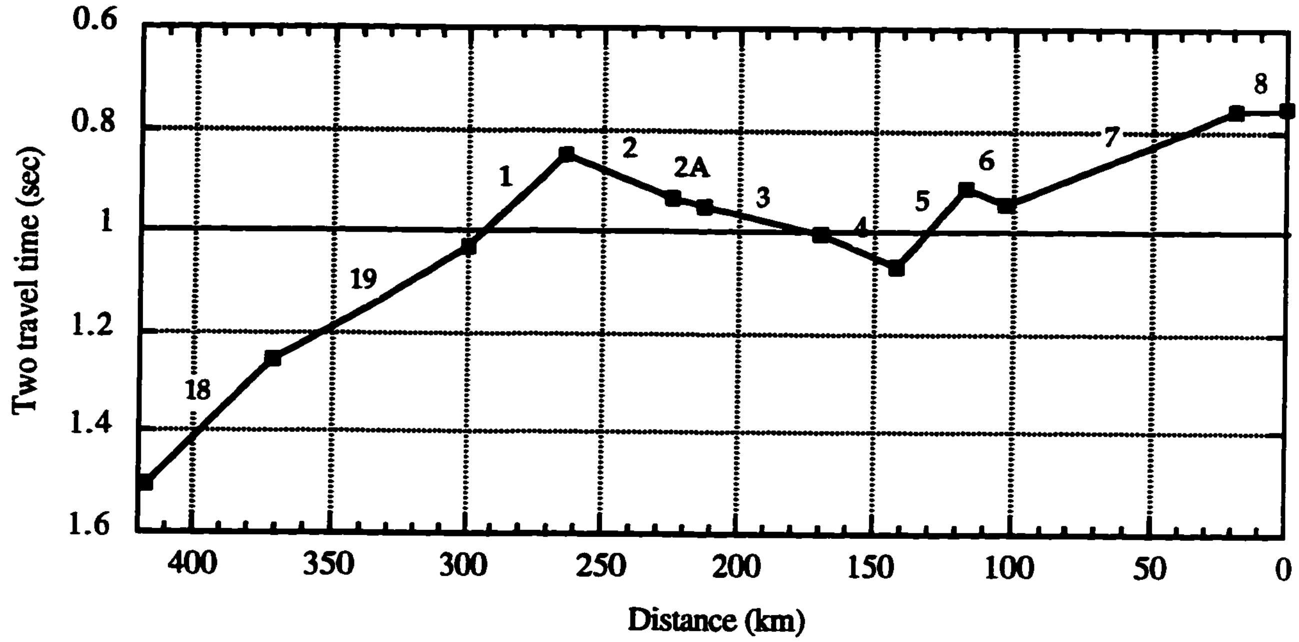

Fig. 3.1 Two way travel-time to 2WS picked from Line 1 - Line 8 - Line18.

Table 3.7 Depth of 2WS and Cambrian in Well#5 to Line 7 and line 8

Layers Depth (m)\Seismic line	Line 7	Line 8
2WS	1136	1056
Cambrian	2325	2245

Line 1 to Line 18. Because of the very different datum selected in PRAISE line, stack seismic data of Line 18 and Line 19 are started from 0.4s - 0.7s instead of 0s. In this case, the largest shifting amount of the reprocessed seismic lines goes to Line 8. When identifying the geological layers below 2WS in the reprocessed seismic section, the shifting depth needs to be taken into consideration. For instance, according to Table 3.8 and Fig. 3.1, the Precambrian depth of Line 8 is 2874 m and the down-shift depth of Line 8

Table 3.8 Depth of 2WS and Precambrian in Well#6 to Line 7 and line 8

Layers Depth (m)\Seismic line	Line 7	Line 8
2WS	1154.6	1074.6
Precambrian	2903.7	2823.7

is around 0.24 s two-way traveltime, the corrected Precambrian depth of reprocessed Line 8 should be 2874 m + 0.24 s /2 * 2400 m/s = 3162 m.

As discussed in Chapter 1, the basement of Western Canadian Sedimentary Basin (WCSB) is comprised principally of igneous, volcanic, metamorphic and sedimentary rocks of Precambrian age. In the research area, the Precambrian is directly overlaid by clastic facies of Cambrian or Devonian age. From the top information of the six wells, the stratigraphic relationships of these clastics and the formations above the basement can be obtained. However, evaluation of formations and location of faults, folds and unconformities, and the thickening and thinning of lithologic sections can only be done by well-to-well correlation studies.

It is useful in seismic interpretation to normalize all well reference depth to a fixed datum. Selecting 900 m above sea level as this fixed datum, six wells (Well#1 to Well#6) were compared using Insight 5 software named *logedit*.

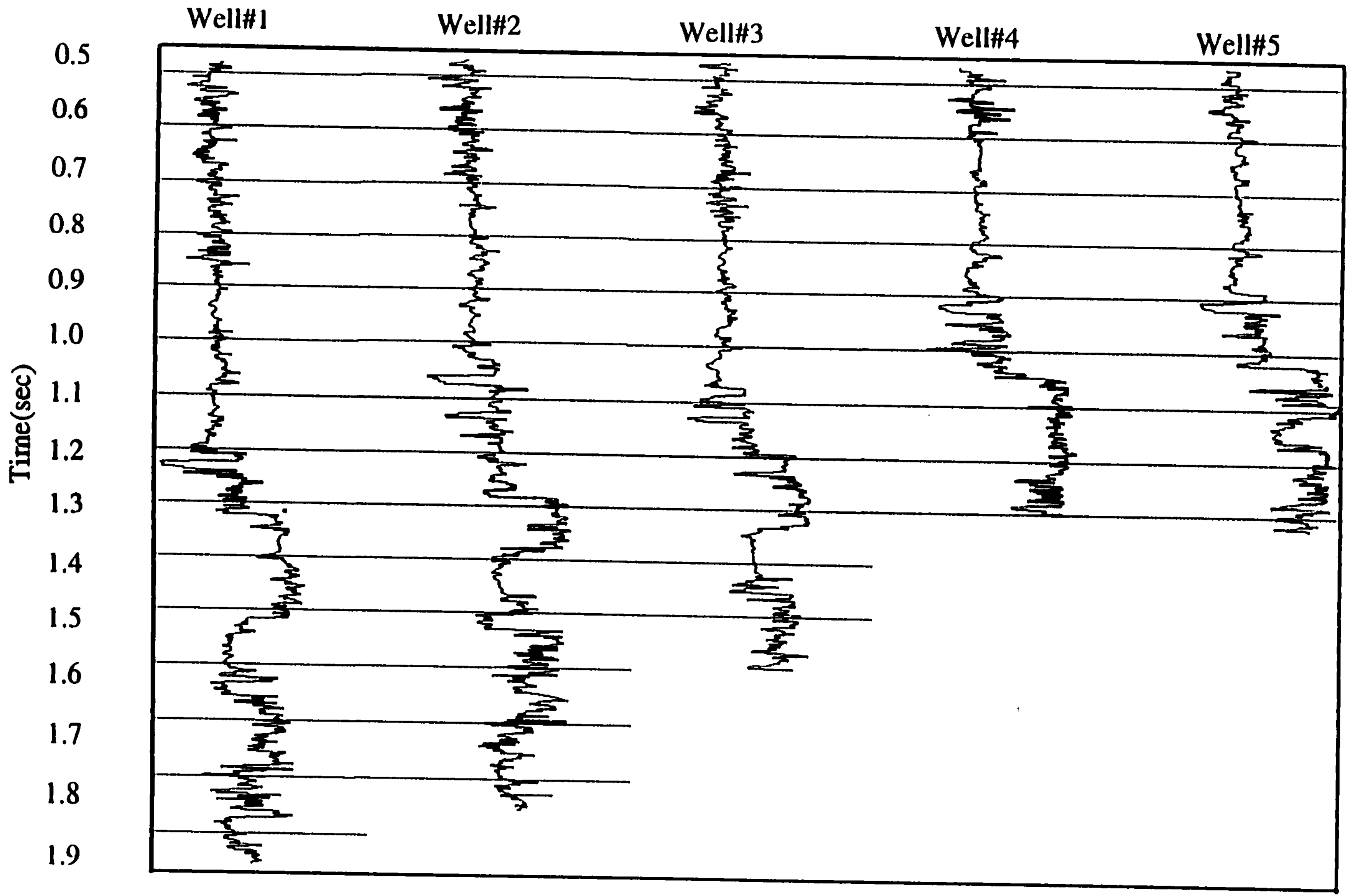

Fig. 3.2 Velocity correlation from Well#1 toWell#5 in time scale.

Fig. 3.2 is the velocity and time correlation between well logs from Well#1 to Well#5. Because of the small section logged and data lost in Well#6, the results are too limited to be useful for correlation. In Fig. 3.2, velocity variation can be compared from well to well and also to the thickness of the related geological layers. The distance between these wells is over 250 km from Well#1 to Well#5, while Well#1 is located closer to the foothills of the Alberta Basin where the thickest sediments occur and Well#5 is located on the flanks of the basin where the thinner sediments were deposited.

A cross-section of sedimentary layers between Well#1 to Well#6 is shown in Fig. 3.3, which is created from the formation tops of these six wells with the reference depth normalized to 900 m above sea level. Since the cross-section with these six wells is in a north-west direction and does not fall along the CAT seismic lines, it can not give exact information of the sedimentary deposition along the seismic lines. But at least the deposition from Fig. 3.3 can be used as an approximate guide.

Table 3.9 gives the name of the sedimentary group and their deposition age as taken from geological reports filed with the well logs. The detailed well log calculation for impedance in the sedimentary layers are shown in Fig. 3.4 to Fig. 3.8. These indicate the main formation tops of every well and the correlation between them. From these figures, it can be deduced that the top of the Mannville Group is a very strong and continuous reflector along these five wells. Besides, other formation tops can be identified on the seismic sections under the guidance of the calculated results of these well logs.

Based on Fig. 3.3 with 900 m above sea level as the surface datum, flattening 2WS and shifting it to 1500 m below the datum, a new isopach of sedimentary layers is shown as Fig. 3.9. With the seismic data corrected in a similar manner, the geological layers in the migrated section can be constructed.

3.2.2 Integrating with Potential Fields

Aeromagnetic maps can provide information on the magnetic properties of the Precambrian basement rocks to depths of about 15 km.

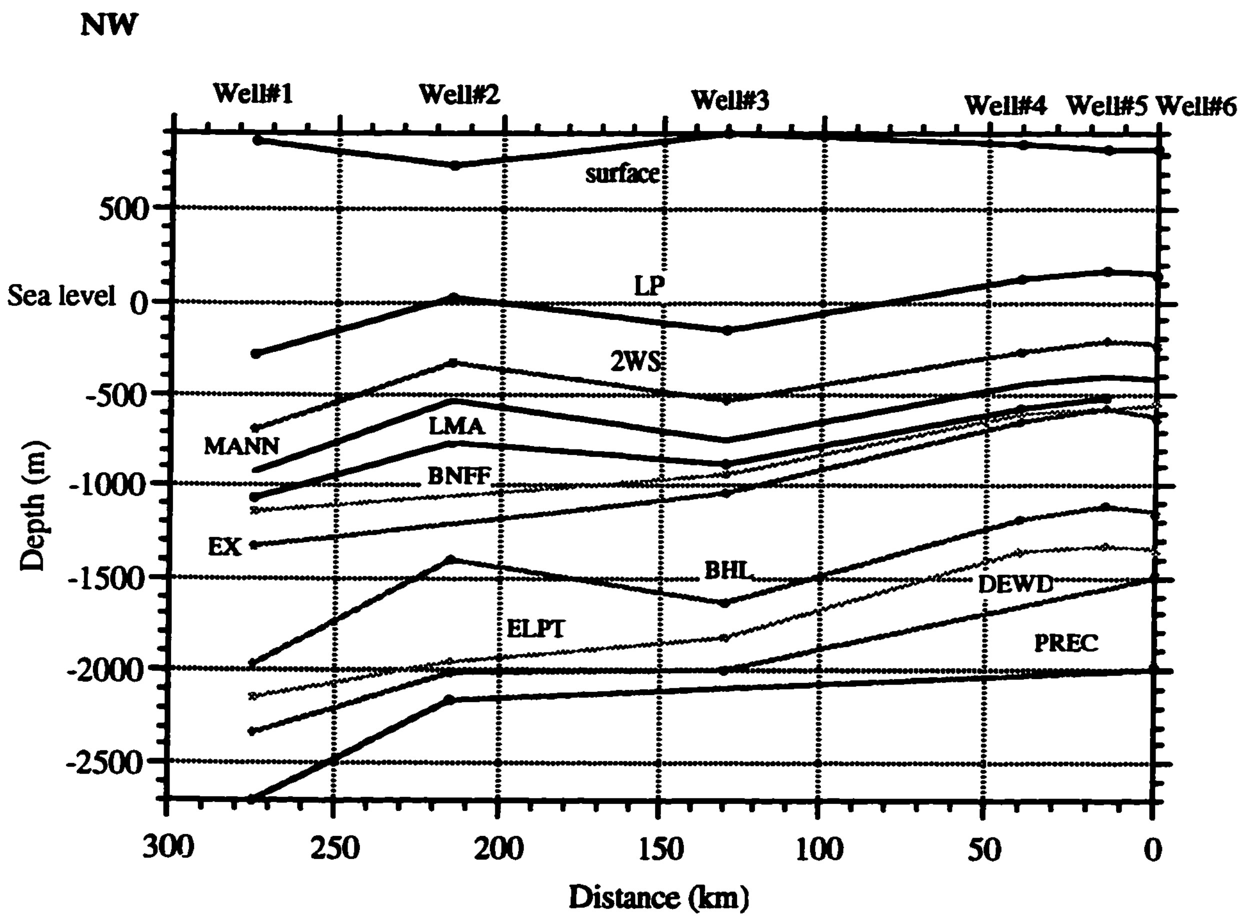

Fig. 3.3 Cross-section of sedimentary layers along Well#1 to Well#6 with datum at 900 m above sea level. (Label name see Table 3.9)

The sediments do not contain much iron bearing material and do not perturb the magnetic field. The gravity anomalies are caused by the horizontal variation in the density of rocks which can be related to structural and stratigraphic features. Density and seismic compressional velocity are related and changes in them cause the elastic waves to be reflected back from depth. So interpreting seismic a section involves the integration of both the magnetic and gravitational potential fields. The

Table 3.9 Name and age of the sedimentary group in Fig. 3.3

Sedimentary group name	Geological period	Age(M.Y.)
LP(LeaPark)	Upper Cretaceous	84.0 ~ 87.5
2WS(Second White Speckled Shale)	Late Cretaceous	90.5 ~ 91.5
MANN(Mannville Group)	Lower Cretaceous	103. ~ 119
L MA(Lower Mannville group)	Early Cretaceous	113 ~ 119
BNFF(Banff)	Early Mississippian	352 ~ 358
EX(Exshaw)	Upper Devonian	358 ~ 362
BH L(Beaver Hill Lake Group)	Middle Devonian	374 ~ 376
ELPT(Elk Point Group)	Middle to early Devonian	376 ~ 408
DEWD(DeadWood)	Upper Cambrian	512 ~ 519
PREC(Precambrian)		> 570

physical basis for the seismic anomalies can be inferred from them.

As the basin sediments are essentially nonmagnetic, the aeromagnetic fabric can be related to structural and compositional trends of the basement rocks. The aeromagnetic features of the basement along the seismic lines is shown in Fig. 3.10. The magnetic data is from the Geological Survey of Canada with the units of nanoTesla. 'E' is the location of Edmonton and 'STZ' is the Snowbird Tectonic Zone. A more detailed discussion was given in Chapter 1, where the nature of these aeromagnetic anomaly highs and

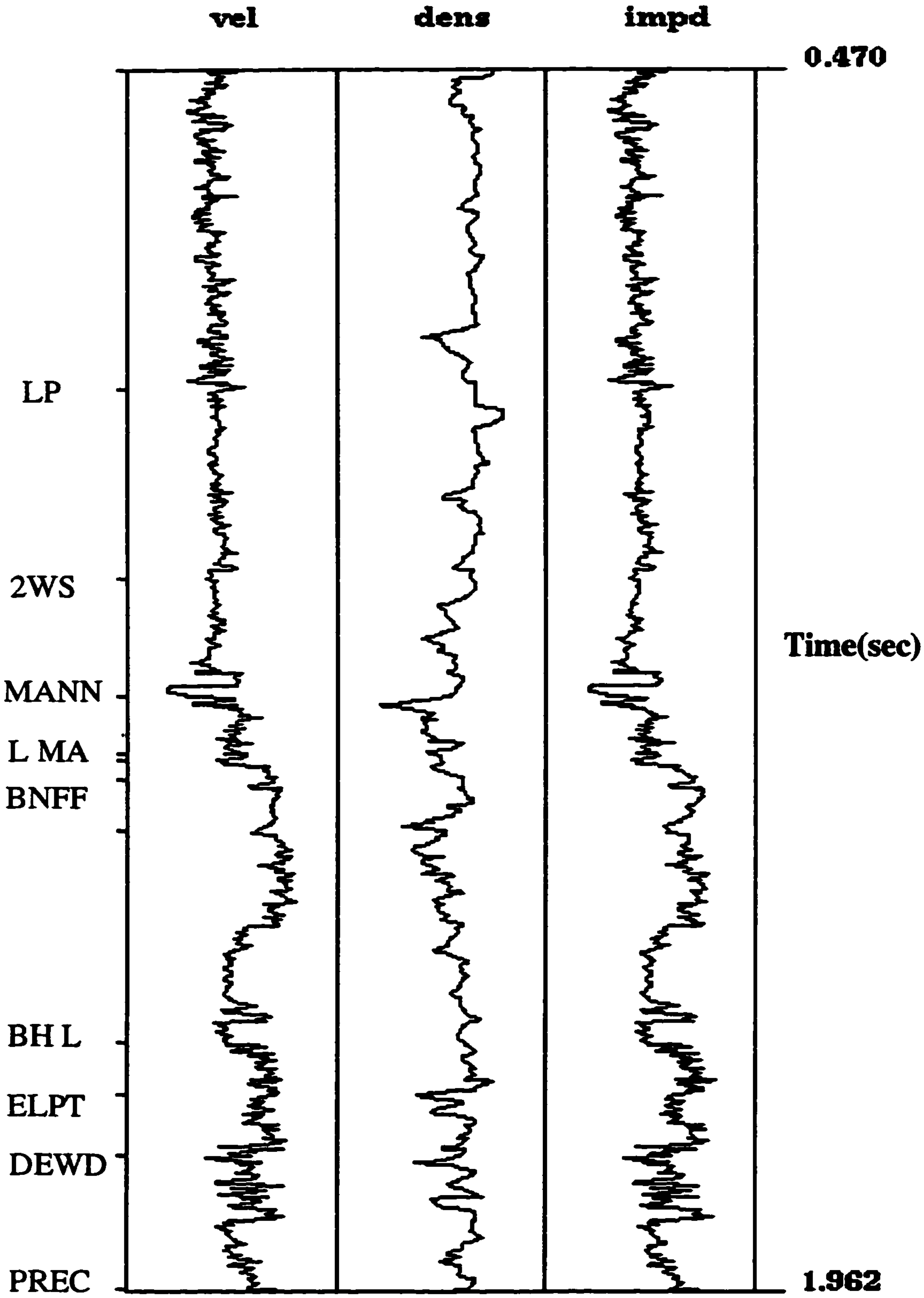

Fig. 3.4 Velocity, density and computed impedance for Well#1.

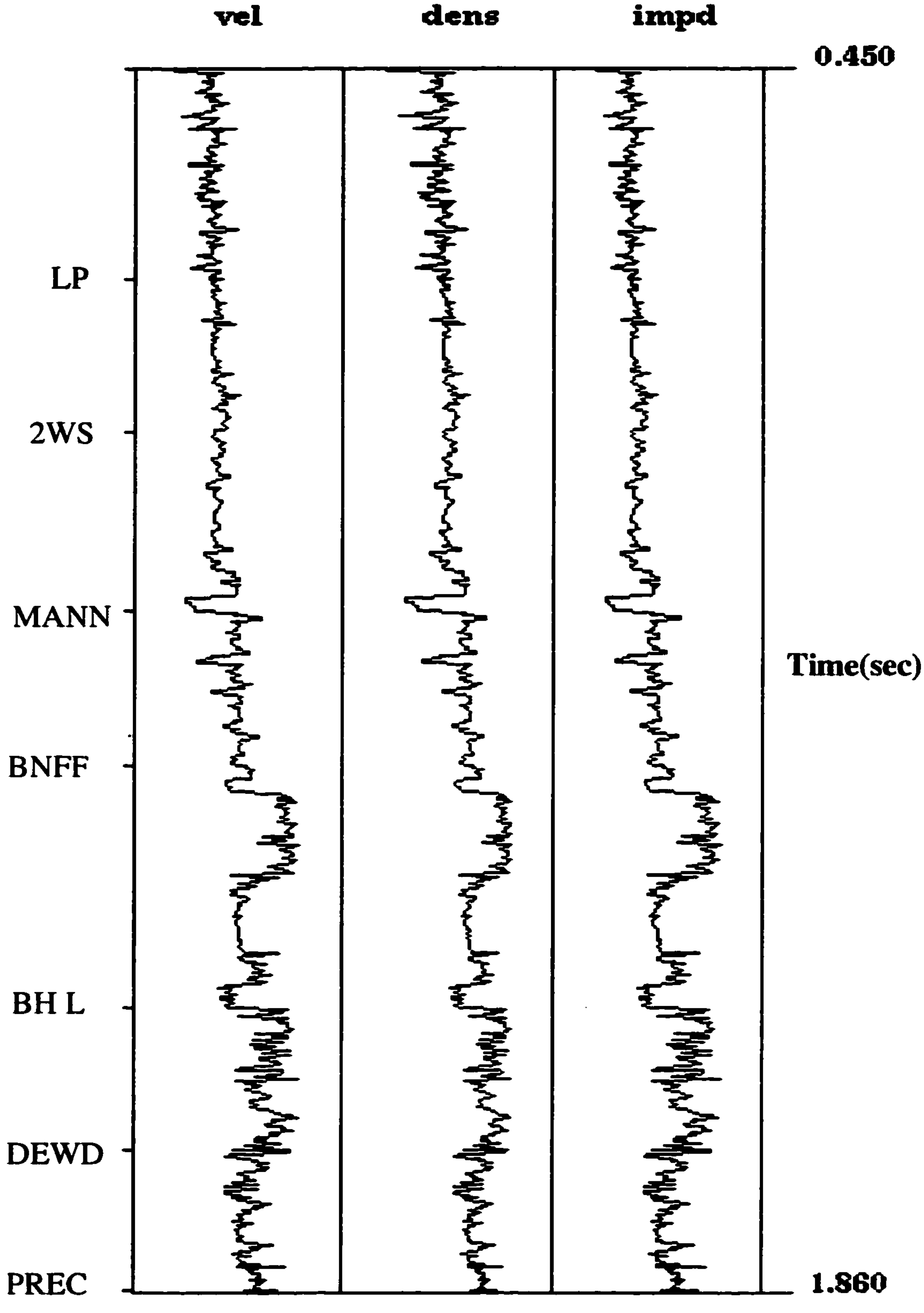

Fig. 3.5 Velocity, density and computed impedance for Well#2.

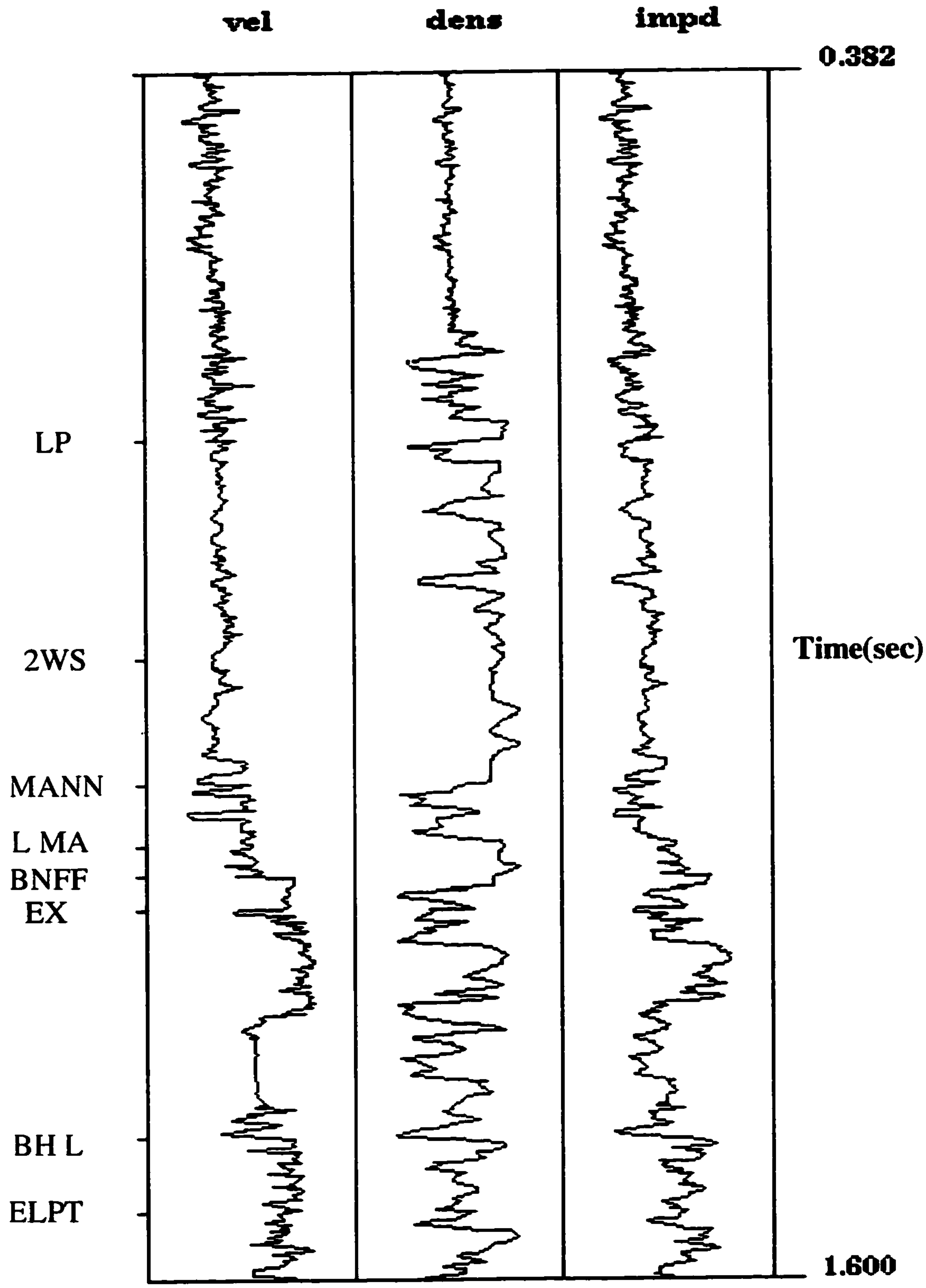

Fig. 3.6 Velocity, density and compted impedance for Well#3.

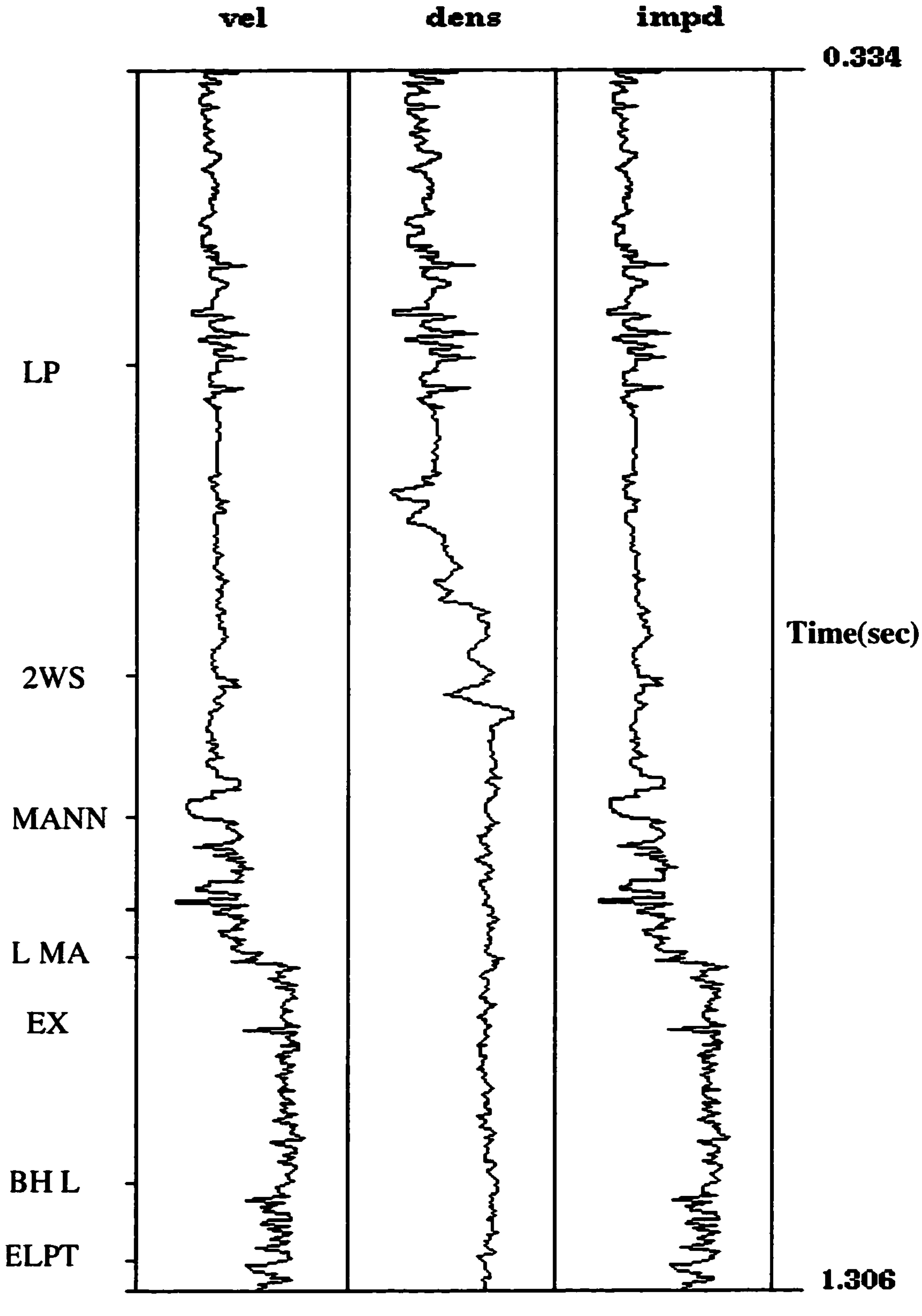

Fig. 3.7 Velocity, density and computed impedance for Well#4.

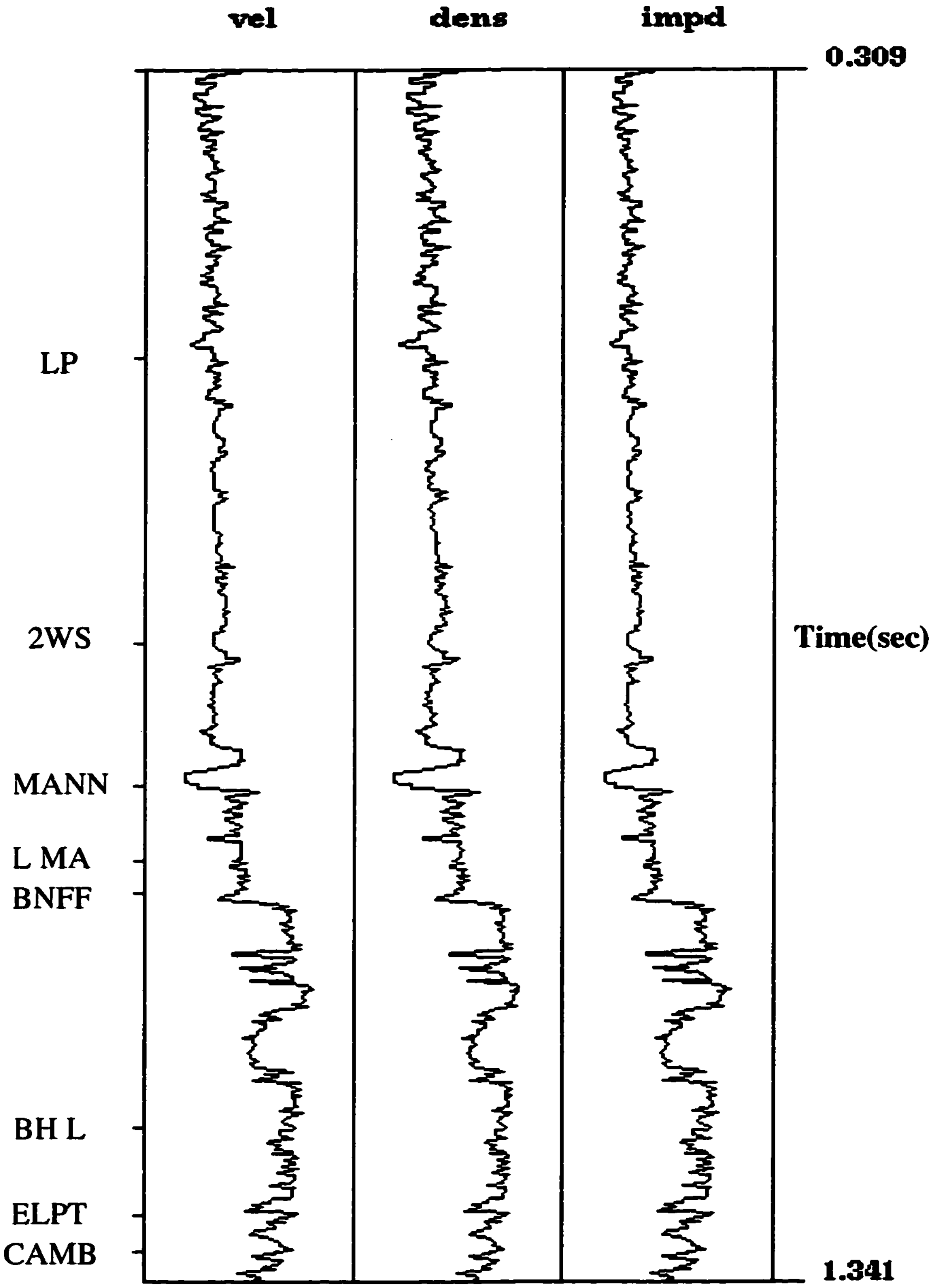

Fig. 3.8 Velocity, density and computed impedance for Well#5.

lows was related to the age of Precambrian core samples. The Central Alberta reflection seismic lines (Line 1 to Line 8), including PRAISE Line 18 and Line 19 cross through six Precambrian magnetic zones, as indicated in Fig. 3.10. From east to west, they are Loverna Block, Bawlf High, Lacombe Domain, Rimbey High, Thorsby Low and Wabumun High. Having different aeromagnetic signatures and geological features as Table 3.10

NW

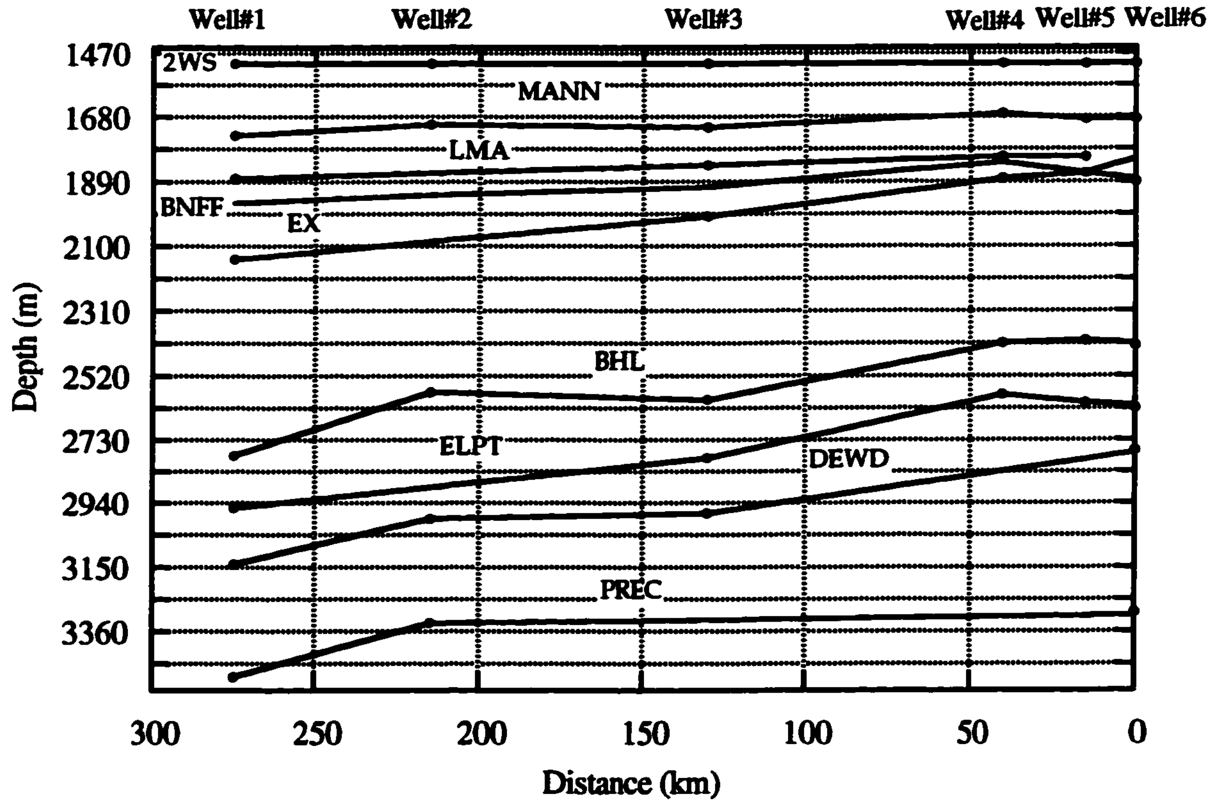

Fig. 3.9 Cross-section of sedimentary layers after flattening 2WS.

basement zones provide some general information on the tectonic evolution of central Alberta. The reflections on the seismic lines traversing different zones should show some correlation with the different potential field anomalies. The strikes of the structures in this area are given by the northeast trending of these aeromagnetic and gravity anomalies. One very long linear feature on both potential field maps is associated in Saskatchewan with the Snowbird Tectonic Zone (STZ). It is an important

Table 3.10 Aeromagnetic signature and geological feature of Precambrian zones

Precambrian domain	Aeromagnetic signature	Geological feature
Loverna Block	negative to neutral local positive	high-grade metamorphic rocks
Bawlf High	positive anomaly belt	circular volcanic remnant
Lacombe Domain	mainly negative local positive	low-grade supracrustal rocks
Rimbey High	positive anomaly belt	biotite granite, magmatic arc
Thorsby Low	negative anomaly belt	high strain zone
Wabamun High	positive anomaly	magmatic rocks

structural boundary which separates the Rae Proterozoic and Hearne Archean provinces (cratons). The Thorsby Low, a narrow north-northeast-trending curvilinear aeromagnetic and gravity low zone, is interpreted to represent the ductile southern extension of the Snowbird tectonic zone and marks the suture zone between the Hearne province (craton) and the western Rae province (Ross et al, 1995). The seismic reflection characteristics on each side of the STZ are different as will be discussed later.

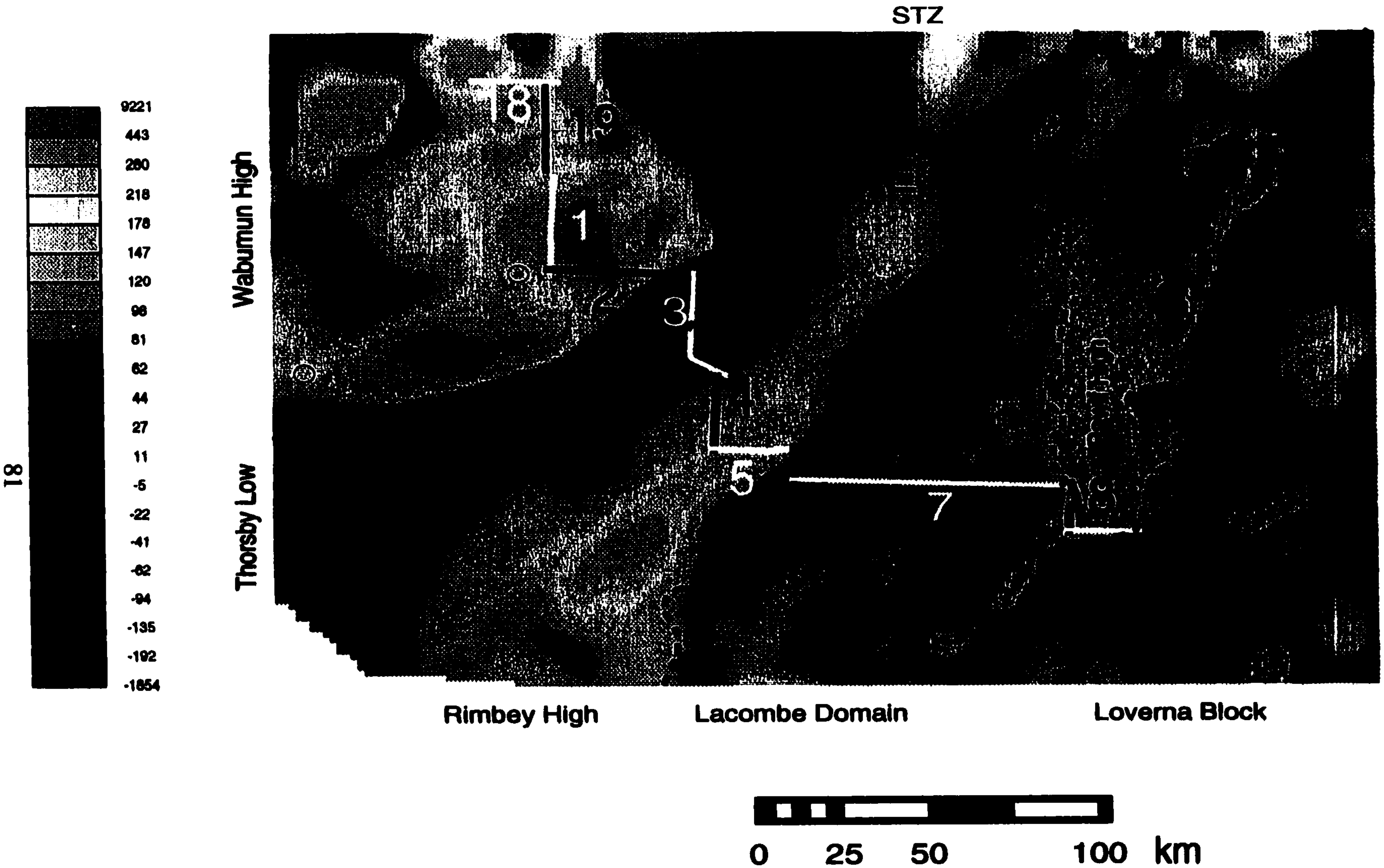

Fig. 3.10 Aeromagnetic anomalies along CAT and PRAISE seismic lines. (Index unit:nT)

Similarly, since the Rimbey granites were viewed as a magmatic arc related to closure of an ocean basin along a southeast-dipping subduction zone (Ross et al, 1995), the structures imaged by the seismic data should have the characteristics of this tectonic model. During the formation of magmatism in the Rimbey belt while the underthrusting of oceanic lithosphere, the northwest-verging crustal imbrication and crustal thickening which occurred at the same time has been interpreted from the migrated seismic reflection data in this area. Thus, the seismic section can be used to determine the tectonic evolution model with the aid of the potential field fabric and outcrop data in northeastern Saskatchewan.

As mentioned in Chapter 1, the reprocessed seismic data interpretation focuses on five points. These are the structural formation of the sedimentary layers, the deformation of the Precambrian basement, the interaction between the Precambrian basement and the Phanerozoic sedimentary cover, the mid-crustal structure and the reflection Moho. For this purpose, the depth of the reprocessed seismic data interpreted is divided into two parts, one is the top 6 km of seismic section, the other is whole depth from the Precambrian top to the base of the crust between 40 and 45 km in depth. In the integrating of the well log data, aeromagnetic and gravity potential fields, the reprocessed seismic reflection data interpretation starts on the east end with Line 8 and finishes northwest of Edmonton with Line 18.

3.2.3 Interpretation of Line 8

The Central Alberta Transect (CAT) seismic Line 8 is a north-south profile with common depth point (CDP)#208 to CDP#974, the total length being 19 km. It is on the edge of the aeromagnetic Bawlf High, which belongs to the Red Deer linear trend. From the top 6 km of this line, shown in Fig. 3.11, it is observed that the reflectors above 1.5 km are strong.

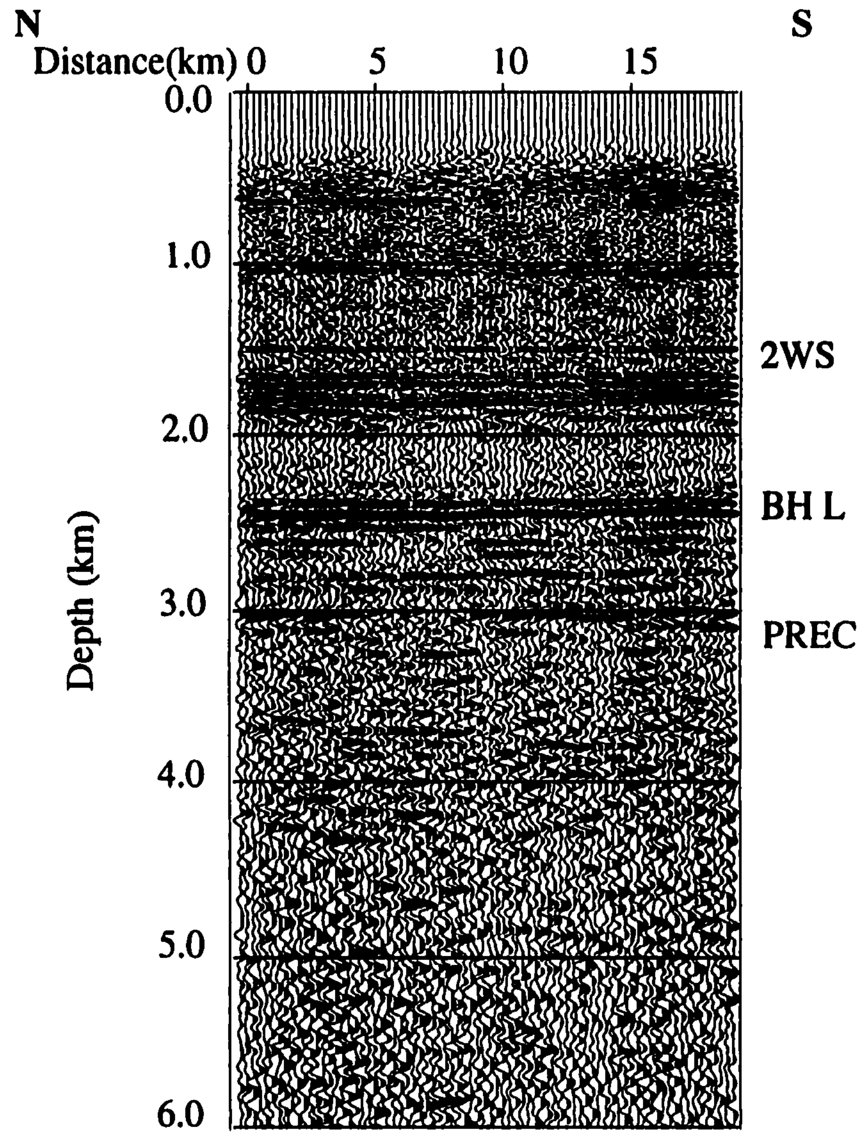

Fig. 3.11 Top 6 km of reprocessed seismic Line 8 with geological layers identified.

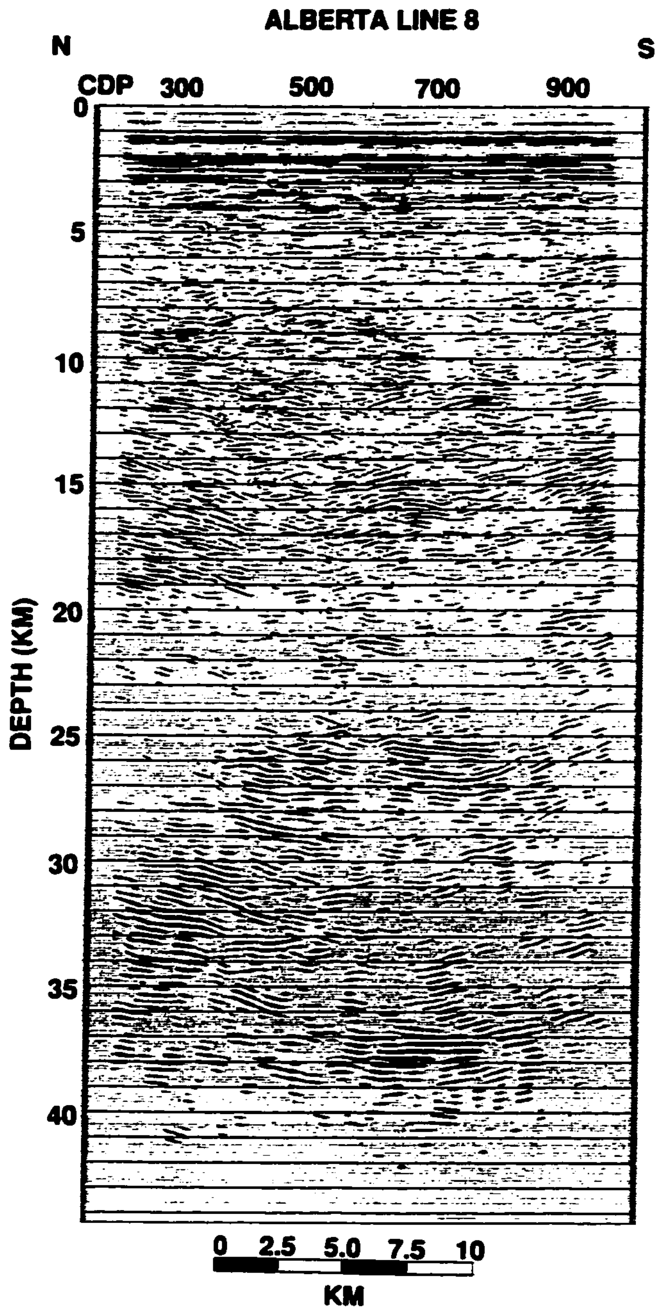

Fig. 3.12 Crustal-scale migrated-coherency-filtered section of Line 8.

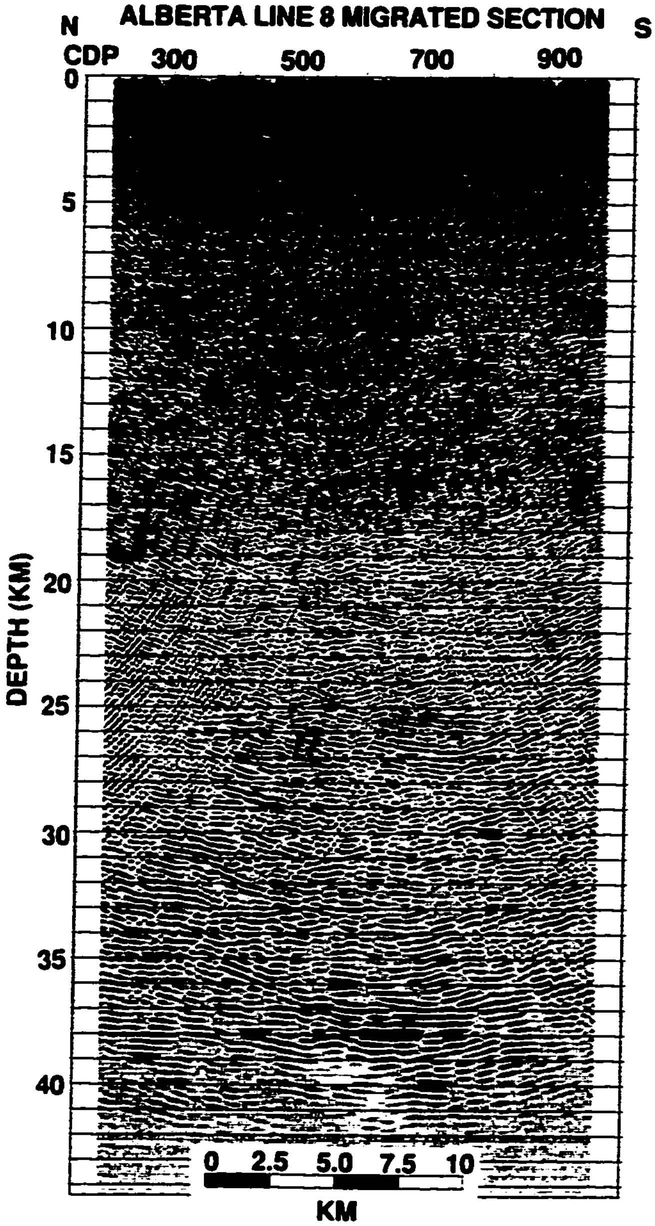

Fig. 3.13 Crustal-scale migrated section of Line 8.

According to the cross-section from the well log data(Fig. 3.9), three geological layers are identified. Actually, the other geological layers can be easily identified in the same way. For instance, the Elk Point(ELPT) reflector is just below the Beaver Hill Lake(BH L) reflector but stronger than it. Below the ELPT, there are a number of discontinuous reflectors which depict the unconformities due to erosion during the Ordovician and Silurian. Above 2 km in Fig. 3.11, two unconformities are evident. One is below the Exshaw(EX) reflector around 1.8 km, the other is Lower Mannville(L MA) around 1.6 km. The buried Precambrian erosional reflectors are less continuous compared to the other formation reflection tops and there are some dipping events within the Precambrian which are not continuous enough to determine their structures.

From the depth section shown as Fig. 3.12 and Fig. 3.13, it is seen that the structures below 5 km are very complicated with steep and complex dips. In Fig. 3.12, showing the migrated-coherency-filtered section of Line 8, it is seen that the main dip direction is to the south. In the mid-crustal part around 16 km, there is a folded fault with the dip direction to south. All these indicate that the tectonic stress came from the south. The Moho boundary is at a depth of 40 km and is characterized by an abrupt loss in reflectivity.

3.2.4 Interpretation of Line 7

Connecting with Line 8 to the west, central Alberta seismic Line 7 extends from west to east with CDP#238 to 3591 and the length is 83.9 km. It crosses the Lacombe Domain which has a mainly negative aeromagnetic anomaly(Fig. 3.10). From the top 6 km of the migrated section shown as Fig. 3.14, discontinuous reflectors were observed below 1.5 km which implied an unconformity. Small vertical relief is seen in the middle of

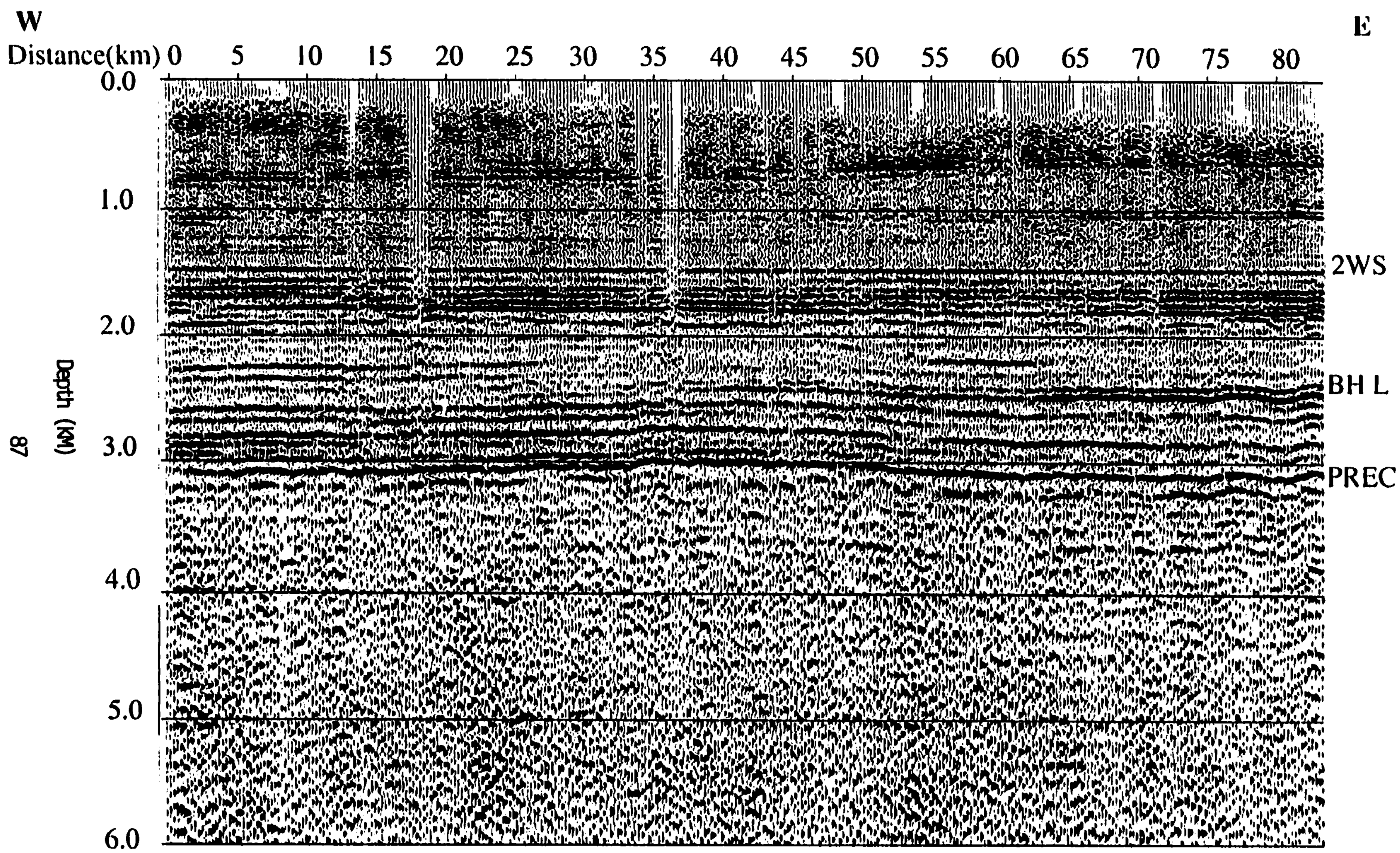

Fig. 3. 14 Top 6 km of reprocessed seismic Line 7 with geological layers identified.

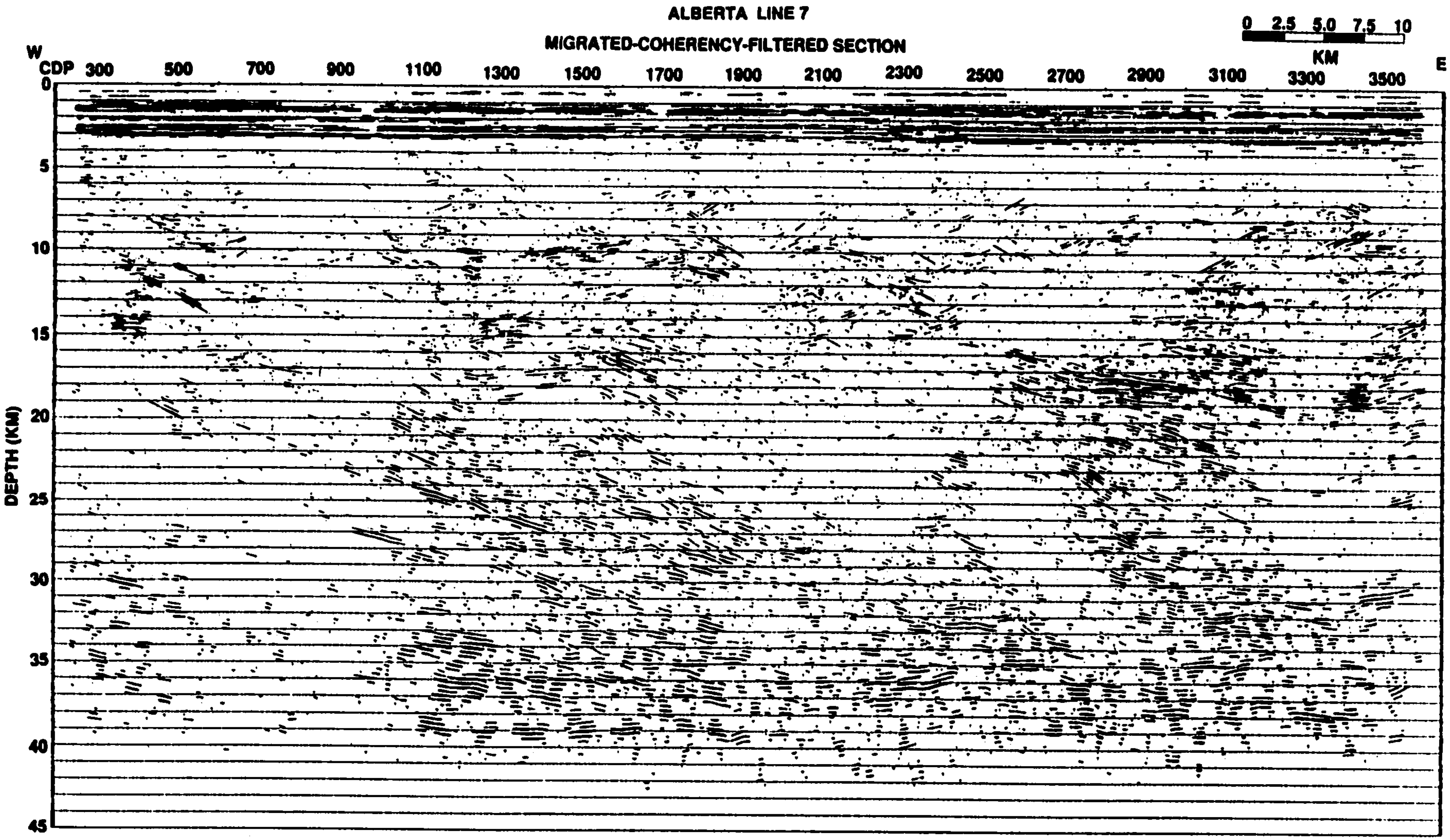

Fig. 3.15 Crustal-scale migrated-coherency-filtered section of Line 7.

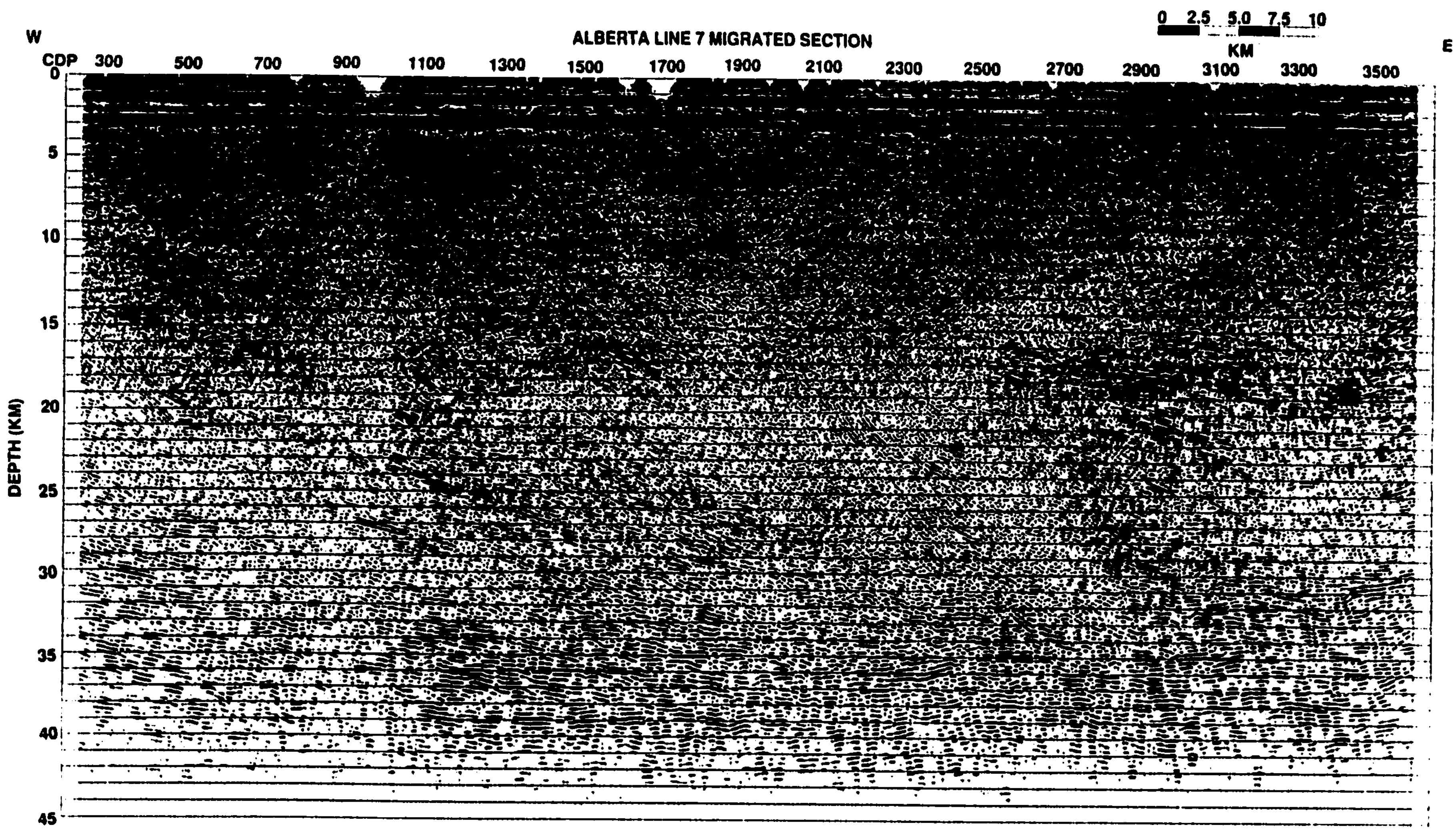

Fig. 3.16 Crustal-scale migrated section of Line 7.

Precambrian section, which appears to have influenced the sedimentary cover up to the top of BH L. At the east end of Line 7 at horizontal distance 75 to 80 km, there is a fold-like structure which is visible from the deeper part of the crust to the top of BH L, but it does not extend to Line 8. This means that a local compressional stress field existed for a period of time. According to Eaton (Eaton et al., 1995), this is because of the low-velocity Cretaceous channel which deflects the Precambrian surface downward.

The deep structure to 45 km for Line 7 is shown on a migrated-coherency-filtered section(Fig. 3.15) and migrated section(Fig. 3.16), in which the former highlights the strongly correlated reflections. It should be noted that east-dipping faults dominate the structure, especially in the mid-crust around 15 ~ 20 km in depth. This suggests that crustal-scale north-west direction thrust imbrication happened during early deformation, which may correlate with the collision between the Rae and the Hearne Province. These thrust structures have been observed to sole out in the lower crust, implying that there may exist a common thrust fault plane near the crust-mantle boundary. The Moho boundary is well imaged at depth of 40 km in Fig. 3.15 and Fig. 3.16.

3.2.5 Interpretation of Line 6

Extending from north to south, central Alberta seismic Line 6 joins Line 7 on the west. It crosses the boundary of the Rimbey High and Lacombe Domain with CDP# 205 to 761. The total length is about 13.9 km. The top 6 km of Line 6 shows several continuous strong reflectors (Fig. 3.17), which indicate the stable deposition environment. A small vertical displacement is observed in the middle of the line between the top of the Precambrian and BH L with the relief gradually reducing. It formed, perhaps, because of salt solution collapse.

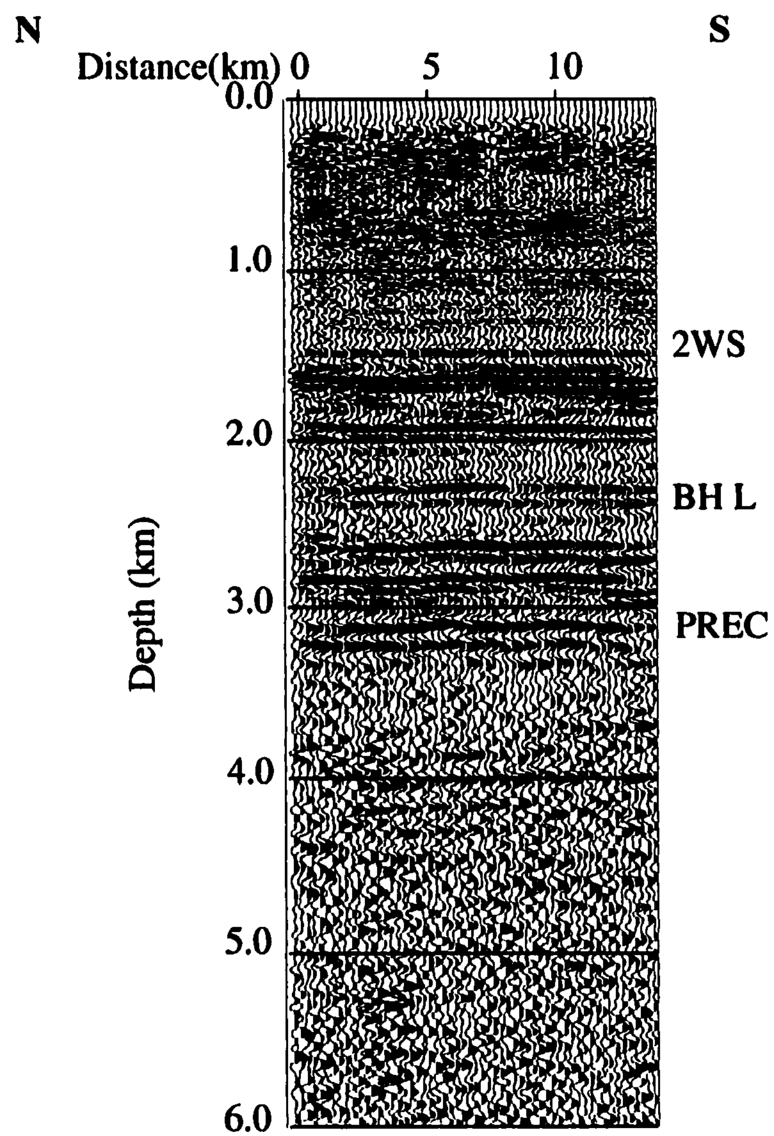

Fig. 3.17 Top 6 km of reprocessed seismic Line 6 with geological layers identified.

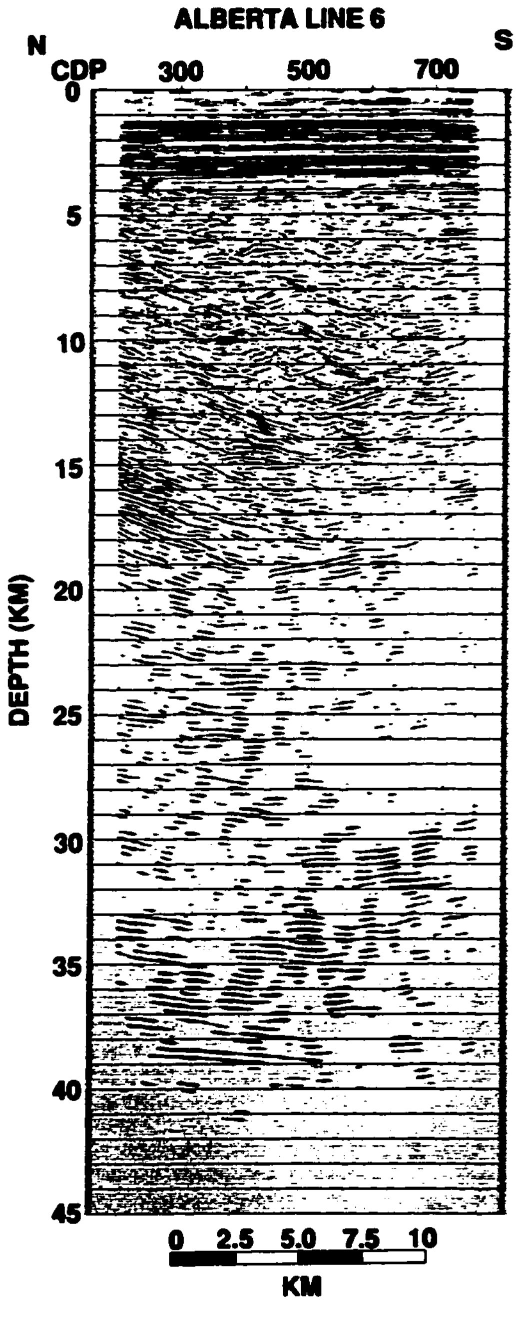

Fig. 3.18 Crustal-scale migrated-coherency-filtered section of Line 6.

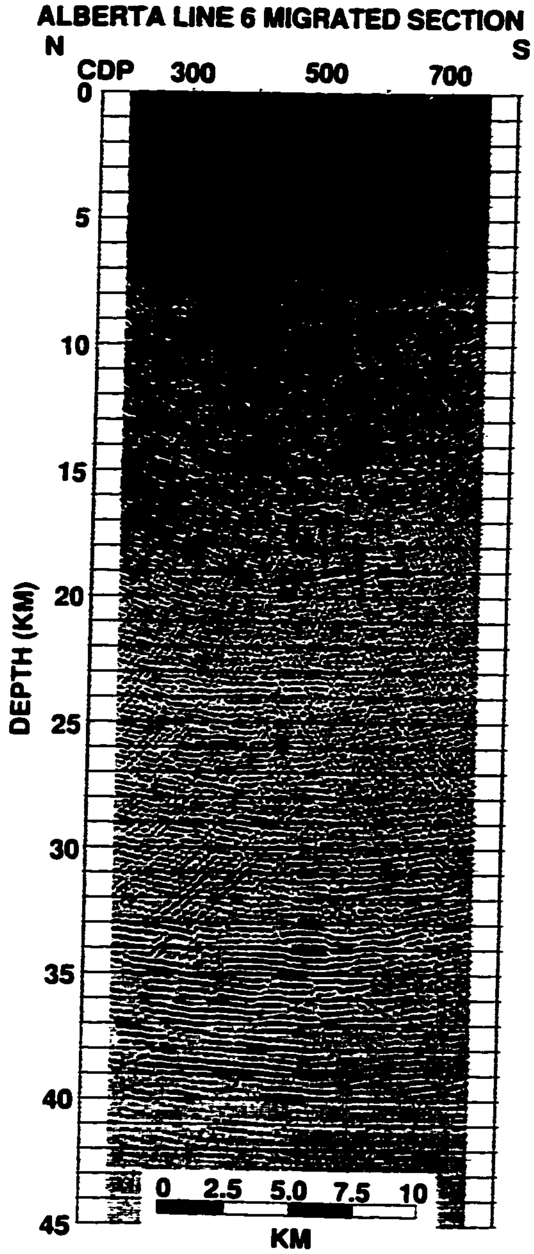

Fig. 3.19 Crustal-scale migrated section of Line 6.

The migrated-coherency-filtered section(Fig. 3.18) and migrated section(Fig. 3.19) show the deep structure of Line 6. The main dipping direction is south except one obvious northern dipping event at a depth of 19 km. Many faulted folds are seen between the depth of 5 km and 17 km with the largest around 15 km, which implies a large amount of north-west crustal shortening. The only northern dipping event may indicate some faulting. The Moho surface along Line 6 is at a depth of 38 km.

3.2.6 Interpretation of Line 5

Crossing the eastern part of the Rimbey Magnetic High, central Alberta Line 5 extends west to east with CDP# from 209 to 1196 and is 24.7 km long. Based on the initial tectonic model which viewed the Rimbey High as a magmatic arc related to the closure of an ocean basin along a southeast-dipping subduction zone, the deep structure imaged by reprocessed seismic data of Line 5 in Fig. 3.20, Fig. 3.21 and Fig. 3.22 can be interpreted reasonably. The variable reflection character in Fig. 3.20 seems to have a deep-seated source at more than 5 km below the Precambrian surface and affected the sedimentary cover to a depth of 1.8 km with almost the same amount of relief. The variable structure may be caused by local magmatic activity or the compressional stress created from the suture zone. There is a reef buildup, called the Rimby reef, on top of the Cooking Lake Formation. Due to the high velocities within the reef, the lower reflection horizons are "pulled-up" giving a false structure.

The mid-crustal structure in Fig. 3.21 shows a much clearer picture of the compressional stress related to the suture zone and the magmatic activities than that of the top 6 km of section. At least three thrust folds are noticed at a depth of between 12 km and 20 km with the dipping direction all to the east. A flat horizontal strong reflector (B1) at 16 km (Fig. 3.42)

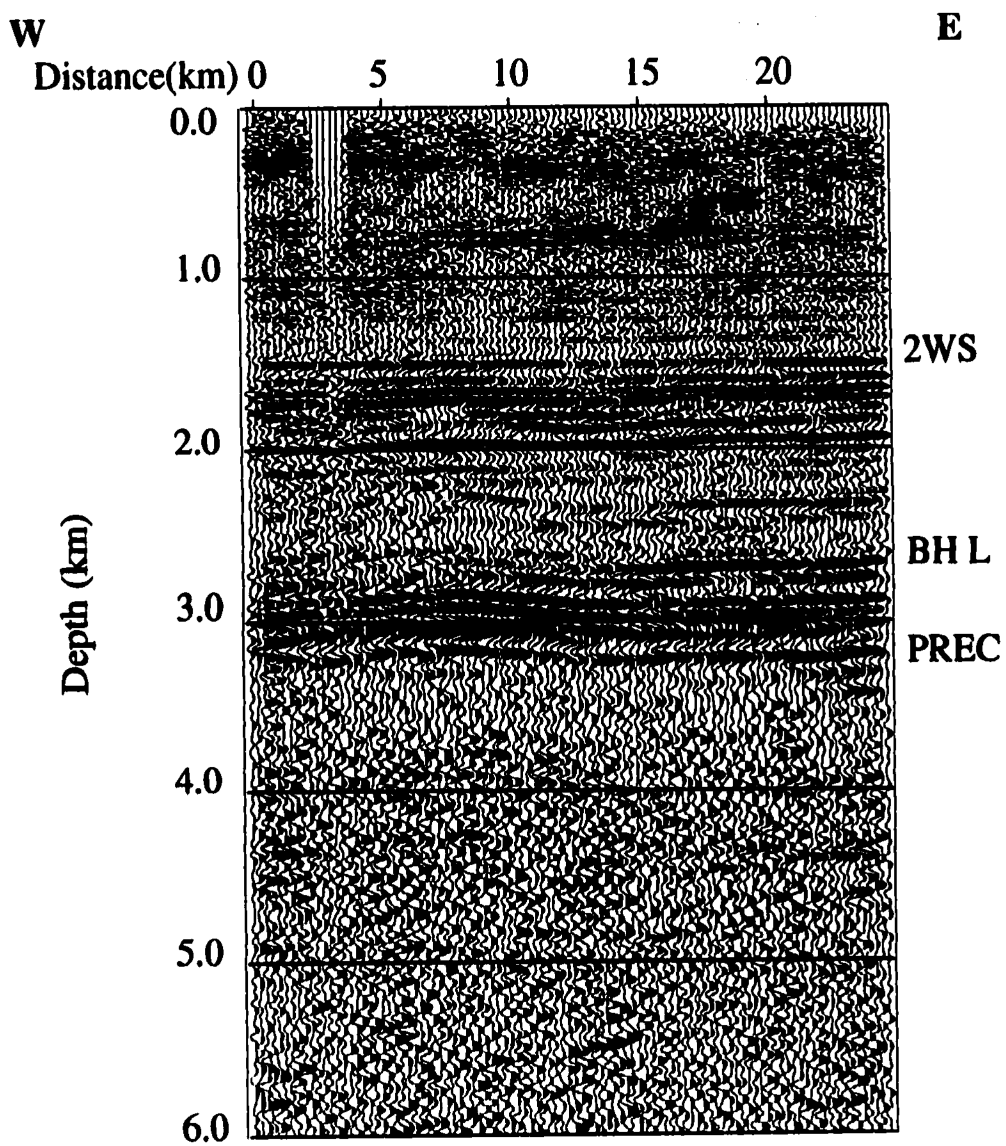

Fig. 3.20 Top 6 km of reprocessed seismic Line 5 with geological layers identified.

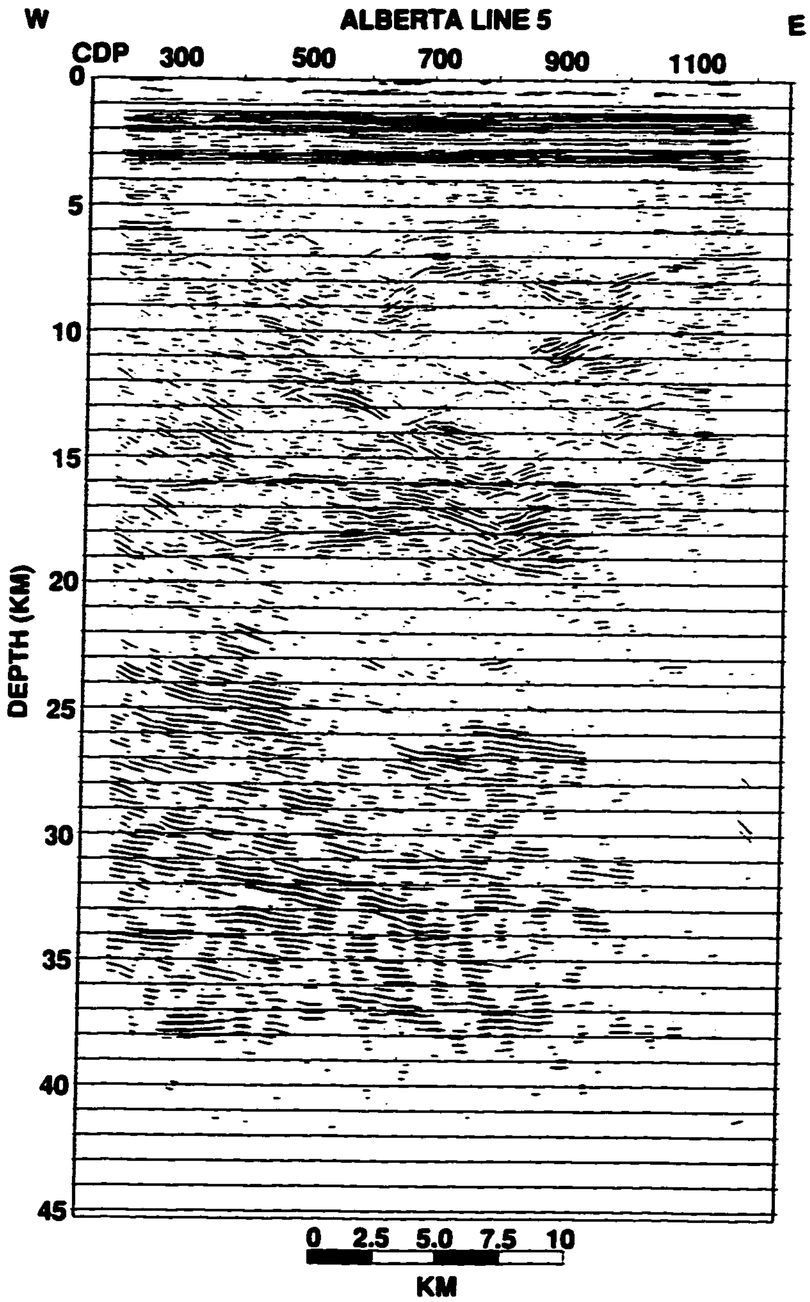

Fig. 3.21 Crustal-scale migrated-coherency-filtered section of Line 5.

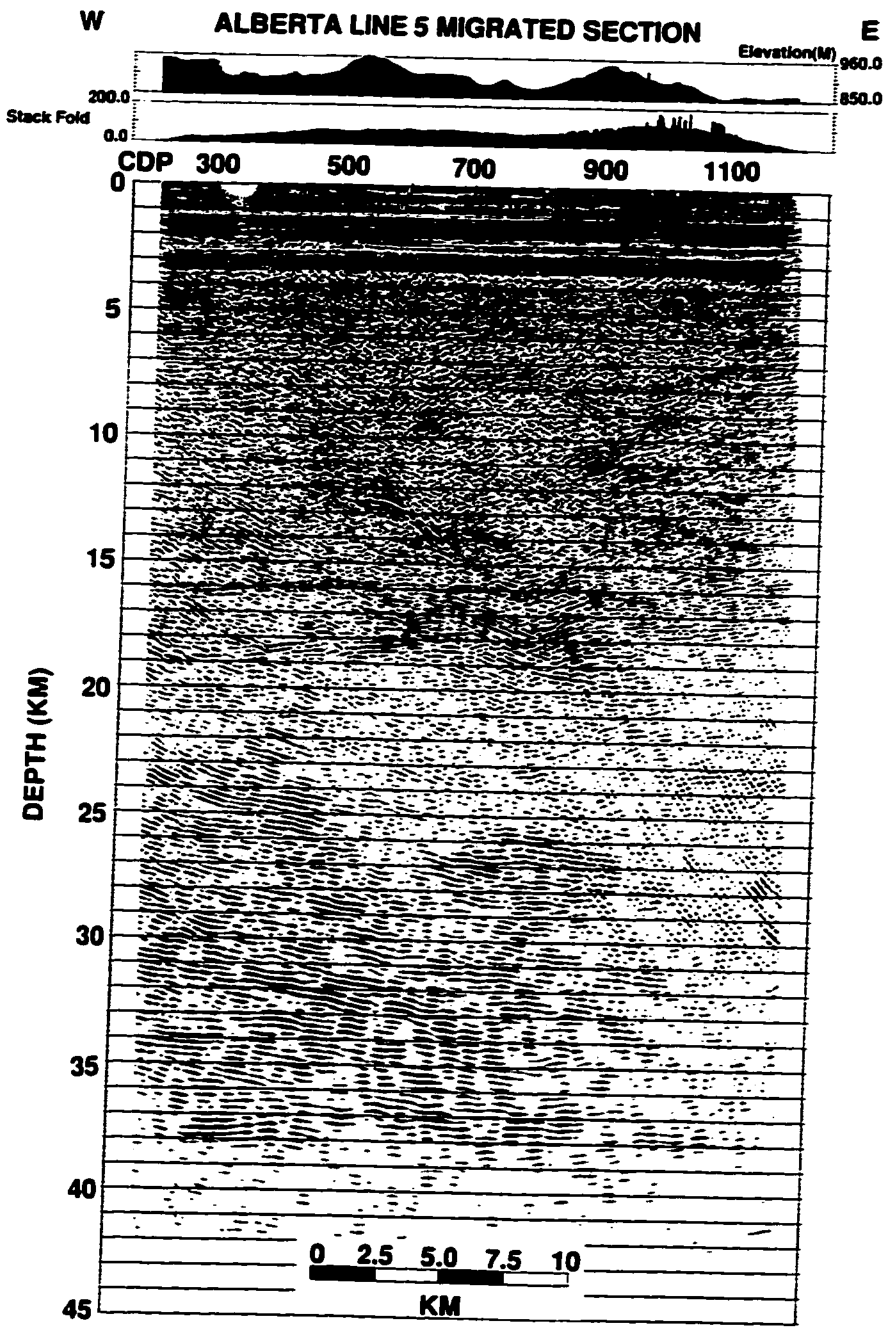

Fig. 3.22 Crustal-scale migrated section of Line 5.

may be interpreted as a sill across the section and is evidence of magmatic activity in this area. The events below 20 km are characterized by east-dipping reflectors with a small dip angle, especially near the Moho which is at about 38 km. Thus, the crust is thinner here compared to Line 7.

3.2.7 Interpretation of Line 4

Central Alberta seismic Line 4 traverses from north to south with CDP# between 206 and 1331 and a total length of 28.2 km, being located in the middle of the Rimbey magnetic High, the top 6 km of the structure of Line 4 (Fig. 3.23) shows minor signs of reactivation within the sedimentary cover and Precambrian surface. The discontinuous reflections along the section can be postulated to be the results of deposition unconformities and periods of erosion. Below the Precambrian subsurface, less reflectivity is shown with no special structure.

The deep structure shown in Fig. 3.24 and Fig. 3.25 is distinguished from that of Line 5 by the smaller angle south-dipping events and more north-dipping reflectors. Since Line 4 is near the Snowbird Tectonic Zone (STZ), which is the structural boundary of two different cratons, the stress field should have changed in this area. The horizontal reflector (a sill) still exists at a depth of 16 km as a continuation from Line 5. The low dips in crustal structure of Line 4 are complicated by the north-dipping and south-dipping faults overlapping in some places. The Moho boundary increases to a depth of 39 km to 42 km. A relict subduction zone (S) exists below 40 km on the reflection section near the base of this line, but is much better imaged with section in Fig. 3.42.

3.2.8 Interpretation of Line 3

Starting from the boundary between Wabamun magnetic High and Thorsby

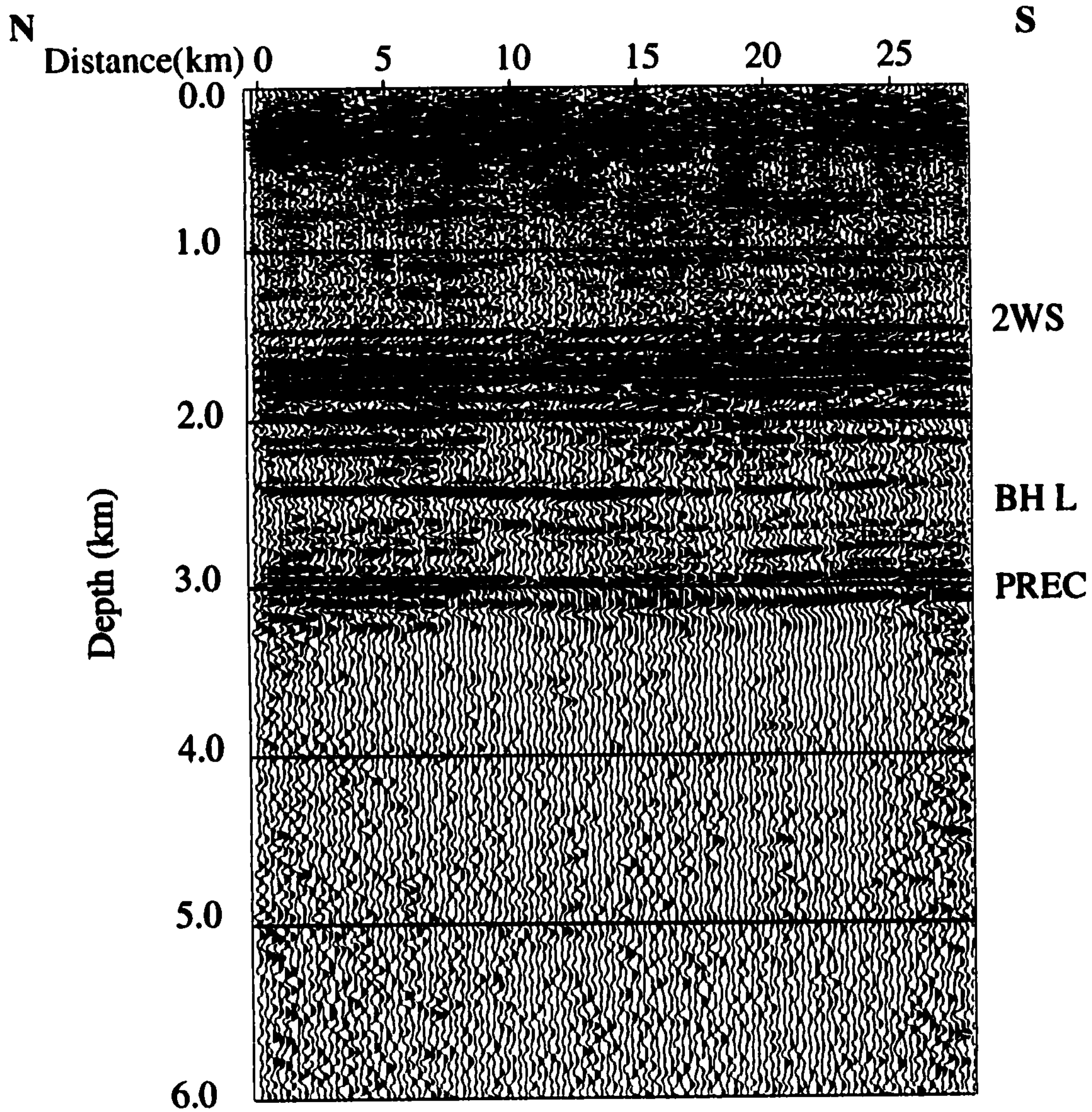

Fig. 3.23 Top 6 km of reprocessed seismic Line 4 with geological layers identified.

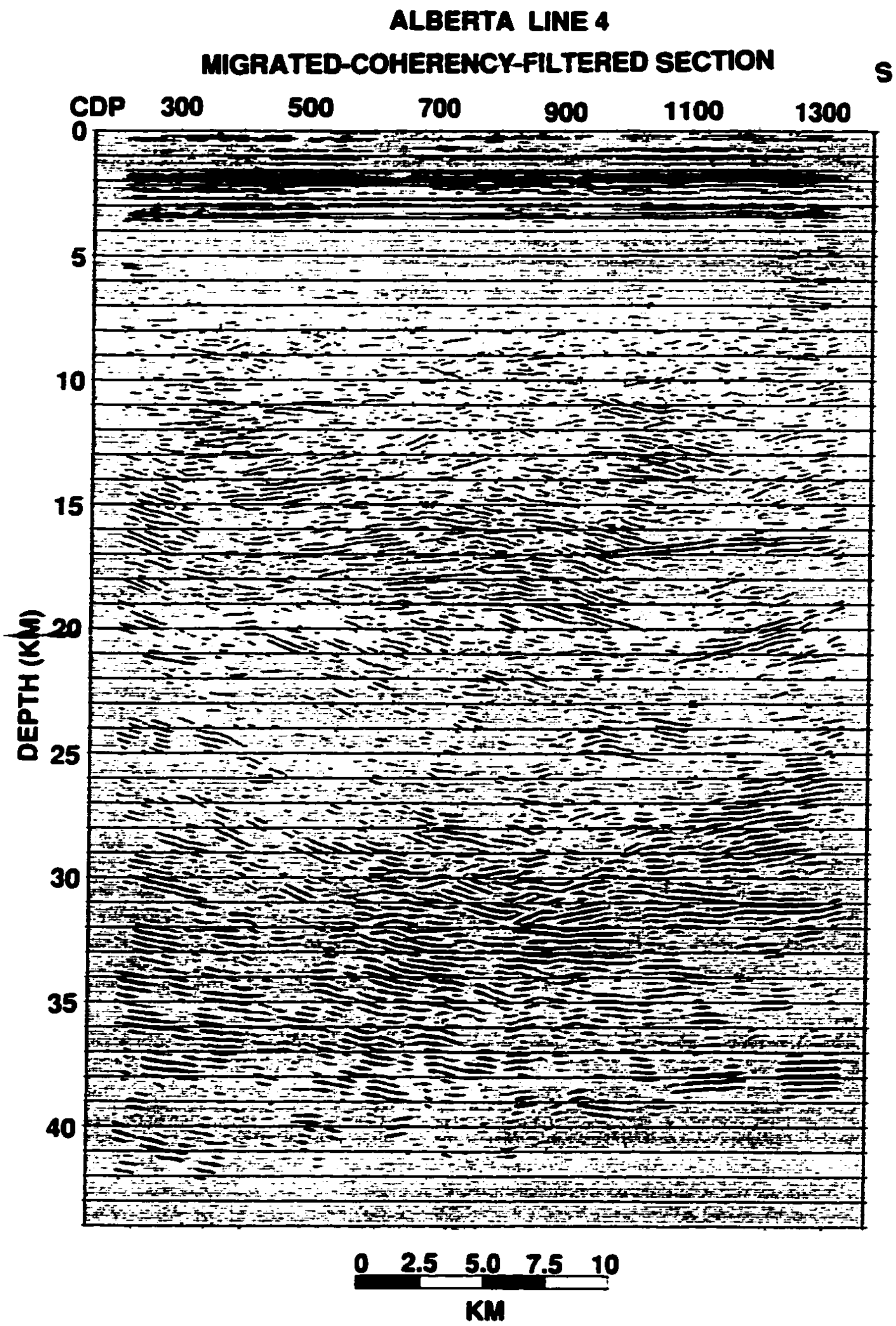

Fig. 3.24 Crustal-scale migrated-coherency-filtered section of Line 4.

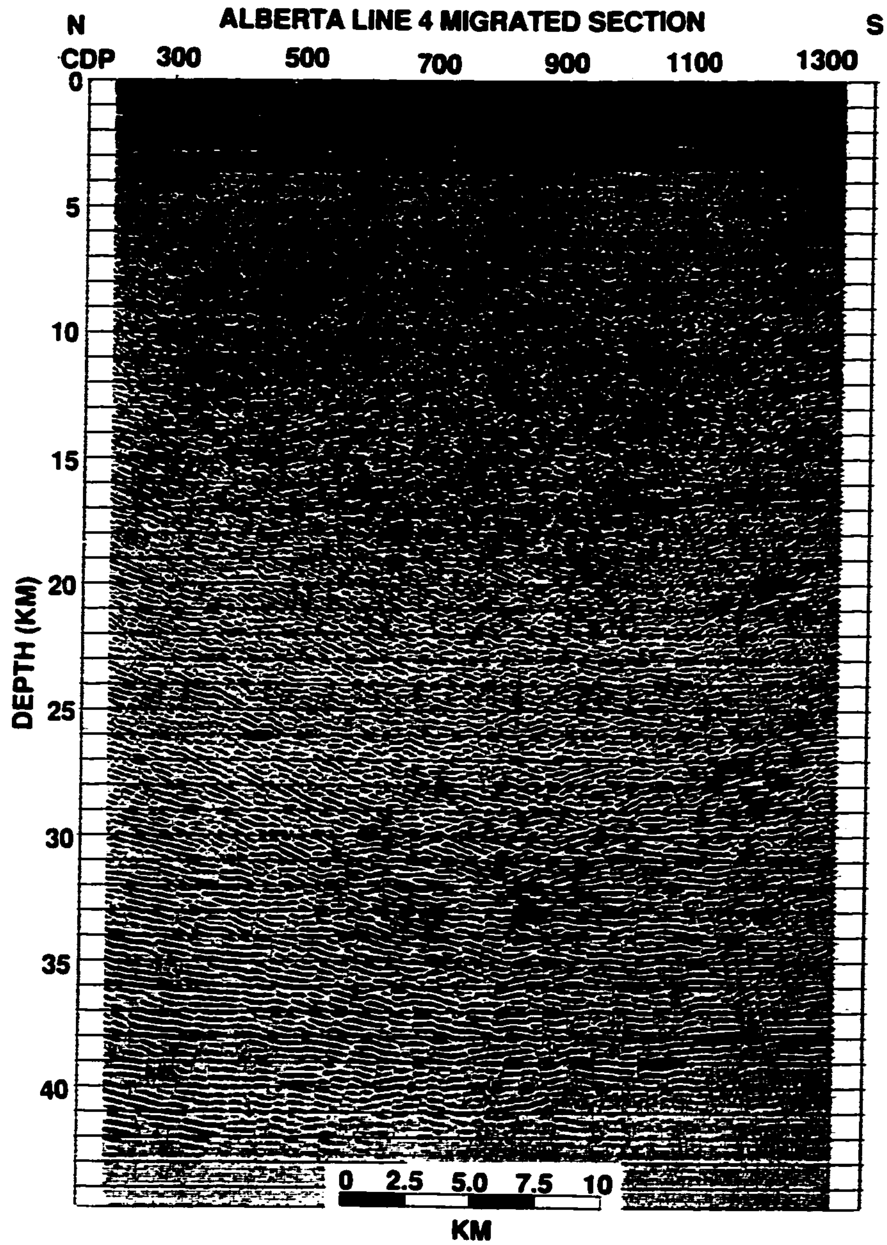

Fig. 3.25 Crustal-scale migrated section of Line 4.

magnetic Low in the north and ending at the Rimbey High to the south, central Alberta seismic Line 3 is 43.5 km long with CDP# from 208 to 1948. The sedimentary reflections in the top 6 km are less continuous, except 2WS and BH L (Fig. 3.26). Some of the discontinuities are due to unconformities from erosion at the end of the Paleozoic Era(depth around 1.6 km). The top of the Precambrian subsurface along Line 3 is more continuous than on line 4.

The dominant dipping events in the migrated-coherency-filtered section (Fig. 3.27) and migrated section (Fig. 3.28) of Line 3 are northern dipping reflections with southeast-directed thrust imbrication which is in a direction opposite to Line 6 and Line 7. The change in dip can be explained if the two cratons (Rae and Hearne) came from different directions and collided near the Thorsby Low along STZ. Since Line 3 is just beyond the suture zone, some southern dipping events exist in the deep part around 30 km. The Moho is recognized at a depth of 40 to 42 km in the above two sections of Line 3.

3.2.9 Interpretation of Line 2 (Line 2A)

The western part of line 2 is over the Wabamun magnetic High, and it extends from west to east into the Thorsby Low. The CDP# is from 205 to 1800 with a length of 39.9 km. An obvious change in depth of the Precambrian can be found across the top 6 km section of Line 2. This change would be slightly larger in the same section without flattening and shifting of the 2WS. From west to east, the top of the Precambrian, surface including BH L has reflectors with small dip angles to the west. The thickness of the sedimentary cover is greatest to the west, where it is near the centre of the Alberta Basin. Because of the relief due to the Mississippian unconformity above BH L, the sedimentary layers between BH L and L MA all have the same shape where there is a discontinuity of

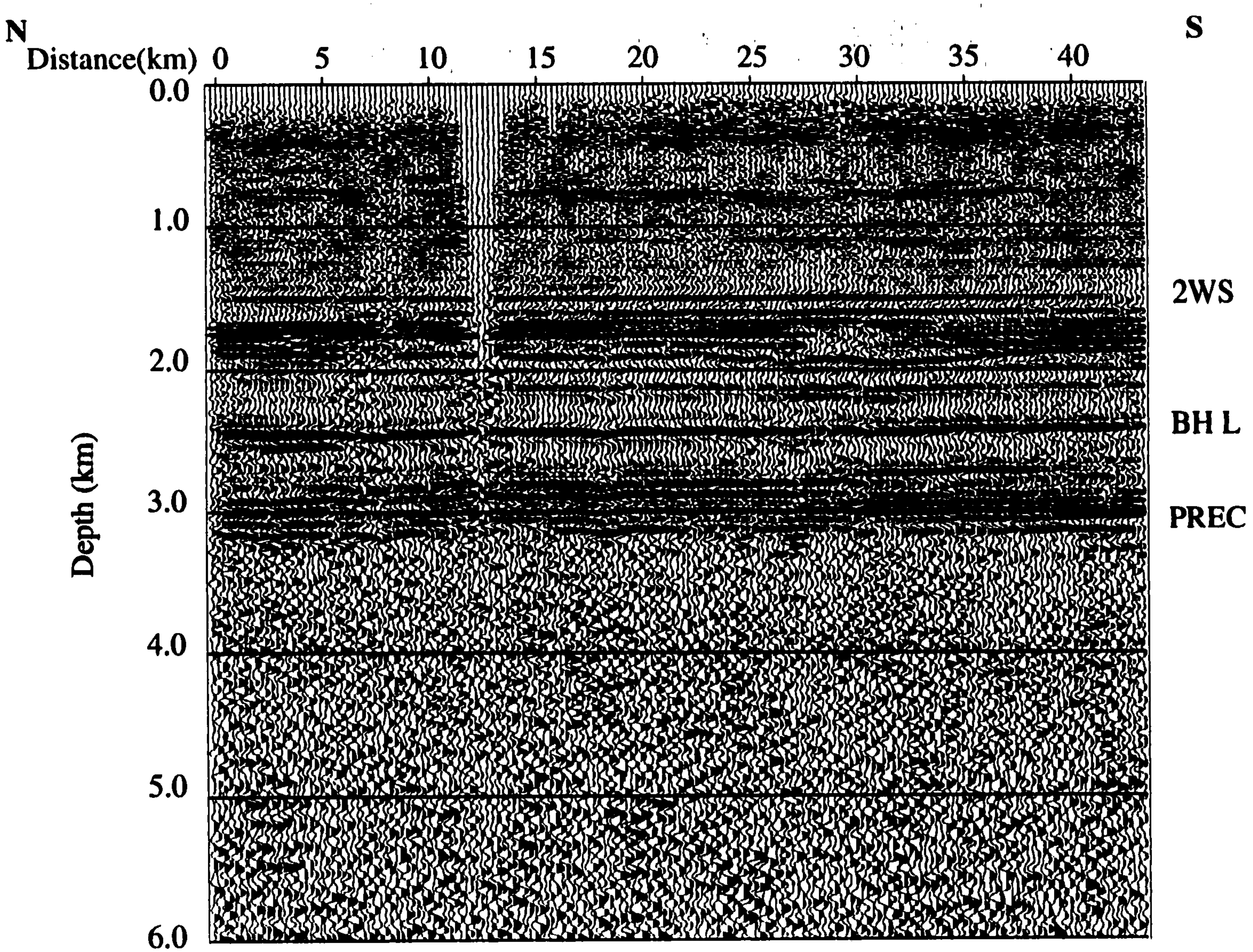

Fig. 3.26 Top 6 km of reprocessed seismic Line 3 with geological layers identified.

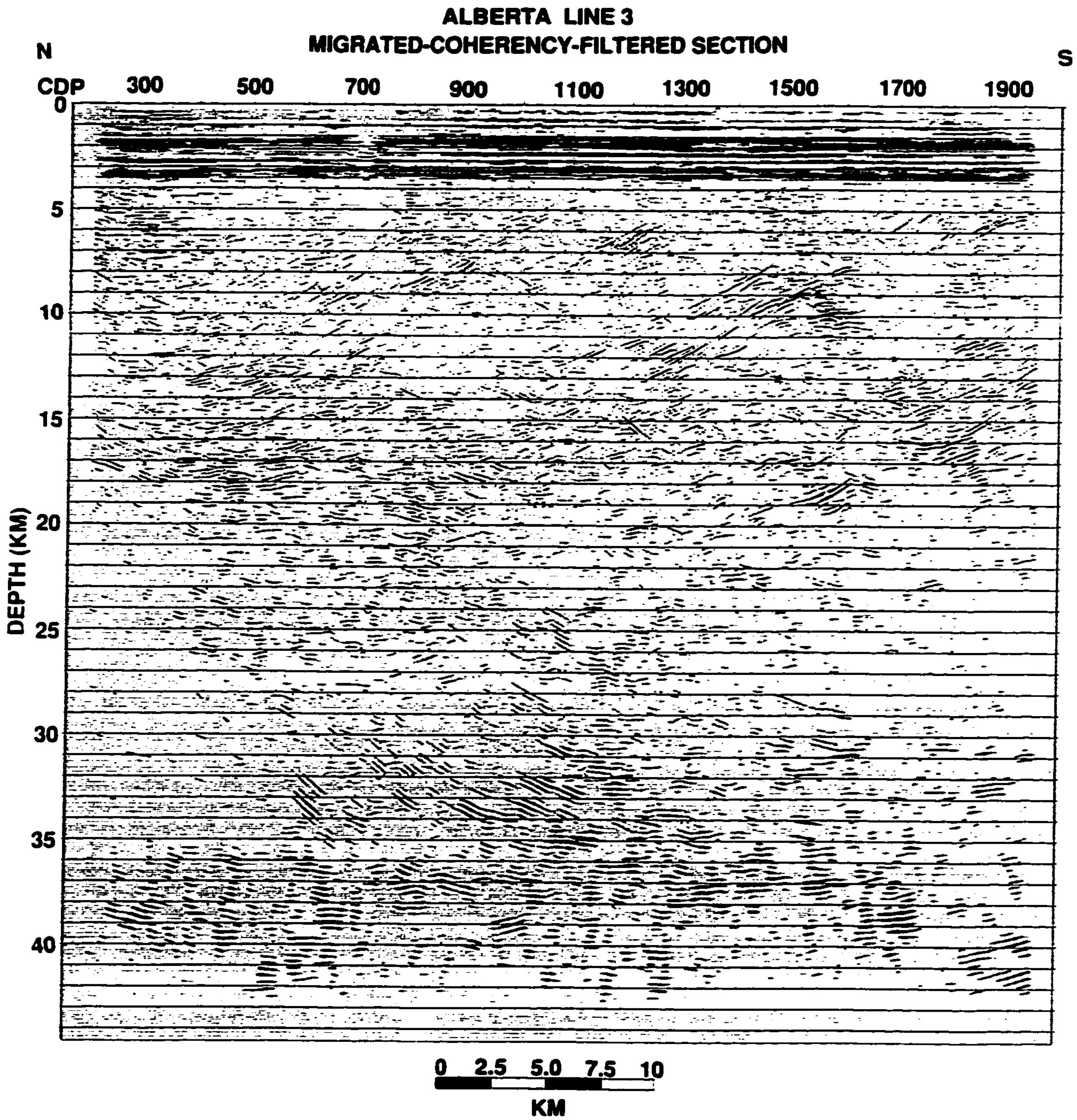

Fig. 3.27 Crustal-scale migrated-coherency-filtered section of Line 3.

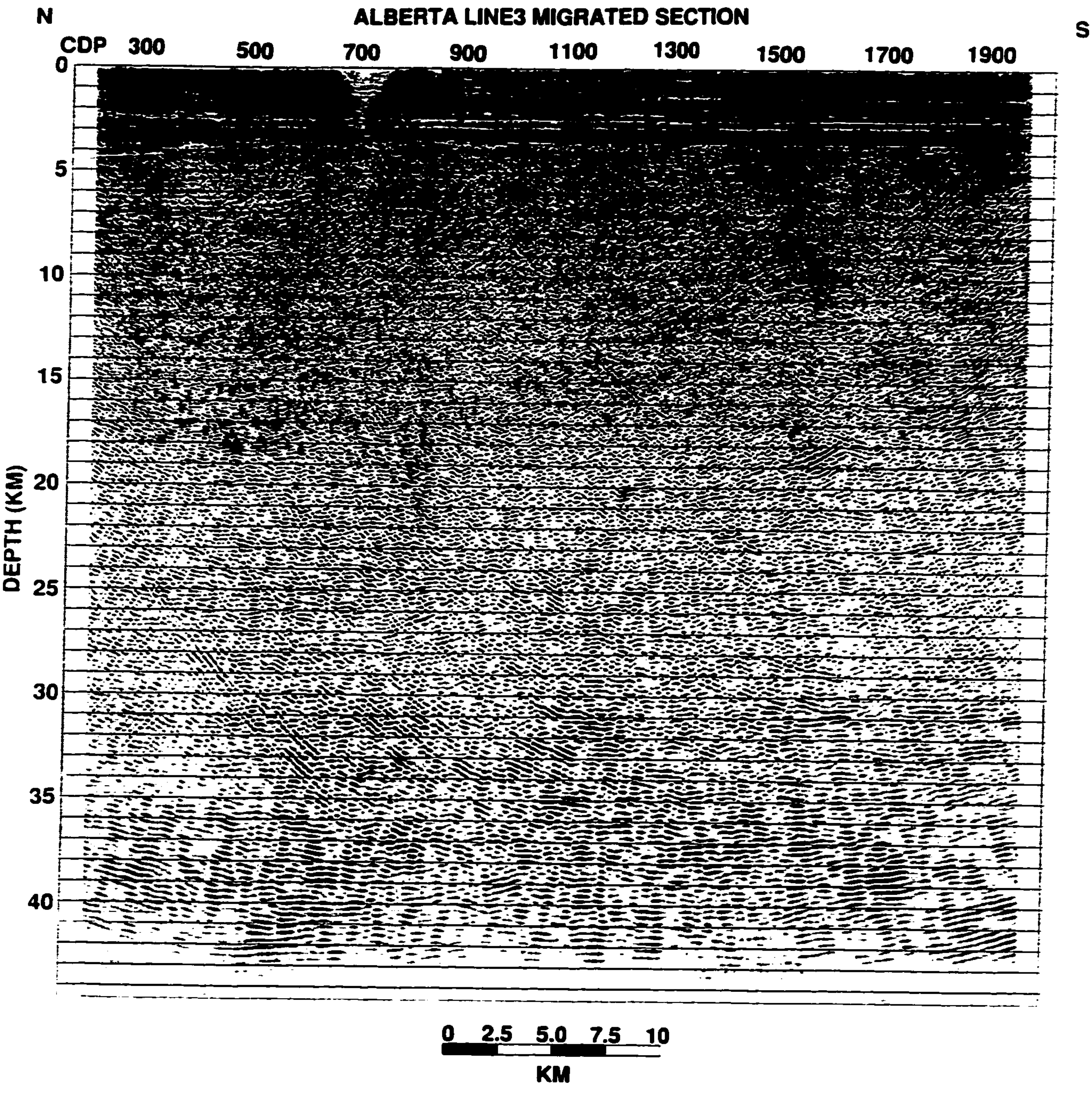

Fig. 3.28 Crustal-scale migrated section of Line 3.

reflectivity. Connecting to the east end of Line 2, Line 2A is only 11.6 km long with CDP# from 1542 to 1996. The top 2.5 km reflectivity were lost because the road was just paved so the vibrators used as sources had to be diverted 3 km to the south. In this case, the only shallow strong reflector along the top 6 km section of Line 2A(Fig. 3.29a) is the Precambrian, which is also dipping to the west. At the east end of Line 2A, the depth of Precambrian is about 3.1 km, while in the west end of Line 2, the depth is around 3.3 km. So there is at least 200 meters change in the depth of Precambrian along Line 2 and Line 2A.

The mid-crustal structure displayed in migrated-coherency-filtered section(Fig. 3.30) and migrated section(Fig. 3.31) of Line 2 is much more complicated than that of Line 2A(Fig. 3.30a). Flat lying strong reflecting events (B) (Fig. 3.42) are seen at a depth of 12 to 16 km and these can be interpreted as high velocity sills. Whenever these events occur at shallower depths one has strong positive aeromagnetic anomalies which are presumably associated with the volcanic activity in the Wabamun. High angle thrust faults and folding are seen clearly with small angle thrust faulting and folding underneath at depths of 10 to 18 km in Fig. 3.30. It is postulated that this part belongs to the forelimb of the deformation created by the post-subduction collision of the Wabamun (southern Rae) domain with the northwest edge of the Hearne craton. The structure at the same depth on Line 2A displays a group of tight thrust faults. The west-dipping and eastern dipping events appear at the same time in the lower crust on Line 2 and Line 2A with the latter dipping at a small angle. The Moho boundary changes its depth from 39 to 42 km along Line 2 and to 43 km along Line 2A.

3.2.10 Interpretation of Line 1

In the eastern part of the Wabamun magnetic High, central Alberta

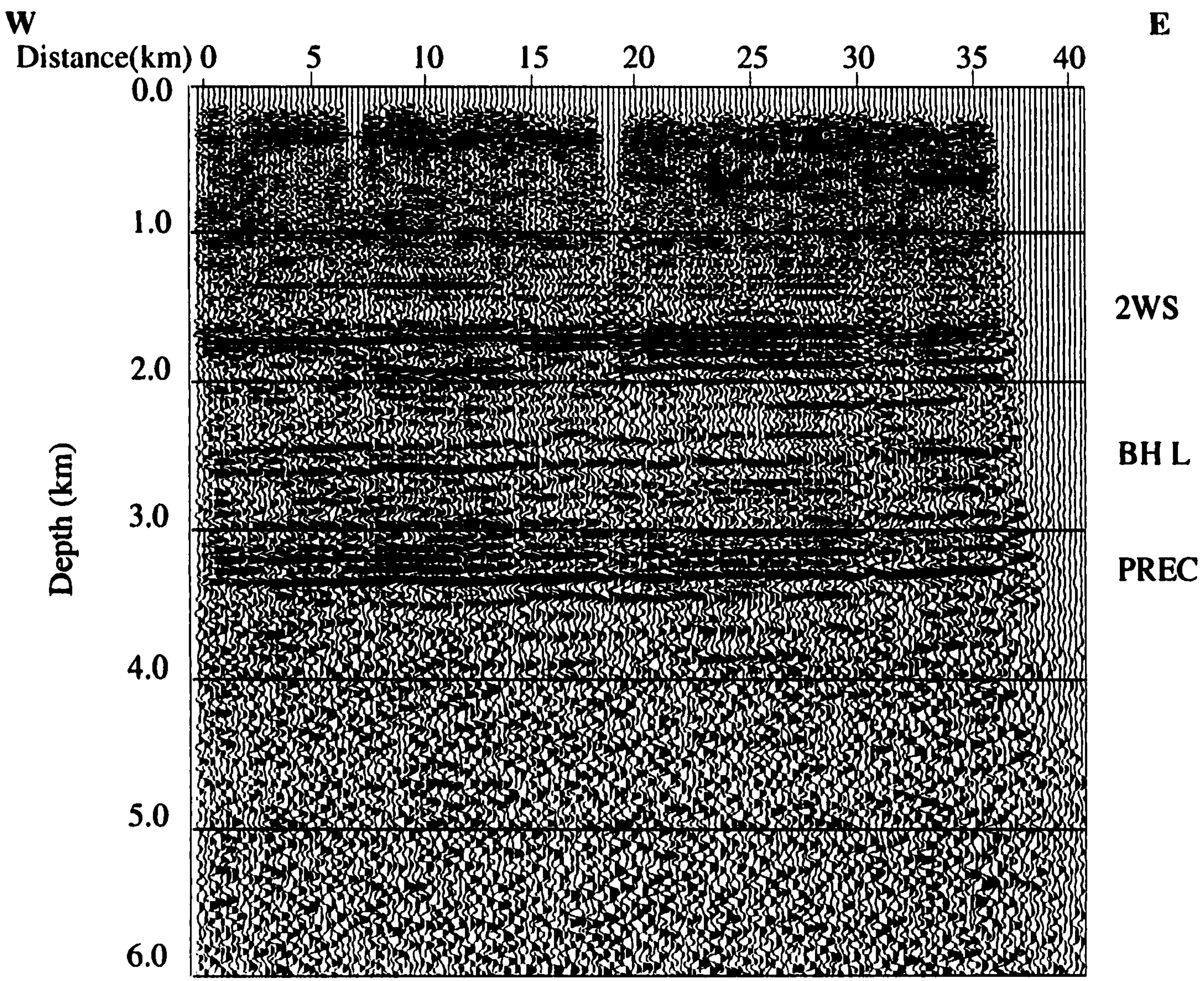

Fig. 3.29 Top 6 km of reprocessed seismic Line 2 with geological layers identified.

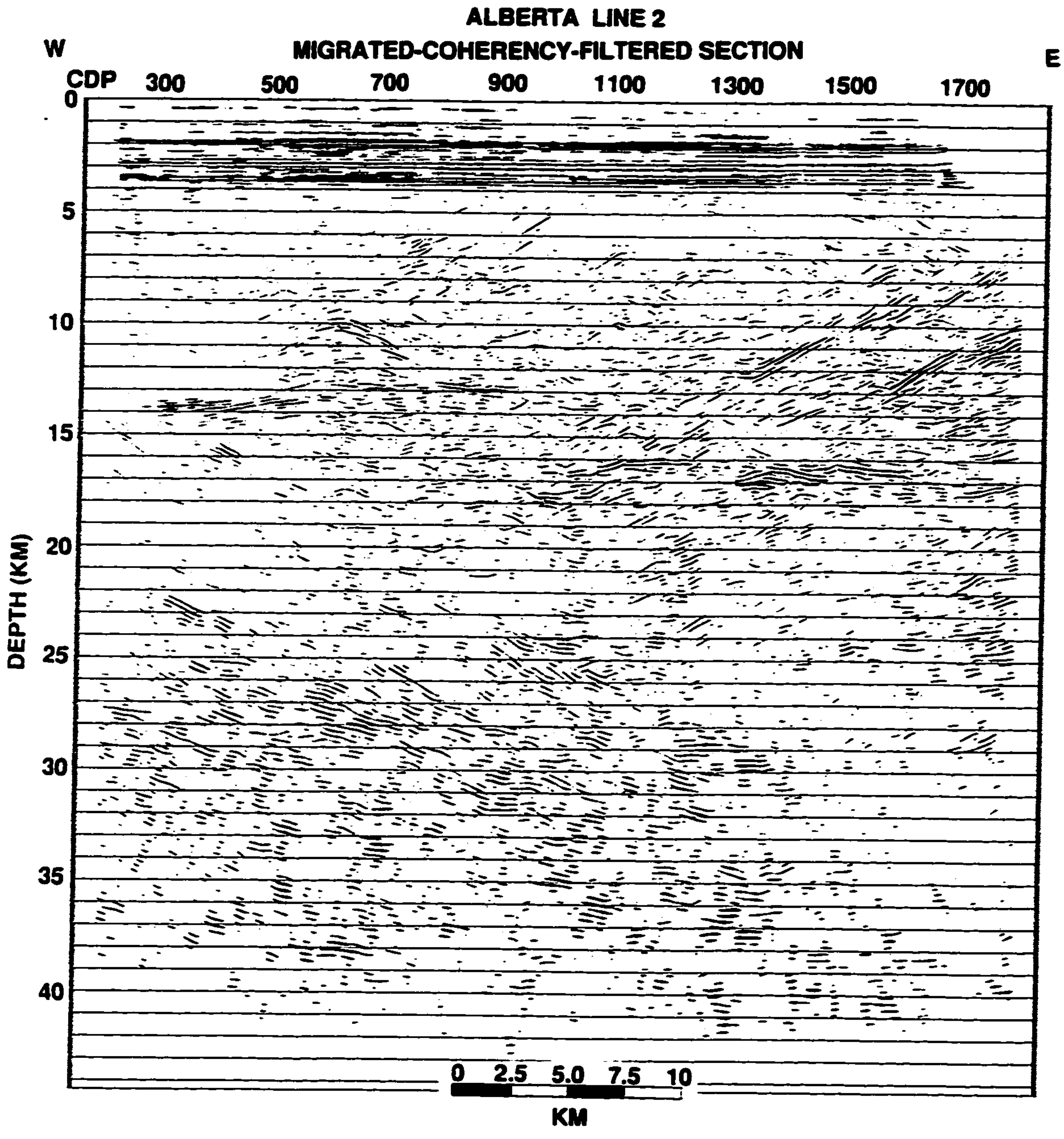

Fig. 3.30 Crustal-scale migrated-coherency-filtered section of Line 2.

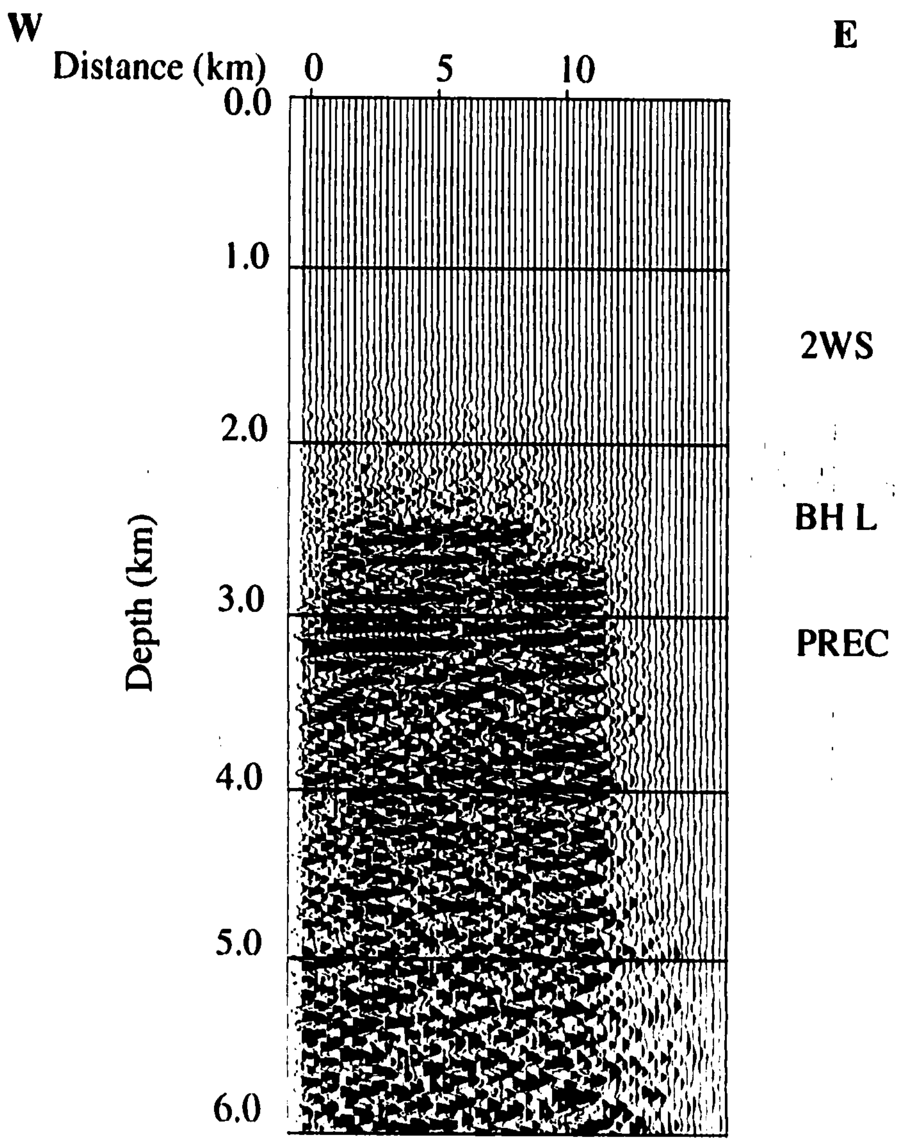

Fig. 3.29a Top 6 km of reprocessed seismic Line 2A with geological layers identified.

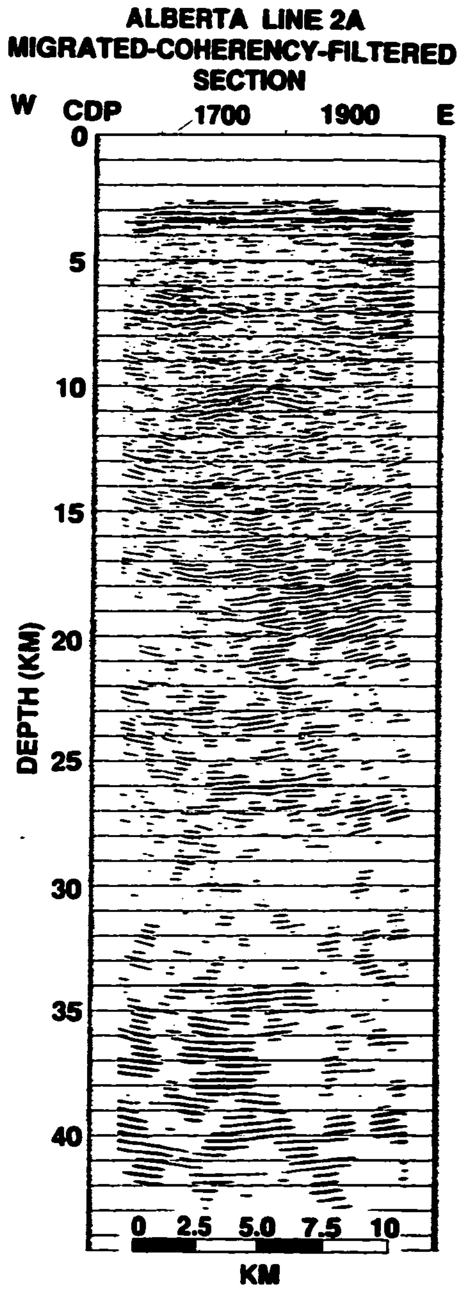

Fig. 3.30a Crustal-scale migrated-coherency-filtered section of Line 2A.

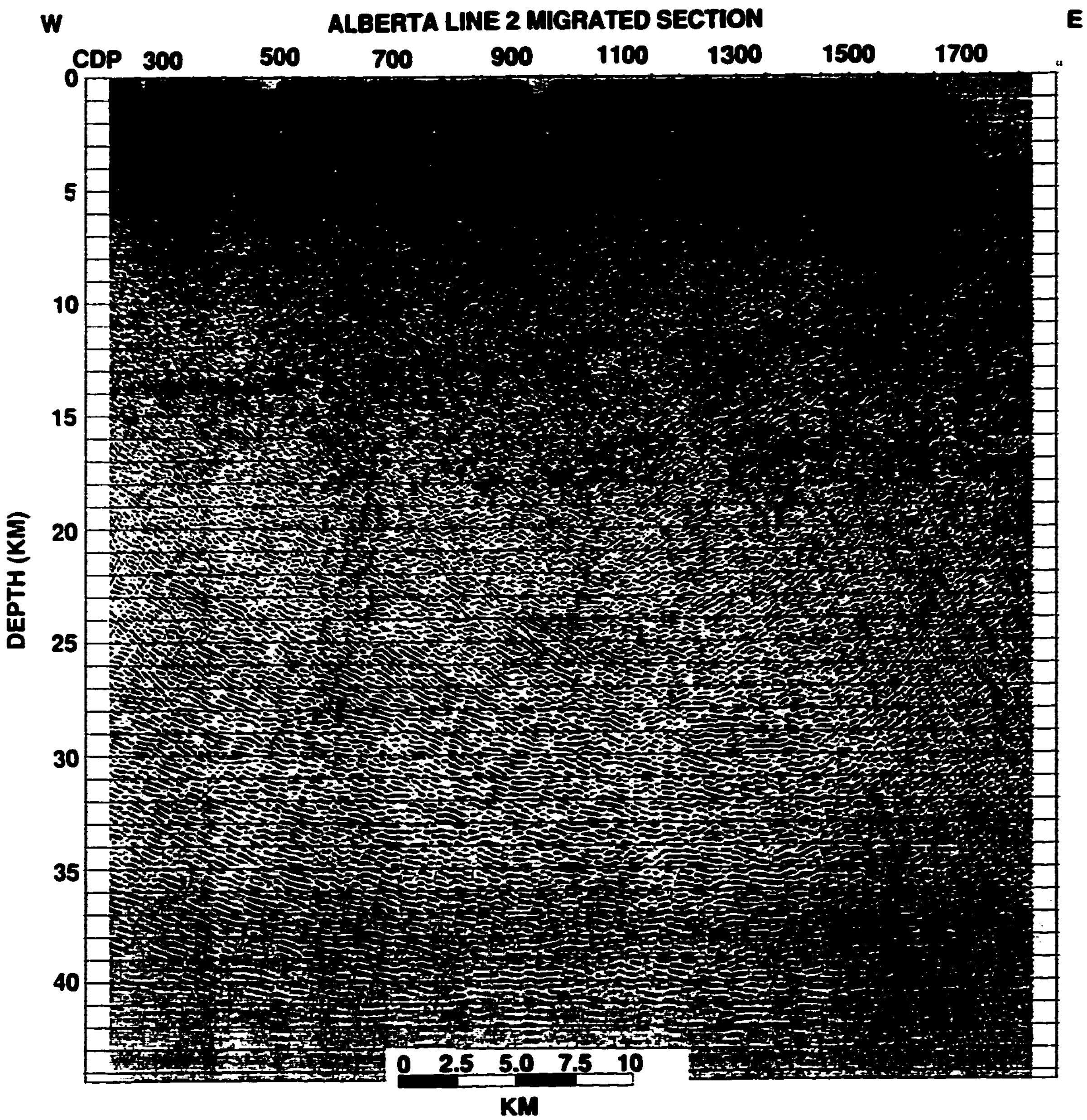

Fig. 3.31 Crustal-scale migrated section of Line 2.

seismic Line 1 traverses from north to south with a total length 35.5 km. The CDP# is from 208 to 1625. As the Wabamun magnetic High is interpreted as a large area magmatic rocks, the Precambrian subsurface mirrors changes the rock character to yield discontinuous reflections. In the top 6 km section of Line 1 (Fig. 3.32) there are two places along the Precambrian basement showing discontinuities. One is at a distance of 5 km from the north, the other is at distance 20 to 25 km from the north. They both influence sedimentary deposition above and create a dome-shaped structures up to the top of MANN.

Evidence of thrust faults in opposite directions can be found in the mid-crust of Line 1 shown on Fig. 3.33 and Fig. 3.34. The sill-like reflecting beds (B) are at a depth of 12 to 15 km. The lower crustal structure is characterized by the northern dipping events with a flat thrust angle near the Moho at a depth of 41 km.

3.3 Extending Seismic Line North to PRAISE Line 18 & Line 19

The Peace River Arch Industry Seismic Experiment(PRAISE 94) was conducted in July 1994. It established another new milestone for LITHOPROBE. The reason for selecting PRAISE line 18 and Line 19 for reprocessing is that the south end of Line 19 is just connected with the north end of Line 1 and these two PRAISE lines traverse the same Precambrian domain (Wabamun magnetic High) as Line 1 does(Fig. 3.10). In this case, by interpreting Line 19 and Line 18, one can obtain a better understanding of the tectonic deformation in this domain.

PRAISE Line 19 starts from the north part of the Wabamun High and its south end is right at the north of CAT Line 1. The line is 70.9 km long and has 2836 CDP's. In the top 6 km of the section of Line 19, shown as Fig. 3.35, three strong continuous reflectors can be observed. According

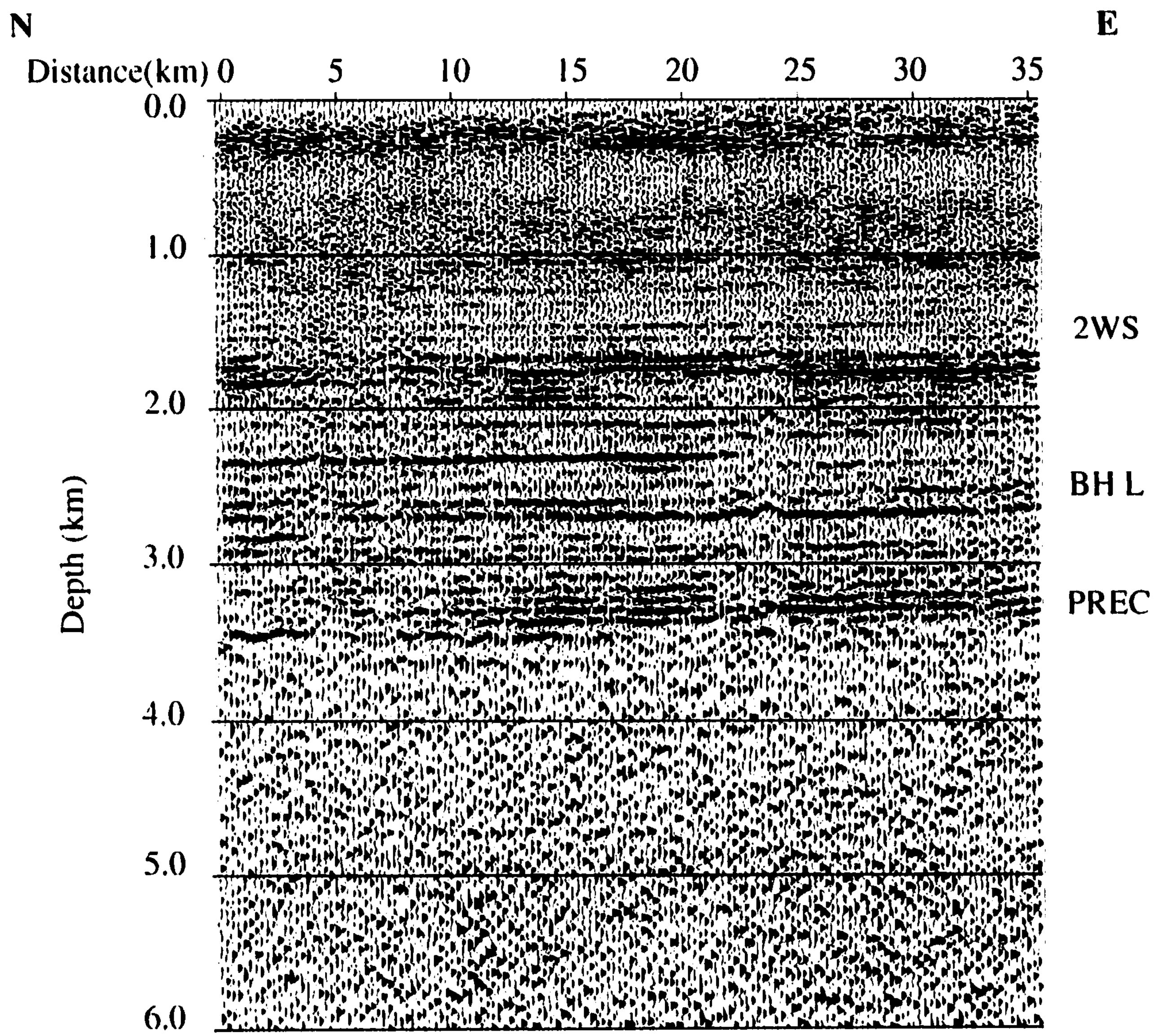

Fig. 3.32 Top 6 km of reprocessed seismic Line 1 with geological layers identified.

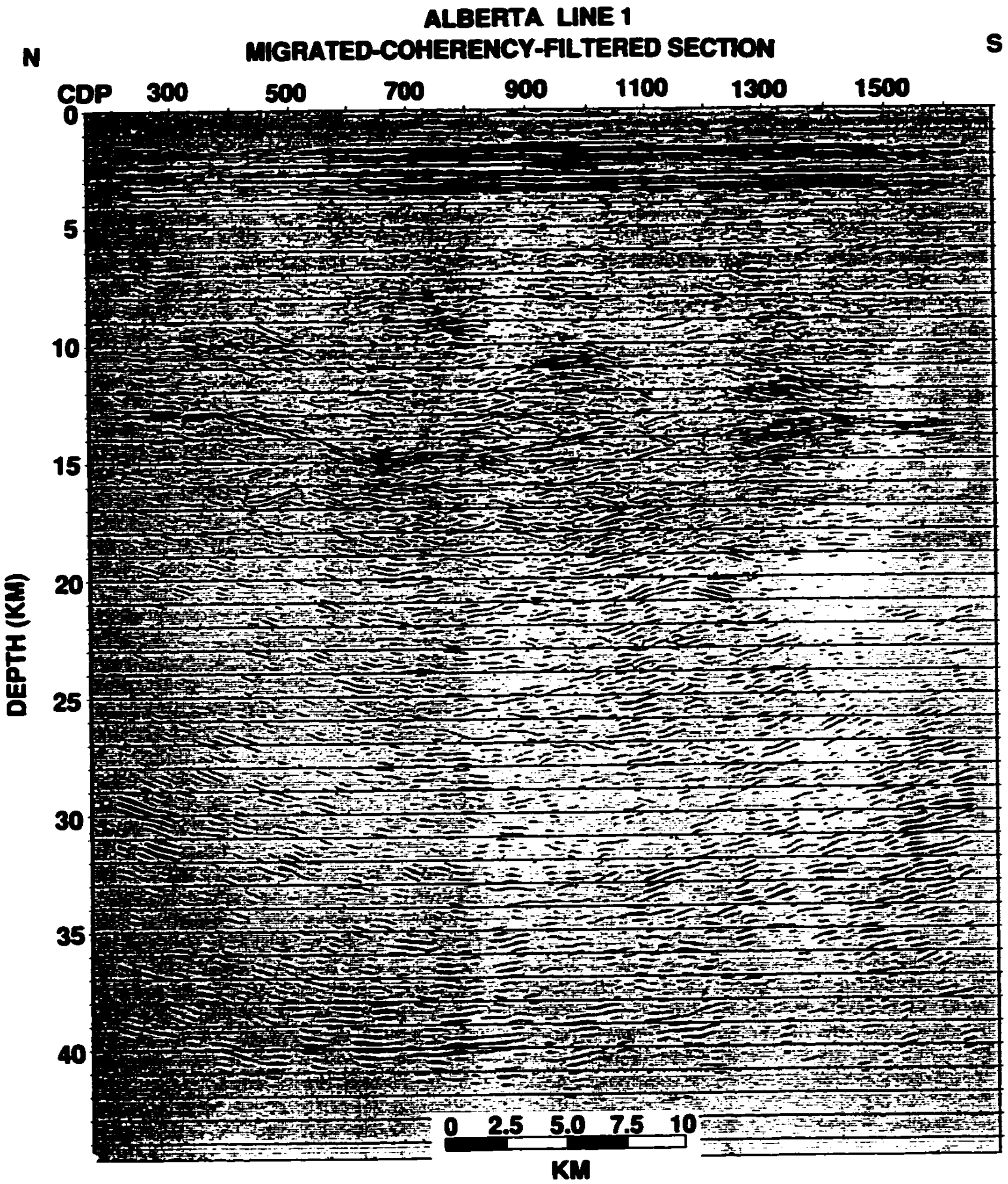

Fig. 3.33 Crustal-scale migrated-coherency-filtered section of Line 1.

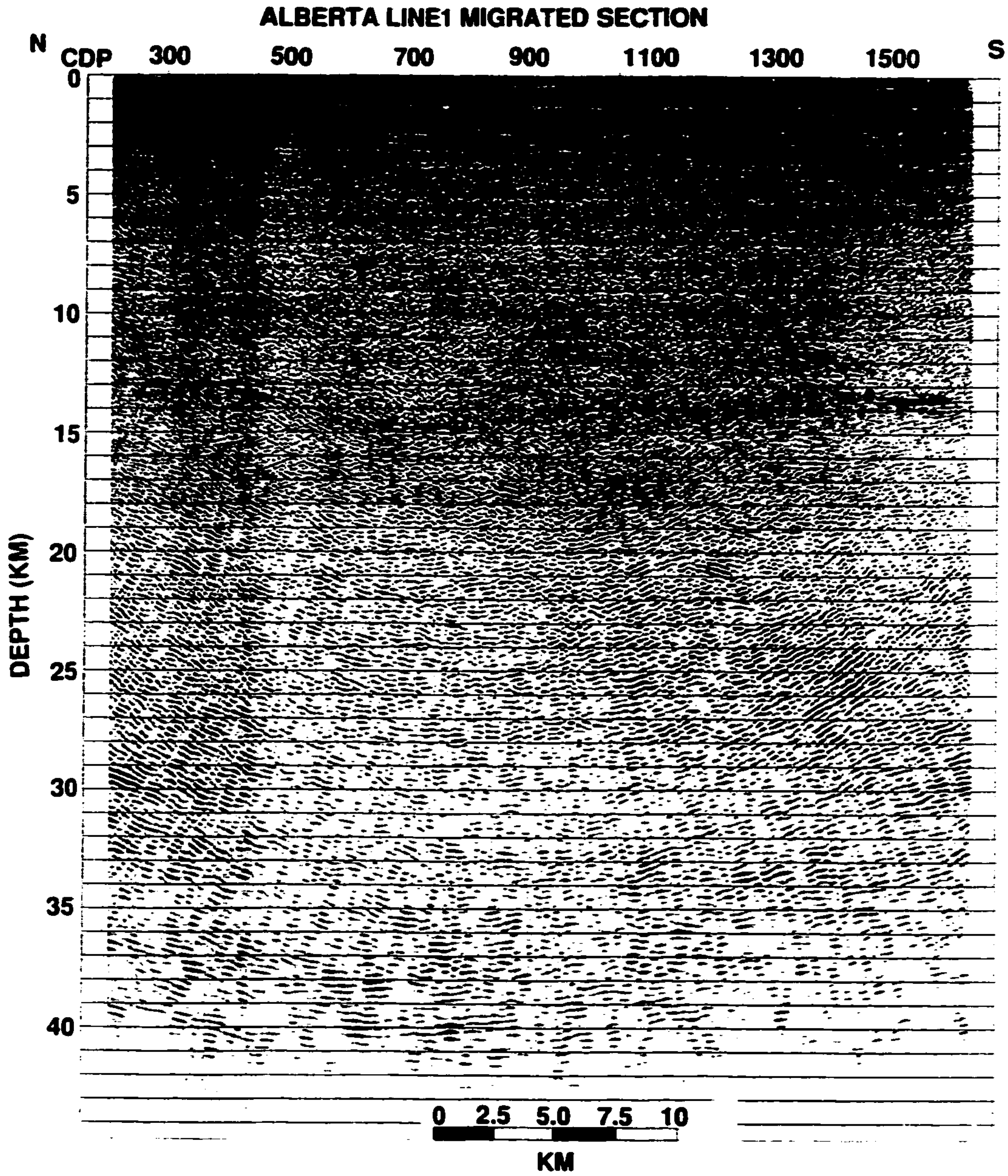

Fig. 3.34 Crustal-scale migrated section of Line 1.

to the well log data in Fig. 3.9, they are BNFF, BH L and Precambrian (PREC) from the sedimentary cover to basement respectively. A surface uplift on the Precambrian basement did affect the sedimentary layer at the distance 20 km, but the influence diminishes below Deadwood (DEWD). The strong reflections between 40 and 47 km may be due to multiples generated by the Precambrian surface.

The strong main dipping events (B) (labeled in Fig. 3.42) in the migrated-coherency-filtered section(Fig. 3.36) and migrated section(Fig. 3.37) of Line 19 show southerly dip with the dipping angle flattening out in the mid-crust around 10 to 15 km. This strong reflector crossing the whole section is actually the continuation from CAT Line 1. These reflections may be evidence of sills within the basement rocks. Simple south dipping reflectors gradually disappear at a depth of 42 km, which is probably the reflection Moho.

PRAISE Line 18 extends from west to east to the north of Line 19. The total length is 46.5 km. The top 6 km of the structure of Line 18 is shown as Fig. 3.38. It is noted that BH L is one of the strong continuous reflector along the section while the Precambrian is less continuous at the east end. The reflectors below Precambrian are suspected to be multiples.

Shown as Fig. 3.39 and Fig. 3.40, the deep structure of Line 18 is characterized by complicated mid-crustal deformation. With dip both in west and east directions, a compressional stress field controlled the mid-crustal tectonic deformation. That strong group of reflectors (B, Fig. 3.42) at a depth of 10 km can still be found along the section with discontinuity. Lines to the north of Line 18 show that these reflections "outcrop" at the Precambrian erosional surface. The Moho subsurface can be recognized on Fig. 3.40 at a depth of 40 km with the loss of all reflectivity at greater depth.

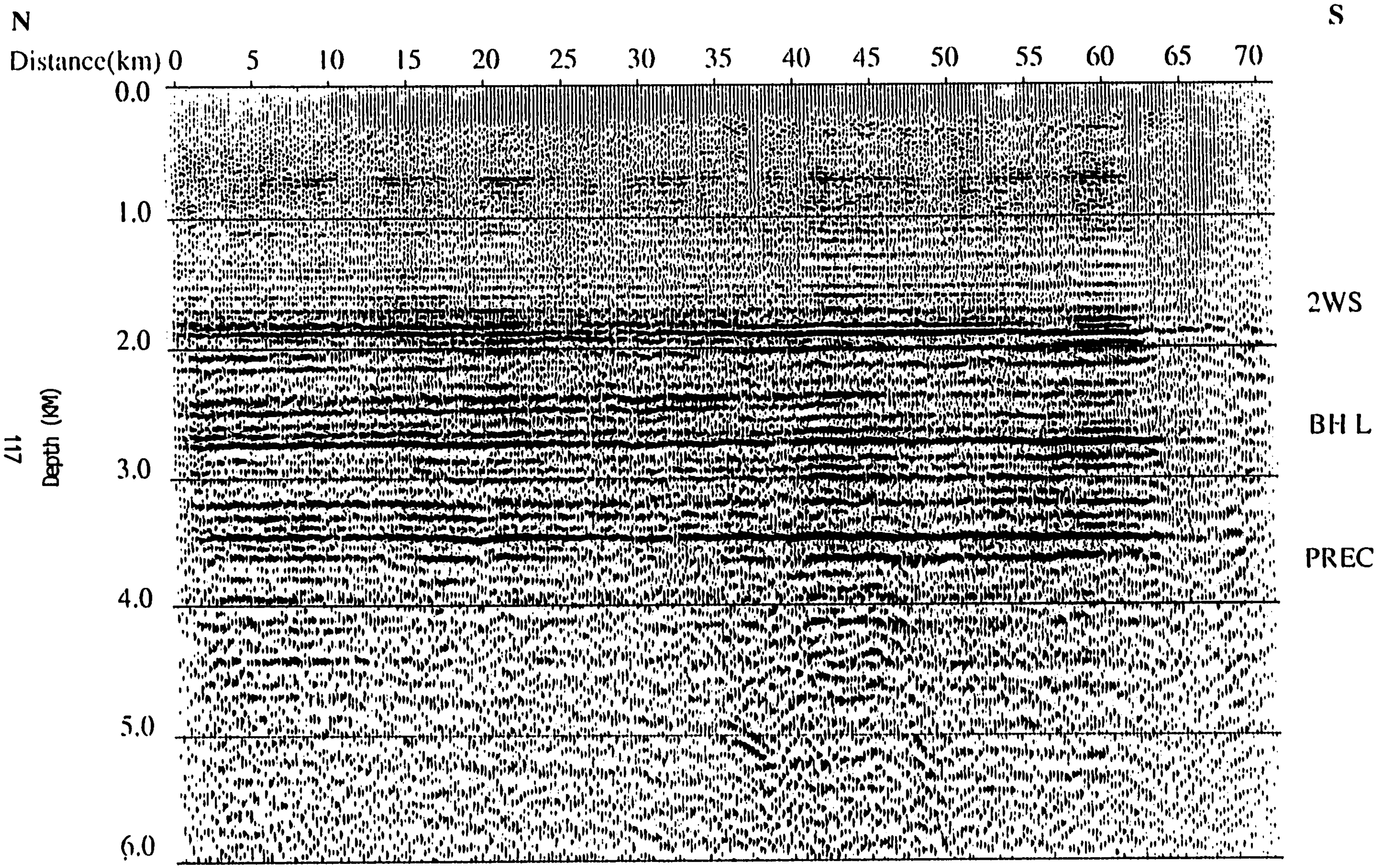

Fig. 3.35 Top 6 km of reprocessed seismic Line 19 with geological layers identified.

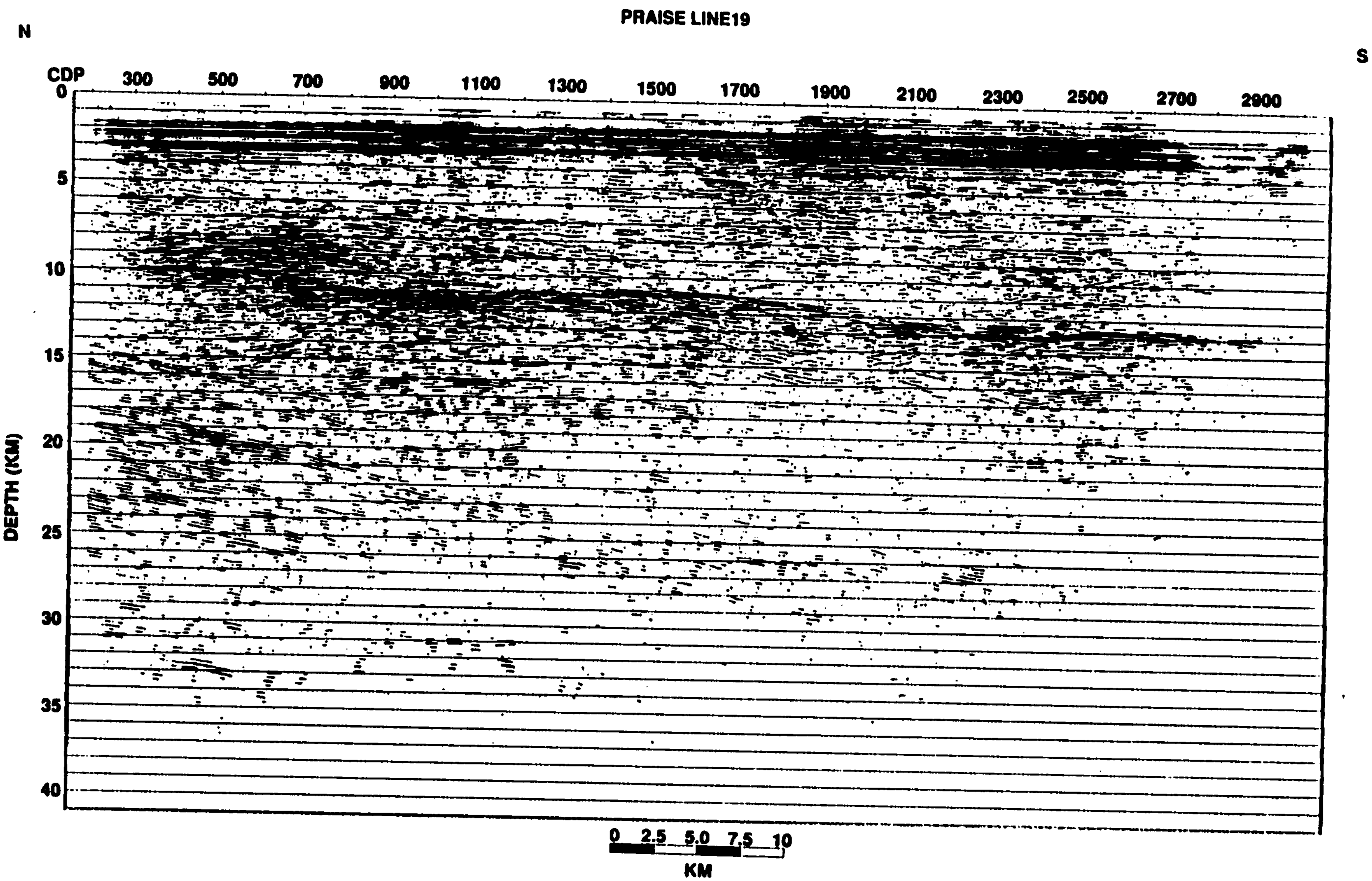

Fig. 3.36 Crustal-scale migrated-coherency-filtered section of Line 19.

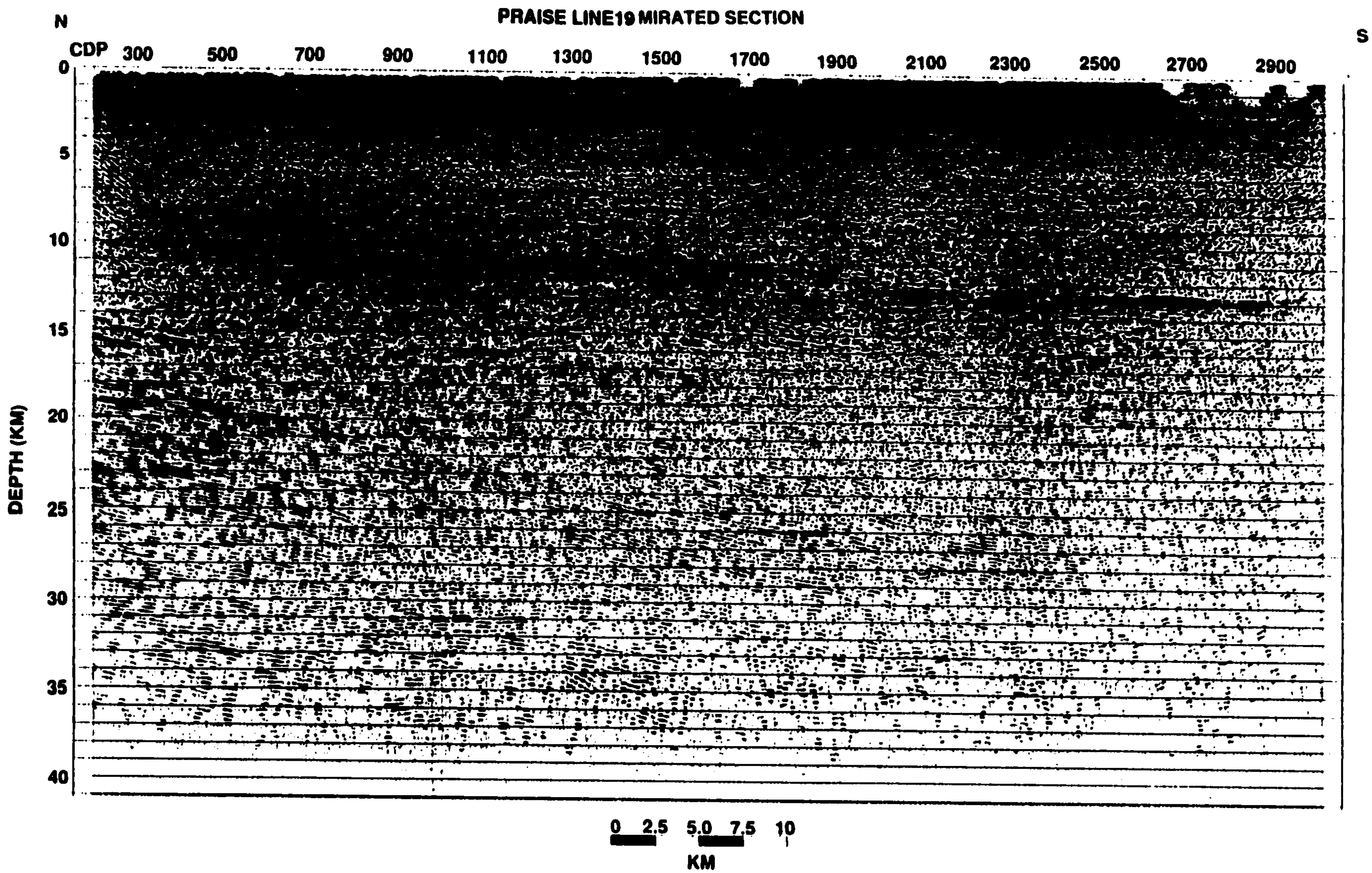

Fig. 3.37 Crustal-scale migrated section of Line 19.

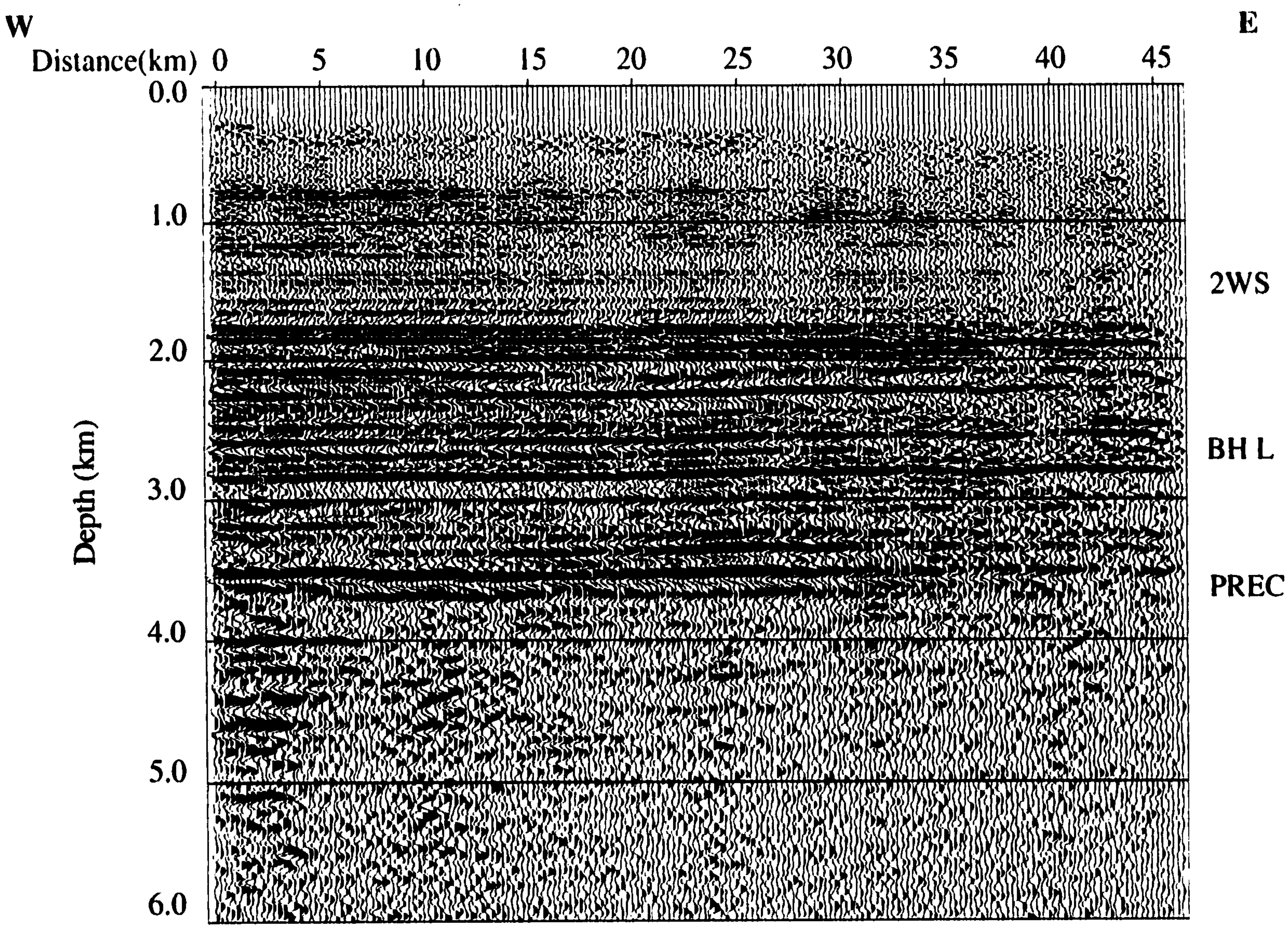

Fig. 3.38 Top 6 km of reprocessed seismic Line 18 with geological layers identified.

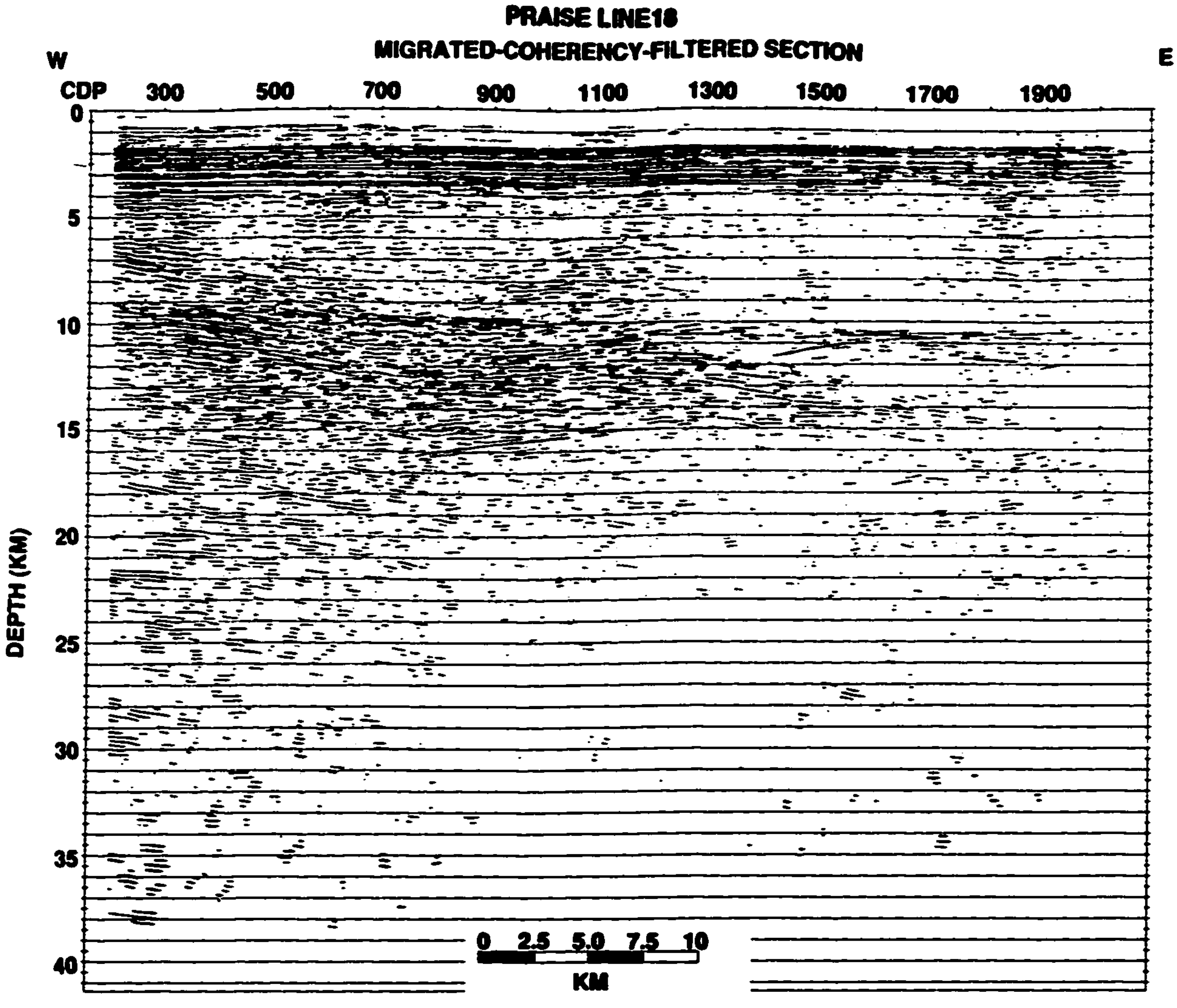

Fig. 3.39 Crustal-scale migrated-coherency-filtered section of Line 18.

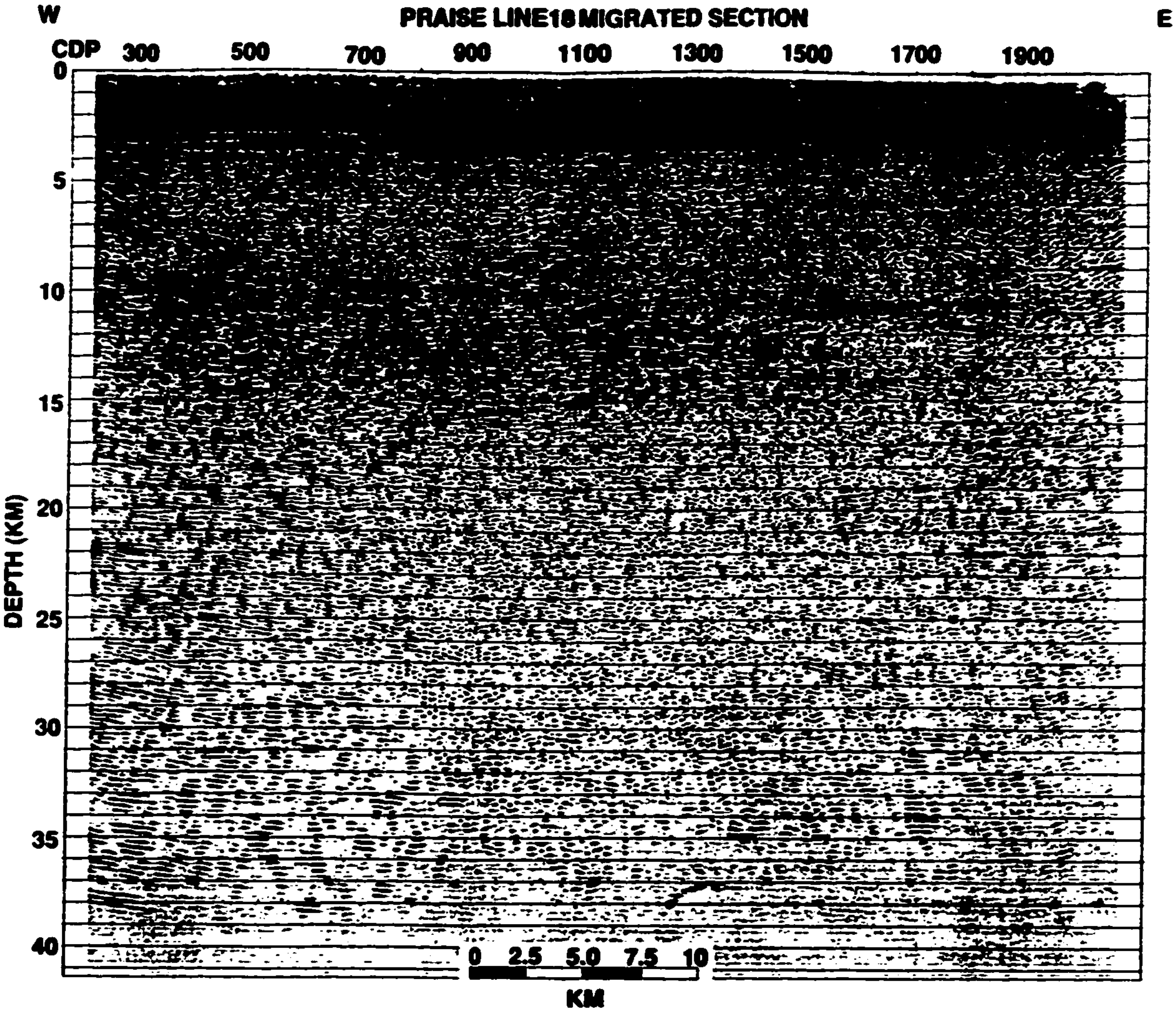

Fig. 3.40 Crustal-scale migrated section of Line 18.

3.4 Discussion

In order to understand the tectonic evolution of the basement and crust in central Alberta, reprocessing and interpretation of LITHOPROBE seismic reflection data across central Alberta in this study has been carried out by correlating the reflection character of seismic data with well log data and potential field fabric. Linking all the reprocessed seismic lines together, Fig. 3.41 and Fig. 3.42 image the entire structure along CAT and PRAISE lines. The former is the migrated section for the top 6 km. The structural formation of the sedimentary layers and the deformation of the basement and the interaction between the Precambrian basement and the Phanerozoic sedimentary cover can be recognized. The latter is the crustal-scale migrated-coherency-filtered section, which may be interpreted to yield the tectonic history of the crustal structure and the reflection features down to the mantle below the Moho.

Since there are many relatively flat reflectors along the profile in Fig. 3.41, it can be postulated that the sedimentary layers were deposited in a comparatively stable environment despite several periods of erosion. There are many facies changes which show some correlation with different tectonic domains. The amplitude and reflection features of the sedimentary beds is very variable along the different seismic lines of the profile. However, the BH L (Beaverhill Lake) is relatively strong and continuous compared with the other formation tops. Their amplitude and reflection features still change greatly when they cross different Precambrian domains.

Since the relative basement relief is gentle in the Western Canadian Sedimentary Basin(WCSB), some interesting basement features may not be detected along the seismic lines when shown graphically at this small scale.

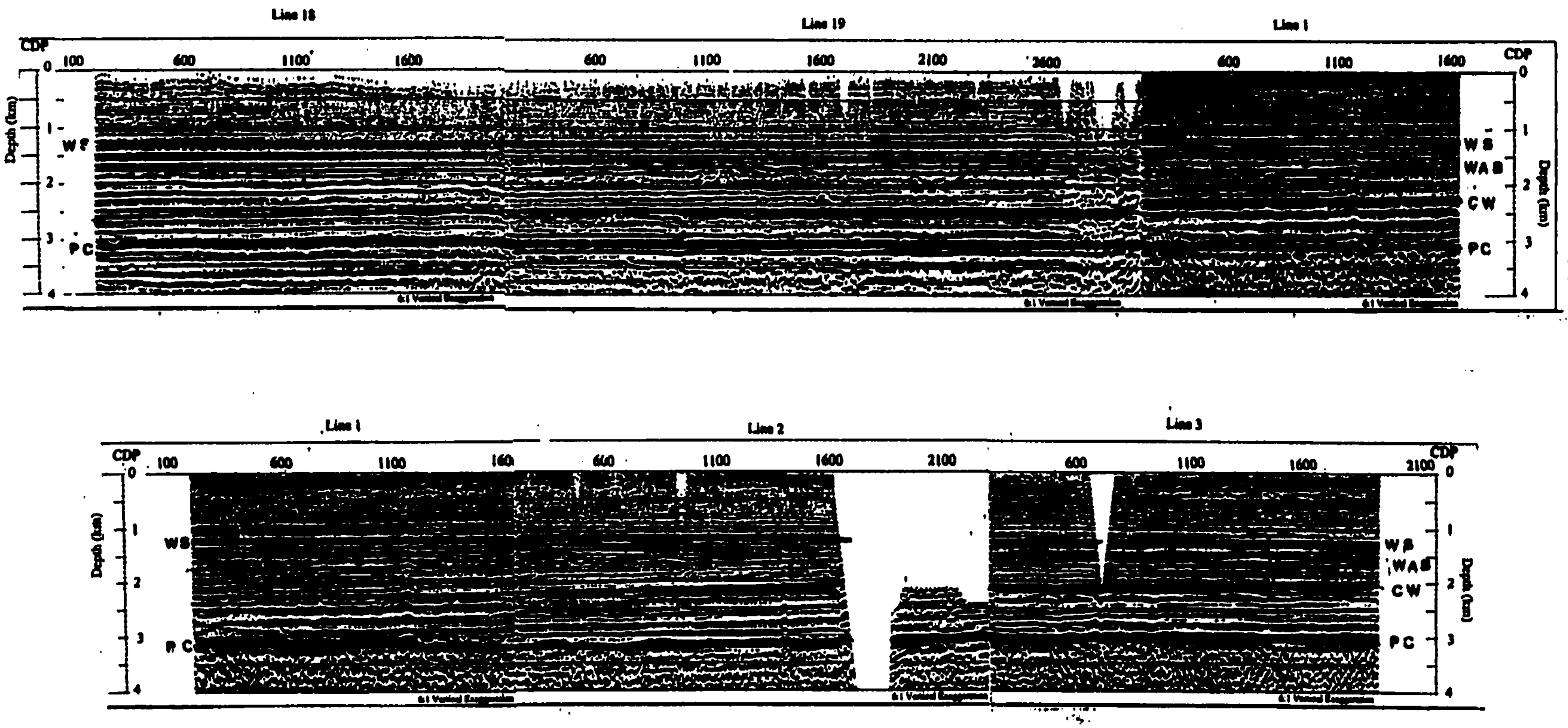

Fig. 3.41 Top 4 km migrated section along CAT and PRAISE seismic lines.

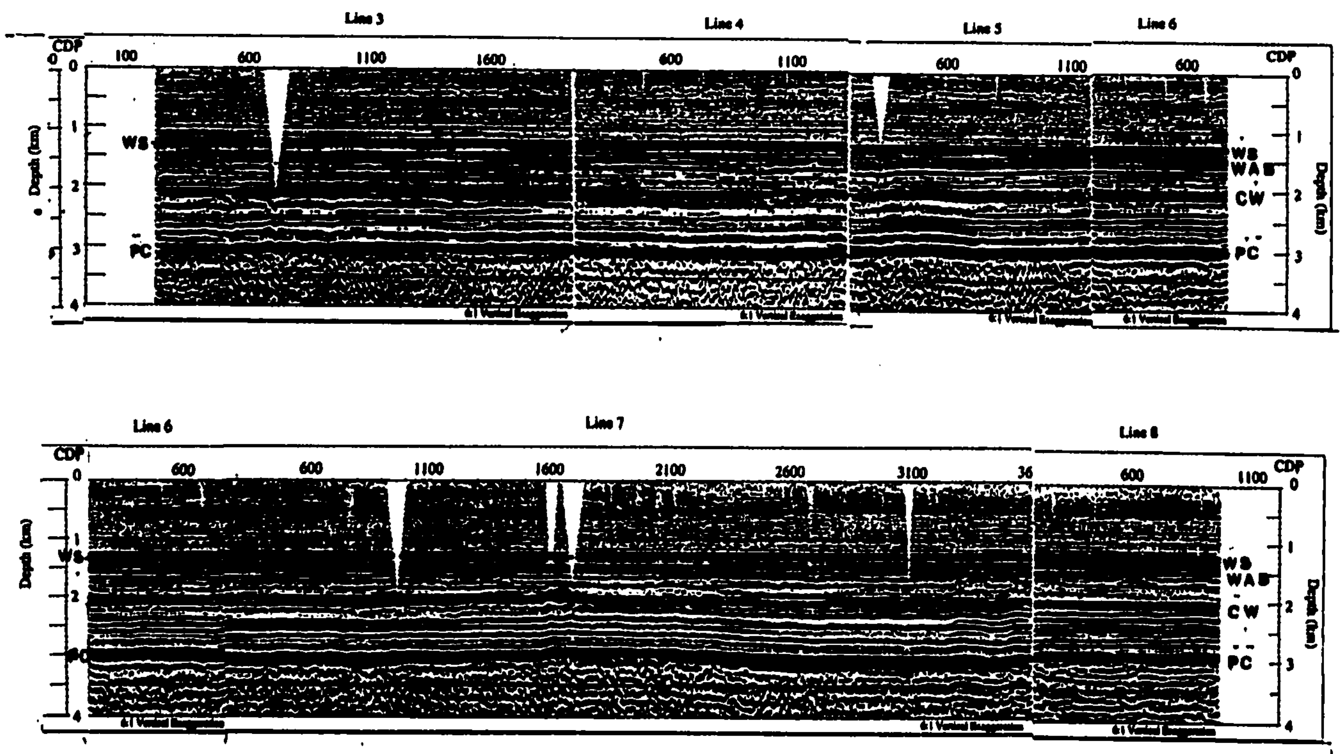

Fig. 3.41 Top 4 km migrated section along CAT and PRAISE seismic lines.

From Fig. 3.41 and recalling the top 6 km of the seismic sections interpreted above, it is seen that the reflection from the Precambrian basement is variable in amplitude and character across the whole transect. In the east part of the profile where the Precambrian rocks belong to the Lacombe Domain, there is a region of low-grade supractustal rocks with a strong northeast-trending linear magnetic high (Villeneuve et al., 1993).

The Precambrian reflection along Line 7 is continuous and strong. In the region of the Rimbey High, a subduction-related magmatic arc with northeast trending aeromagnetic high, the Precambrian reflection of Line 4 and Line 5 is less continuous and weaker than that of Line 7. This is similar to Line 3, which traverses the Thorsby Low, the ductile southern extension of STZ with curvilinear aeromagnetic low (Ross et al., 1991).

While seismic lines 1-2 and 18-19 are in the Wabamun High, an area which is a structurally-bound wedge of largely undeformed magmatic rocks with high aeromagnetic and Bouguer gravity values (Villeneuve et al., 1993), the reflections from the Precambrian have relatively high amplitudes and continuous features. Because this part of WCSB is an undulating southwest-dipping monocline, the depth of the Precambrian becomes gradually greater to the west of the profile in Fig. 3.41. PRAISE Line 18 has the deepest Precambrian basement along the profile.

Eaton et al.(1995) recognized three styles of basement influence with distinct seismic expressions, such as 1) passive topographic effects, indicated by onlap, drape and infill of basin sediments over relief on the basal unconformity, 2) faulting of the basement and overlying Cambrian strata, 3) abrupt lateral facies changes of uncertain origin, vertically overlying a deep-seated tectonic boundary. They also gave several models to provide a plausible mechanism for these basement influences. Actually, the Precambrian basement and the tectonic domain underneath affected the

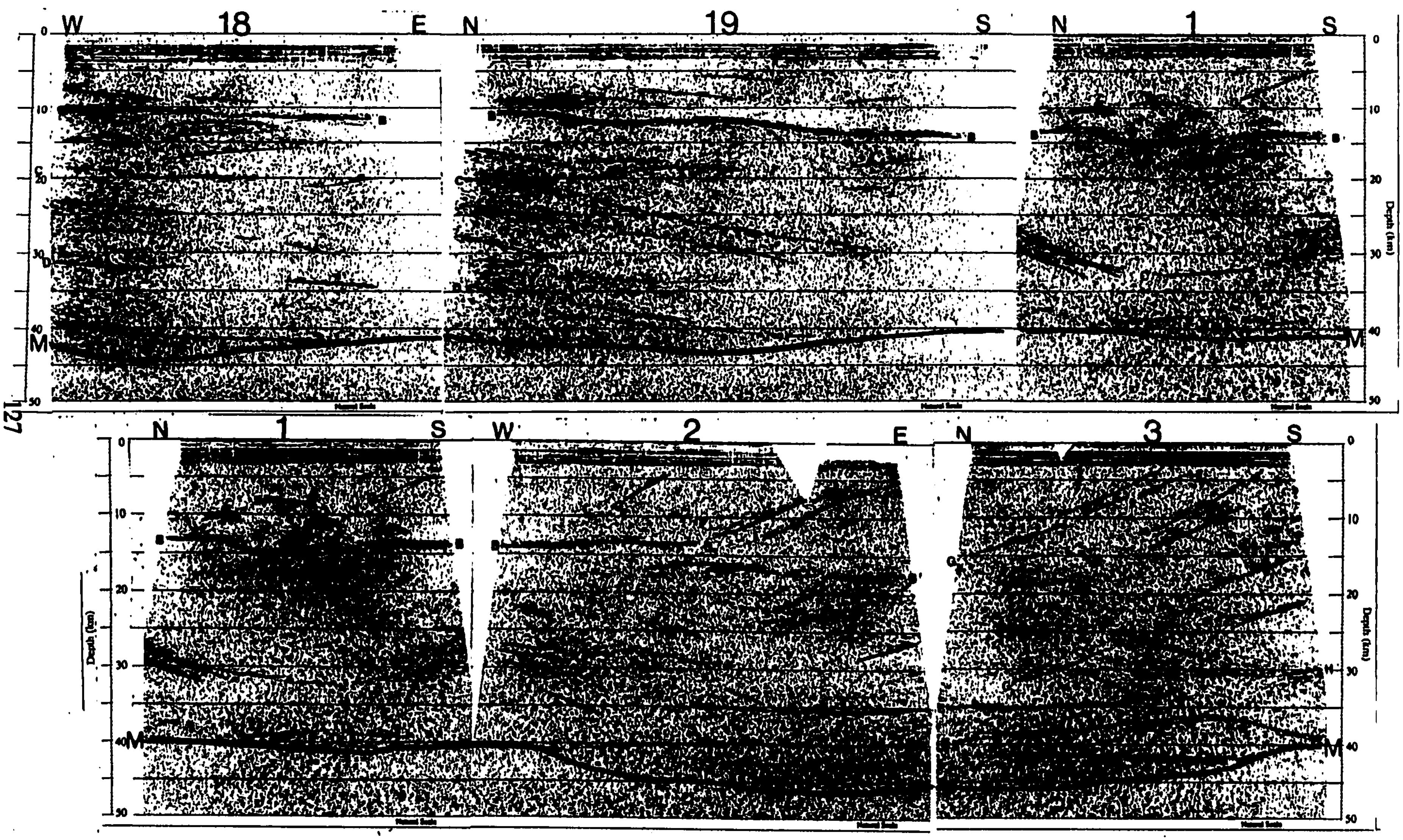

Fig. 3.42 Crustal-scale migrated-coherency-filtered section along CAT and PRAISE seismic lines.

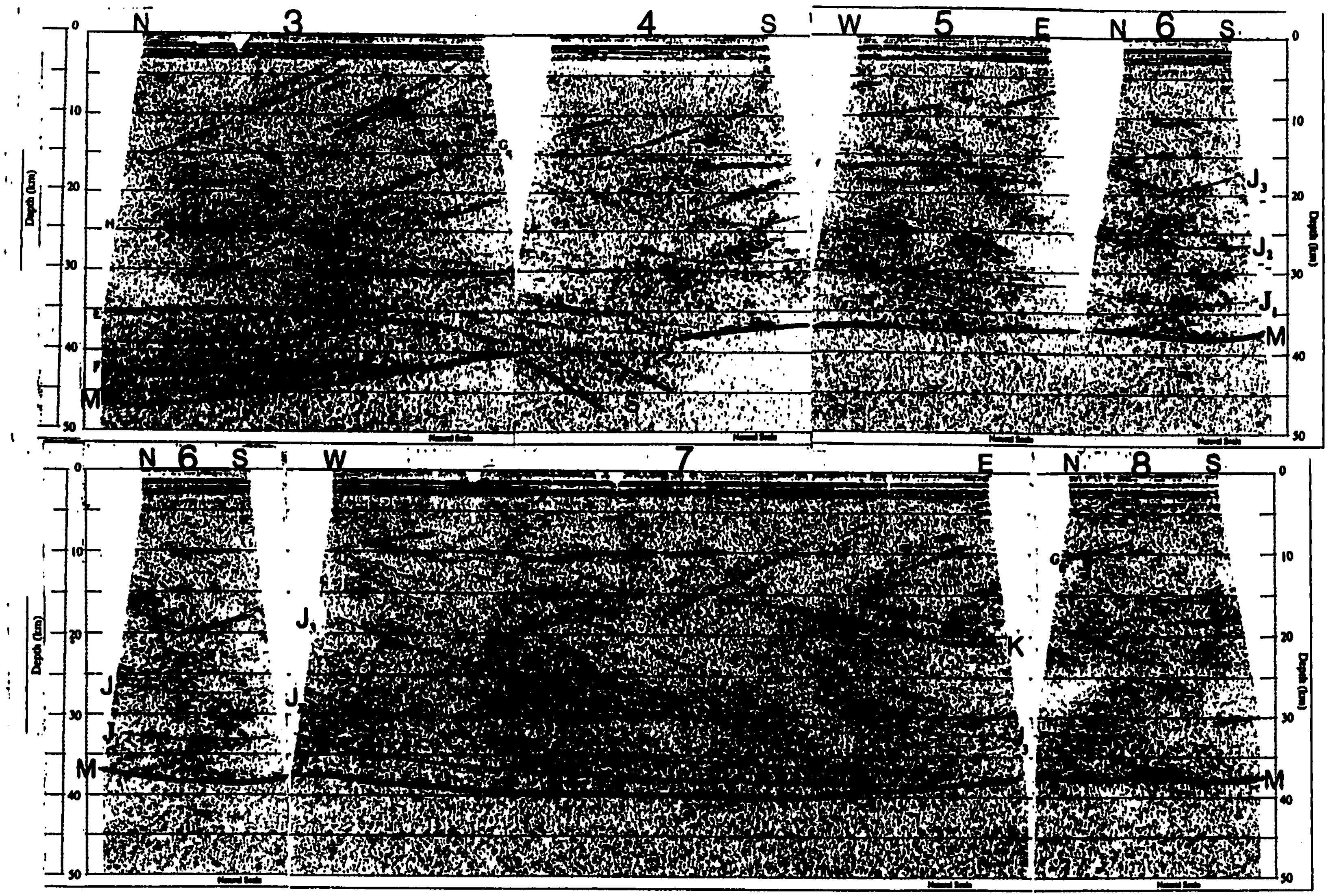

Fig. 3.42 Crustal-scale migrated-coherency-filtered section along CAT and PRAISE seismic lines.

sedimentary deposition with a different style along some of the seismic lines in Fig. 3.41. As discussed before, small vertical relief influencing the sedimentary cover up to the top of BH L is seen in the middle of Line 7. At the east end of Line 7, a fold-like structure appears below the basement and up into the sediments. Several domal features represent reefs and these are seen on several lines, notably the Rimby reef on Line 5. Another domal structure was noted on Line 3 with the influence extending from the basement to the top of MANN.

Tracing the mid-crustal structure along the profile shown in Fig. 3.42, it is found that southeast dipping reflections dominate along Line 4 to Line 8 and northwest dipping reflections dominated along Line 1 to Line 3. The dip changes occur in the region underlaid by the Rimbey High, along which Line 5 extends. Traversing the dip changing area, the mid-crustal structure of Line 5 and Line 4 is characterized by thrust folds and a horizontal sill which continues from Line 5 to Line 4 at the same depth. In fact, the fold and fault structures along Line 4 to Line 8 can be interpreted as being part of a regional, northwest-verging thrust belt (Ross et al., 1995). Lines 4 to 8 have quite different crustal structure when compared to Lines 3 to Line 1. They originated within another tectonic domain which has a thrust-imbricated unit. The mid-crustal structure of Line 19 and Line 18 show the effect of post tectonic movement along this thrust-imbricated unit.

In the lower crust level along the profile in Fig. 3.42, the reflections appear to flatten out into the crust-mantle boundary. In addition, uniformly dipping reflection packages related to the subduction zone are seen in the lower crust and disappear at the Moho subsurface. Across the whole transect, the Moho is laterally continuous and changes in depth from 36 to 43 km. The relict subduction zone (S) imaged on Line 4 is a major discovery of this aspect of Lithoprobe studies and reveals the value of quality reprocessing and migration.

Chapter 4 Conclusions

As a part of the Lithoprobe project, two-dimensional, high-quality crustal-scale seismic reflection data from central Alberta have been reprocessed and interpreted in this thesis. The migrated and migrated-coherency-filtered seismic sections show the structure of the sedimentary layers, the deformation of the Precambrian basement, the interaction between the Precambrian basement and the Phanerozoic sedimentary cover, the mid-crustal reflection packages and the reflection features near the crust-mantle boundary.

Through reprocessing of the crustal-scale seismic reflection data, this thesis has provided superior images of the lithosphere structure in the research area. Some effective techniques such as a static processing method, correlation, phase shift and depth migration and coherency-filtering have been used. For the depth migrated section a trace bias was used in filling in positive peaks. This produced more readily interpretable sections than the coherency filtering method. It should be noted that this part of the processing and migration imaging made exclusive use of University of Alberta algorithms, written in the Seismology Laboratory and Computing and Network Services bank of IBM workstations, operating in parallel.

For the ten deep crustal seismic lines reprocessed (Line 1 - Line 8 - Line 18 - Line 19), the continuous geological structure from the top of the sedimentary section through the crystalline basement to the Moho can be observed along the whole profile. A small amount of faulting of the basement and the overlying Cambrian strata was observed. There are also lateral facies transitions. A broad region of crustal-scale thrust imbrication and corresponding deflection in the crust-mantle boundary is evident. The reflection Moho can be recognized clearly on most of the seismic lines.

Phase-shift migration and coherency filtering was applied in the reprocessing with 2WS flattened and shifted in time to remove the structural ambiguity introduced by the different processing datum elevations of the individual seismic lines. Integrated with well-log data and potential-field signatures, the interpretation of the reprocessed seismic data has resulted in the identification of geological layers in the upper 3 km of the seismic sections and provided some interesting lithospheric structures imaged by the reprocessed seismic data. The depositional environment of the sedimentary cover in this part of the Western Canadian Sedimentary Basin(WCSB) was relatively stable except for many episodes of uplift, erosion and subsidence. The amplitude and the reflection features of the geological layers in the sedimentary cover are variable due to the changes in sedimentary facies over the different tectonic domains and are indicative of differential vertical movement.

The deformation of Precambrian basement is partly characterized by variation of reflection amplitudes, this is due mainly to its erosional characteristic. Some basement structures did affect the overlying sedimentary deposits in different ways along some segments of the seismic profile. Recent basement reactivation only affected the sedimentary cover in a subtle manner.

The reflection packages in the deeper crust with north-west or south-east dipping events and many thrust-folds in the mid-crust strongly suggest that a regional compressional deformation happened in this area. The dip changing from southeast to northwest along Line 4 and Line 5 indicate the suture zone where the Hearne craton and Rae craton collided. The magmatic activity and some post-subduction deformation originated from the collision. The reflections in the lower crust arise mostly through the changes in rock character during episodes of thrusting and sole into the crust-mantle boundary. The Moho is well imaged and there is a sudden loss in reflectivity throughout the entire reflection profile below the Moho indicating a more homogeneous mantle as compared to the crust. Some mantle reflection events are visible, most notably the relict subduction layer on Line 4.

Developing a comprehensive understanding of the structure of the lithosphere in the central Alberta Basin by using crustal-scale reflection seismic data is the main objective of studies such as this. Such information is not only valuable for the petroleum industry to get a framework for their exploration, but also useful for the seismologist who is interested in the evolution of the lithosphere and its role in the formation of mineral deposition. The structures imaged by the Lithoprobe seismic-reflection data offer guidance in formulating tectonic models of central Alberta and provide further details of the geometry and magnitude of deformation.

Exploration activity has become increasingly dependent on the capability of the seismic interpreter and the continually improving seismic reflection method. In fact, the seismic data displays provide the best two-dimensional, cross-sectional images of the earth's subsurface. They are extremely useful for exploration but particularly in increasing our fundamental understanding and knowledge of how the continental crust formed. Further work should focus on enhancing the processing techniques to increase the resolution of the seismic data and obtain an ideal picture of lithosphere structures. In particular, the problem of multiple reflection suppression needs to be addressed. The resolution of the data can be further improved with proper field recording methods, use of 3D recording, and correlations of the effect of attenuation with depth.

Bibliography

Andson, N. L., Hills, L.V.,and Oderwell, 1989, The CSEG/CSPG geophysica atlas of Western Canadian hydrocarbon pools. The Canadian Society of Exploration Geophysicists, The Canadian Society of Petroleum Geologists.

Beaumont, C., Quinlan, G. M. and Stockmal, G. S., 1993, The Evolution of the Western Interior Basin: Cause, Consequences and Unsolved Problems, in Caldwell, W.G.E. and Kauffman, E.G. (ed.), Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper, P. 97-117.

Burianyk. M. J. A., 1994, Properties of lithosphere in southern British Columbia and Alberta from seismic experiments. Ph.D. Thesis, University of Alberta.

Clowes, R. M., 1993, Lithoprobe - geoscience probing of inner space leads to new developments for mining exploration, Geological Society of CIM, v. 87, p. 36-48.

Collerson, K. D., Van Schmus, W. R., Lewry, J. F., and Bickford, M. E., 1988, Buried Precambrian basement in south-central Saskatchewan: provisional results from Sm-Nd model ages and U-Pb zircon geochronology. in Summary of Investigations 1988, Saskatchewan Geological Survey, Saskatchewan Energy and Mines, Miscellaneous Report 88- 4, p. 142- 150.

Dietrich, J. R., 1996, Seismic characterization of lower Paleozoic strata, central Alberta Lithosphere transect. unpublished, written comm.

Eaton, D. W., Milkereit, B., Ross, G. M., Kanasewich, E. R., Geis, W., Edwards, D. J., Kelsch, L., and Varsek, J., 1995, Lithoprobe basin-scale seismic profiling in central Alberta: influence of basement on the sedimentary cover. Bulletin of Canadian Petroleum Geology, v. 43, p. 65- 77.

Eaton D. et al., 1993, LITHOPROBE crustal reflection profiling in the Alberta basin: styles of basement-cover interaction and regional seismic stratigraphy, written comm.

Gazdag, J. and Sguazzero P., 1983, Migration of Seismic Data by Phase Shift Plus interpolation, V. 49, P. 124-131.

Gazdag, J., 1978, Wave Equation Migration With the Phase-shift Method, Geophysics, V 43, P. 1342-1351.

Hoffman. P. F., 1989, Precambrian geology and tectonic history of North America. in The geology of North America-an overview. A. W. Bally, A.R. Palmer, eds., Geological Society of America, The Geology of North America. V. A., P447-512.

Hoffman. P. F., 1990, Subdivision of the Churchill province and extent of the Trans-Hudson Orogen. in Lewry, J.F., and Stauffer, M. R., eds., The Early proterozoic Trans-Hudson Orogen of North America, Geological Association of Canada, Spec. Paper 37, p. 15-39.

Hepburn, H. and Winarsky, R., 1993, Central Alberta Basement Transect - a Lithoprobe project, Pulsonic geophysical Ltd.

Kanasewich, E. R., Burianyk, M. J. A., Dubuc G. P., Lemieux, J. F., and Kalantzis, F., 1995, Three-dimensional seismic reflection studies of Alberta basement. in Alberta Basement Transects Workshop. Ross, G.

M. ed. LITHOPROBE Report No. 47, p. 22- 34.

Kanasewich, E. R., 1994, Alberta Basement Transect report on activities at the University of Alberta in 1993. in Alberta Basement Transects Workshop. Ross, G. M. ed. LITHOPROBE Report No. 37, p. 59 -64.

Kirlin, R .L., 1992, The relationship between semblance and eigenstructure velocity estimators, Geophysics. v. 57, N. 8, p. 1027-1033.

Landmark/ITA Ltd., 1992, Insight Unix User Guide.

MacDonald, R., 1987, Update on the Precambrian geology and domainal classification in northern Saskatchewan. in Summary of Investigations 1987, Saskatchewan Geological Survey, Saskatchewan Energy and Mines Miscellaneous Report 87-4, p. 87-104.

Mccrossan, R. G. and Glaister, R. P., 1964, Geological history of western Canada, Alberta Society of Petroleum Geologists.

Mossop. G. and Shetsen, I. (compiled), 1994, Geological atlas of the Western Canada Sedimentary Basin, Canadian Society of petroleum geologists, the Alberta Research Council, Alberta Geological Survey.

Rong. L., 1994, Seismic reflection evidence for paleozoic and precambrain tectonic activity in east central Alberta, MSc Thesis, University of Alberta.

Ross, G. M., Broome, J., and Miles, W. 1994, Potential fields and basement structure, Western Canadian Sedimentary Basin. in Atlas of Western Canadian Sedimentary Basin, Mossop, G. D. and Shetsen, I.eds., Canadian Society of Petroleum Geologists and Alberta Research

Council.

Ross, G. M., Milkereit, B., Eaton, D., White, D., Kanasewich, E. R., Burianyk, M. J. A., 1995, Paleoproterozoic collisional orogen beneath western Canadian sedimentary basin(WCSB) imaged by 195-199.

Ross, G. M. and Parrish, R. R., 1991, U-Pb detrital zircon geochronology of metasedimentary rocks in the Canadian Cordillera and the age of continental basement. Canadian Journal of Earth Sciences, v. 28, p. 1254-1270.

Ross, G. M., Parrish, R. R., Villeneuve, M.E. and Browring, S.A. 1991. Geophysics and geochronology of the crystalline basement of the Alberta Basin, western Canada. Canadian Journal of Earth Sciences, v. 28, p. 512-522.

Sheriff, R. E., 1989, Geophysical methods, Prentice Hall, Englewood Cliffs, New Jersey 07632.

Villeneuve, M. E., Ross, G. M., Parrish, R. R., Theriault, R. J., Miles, W. and Broome, J. 1993, Geophysical subdivision, U-Pb geochronology and Sm-Nd isotope geochemistry of the crystalline basement of Western Canadian Sedimentary Basin, Alberta and northeastern British Columbia. Geological Survey of Canada, Bulletin 447.

Wright, G. N., McMechen, M. E., and Potter, D. E. G., 1994, Structure and Architecture of the Western Canada Sedimentary, in Atlas of Western Canada Sedimentary Basin, Mossop, G. D. and Shetsen, I. ed., Canadian Society of Petroleum Geologists and Alberta Research Council, p. 25-40.

Wickens, A. J., 1971, Variations in lithospheric thickness in Canada, Canadian Journal of Earth Science, v. 8, p. 1154-1162.

Yilmaz, Özdogan, 1987, Seismic Data Processing, SEG, Tusla.