CANADIAN JOURNAL OF EXPLORATION GEOPHYSICS
VOL. 32, NO. 2 (DECEMBER 1996), P. 104-112

MIGRATION OF A MULTIOFFSET VSP: A CASE STUDY IN NE BRITISH COLUMBIA[1]

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ABSTRACT

A walkaway vertical seismic profile (VSP) was performed in the Talisman-Ocelot c-54-J/93-P-4 well to image the Triassic anticlinal structure. Twenty sources, approximately paralleling the dip direction, were deployed. Seismic images acquired in the complex geological regimes of the foothills of NE British Columbia are often very difficult to interpret. In this study the VSP provided important information at a critical stage of the drilling program. The initial trajectory of the well failed to encounter the structure at the anticipated depth. The evaluation of the migrated VSP image, along with other data, including dipmeter, well logs and surface seismic, helped to direct the wellbore trajectory and successfully penetrate the structure.

The acquisition of all 20 offsets (ranging on either side of the wellhead from the near offset to about 1200 m), processing and interpretation was performed in about 50 hours. Vibroseis trucks were used as the energy source. Twenty-seven receivers in the borehole were positioned 20 metres apart at depth between 1400 m and 1940 m. Following processing, the final image of the subsurface was derived using the Kirchhoff migration scheme which combined all offsets. A relatively large number of source-receiver pairs as well as the acquisition geometry which had sources, receivers and raypaths contained in a single plane, resulted in the necessary conditions for effective use of our Kirchhoff migration method.

The VSP offers several advantages as compared to surface seismic surveys. Notably, positioning of receivers in the wellbore can allow for the location of targets with respect to the wellbore.

INTRODUCTION

In May 1994 a VSP was acquired in the c-54-J/93-P-4 Talisman/Ocelot well in northeastern British Columbia. Prior to this study there had been numerous other VSP surveys acquired in this area. The special characteristic of this study lies in the fact that 20 surface source locations were used in gathering the VSP data. The sources were all approximately collinear and coincided with the regional dip direction and borehole deviation as shown in Figure 1. This recording geometry allowed for a proper application of the VSP-Kirchhoff-Depth Migration algorithm, which, for optimal operation, requires that all sources, receivers and raypaths be coplanar.

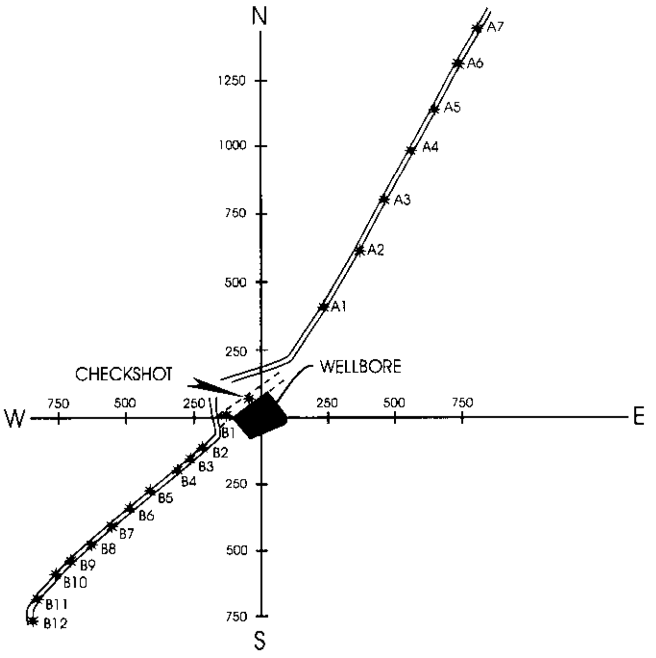

Fig. 1. Plan view of wellbore deviation and source locations A1-A7 and B1-B12. Axes are annotated in metres. The "lease road" on which sources are deployed approximately parallels the dip direction.

Imaging of complex structures by VSP migration has been investigated by several researchers. For instance, an insightful synthetic study was presented by Payne et al. (1994). A study including field examples was described by Zhu and Lines (1994).

The purpose of this paper is to present a case study where a multioffset VSP was used successfully in an operational setting to help determine the location of the target and adjust the

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[1] Presented at the CSEG National Convention, Calgary, Alberta, May 11, 1995.

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The authors would like to thank Talisman Energy Inc. for supporting the study, Ocelot Energy Inc. for allowing release of the data, and Western Atlas for their support. In particular we would like to thank Messrs. M. Crous, P. Pelletier, C. Welsh, R. Green, B. Quartero of Talisman, Mr. M. Riemer of Ocelot, and Mr. D. Quinn of Western Atlas. Also, the authors would like to thank Dr. R.J. Brown for his critical review of the manuscript.

drilling program in progress. We believe this is an important example of the use of a VSP in an exploration setting.

EXPLORATION SETTING

Gas is trapped in Triassic (Late Carnian-Norion) Pardonnet and Baldonal carbonates in open to tight asymmetric anticlines, which may be detached from the underlying Charlie Lake anhydrites and Lower Triassic (Doig/Montney) siltstones and shales. Fractures, optimally developed in the fold hinge, allow the reservoir to produce at very prolific rates (20-80 mmcf/d). However, the asymmetry of the folds makes the optimal target narrow and easy to miss, resulting in either a low-productivity "backlimb" well or missing the crest and forelimb altogether.

Rugged surface topography, variation in thickness and velocity of the surface layer, and complex subsurface geology, make the interpretation of the seismic data difficult. To constrain the interpretation, we have used surface geology, well control, and seismic data. In addition, checkshot surveys and VSPs provide us with regional velocity for depth conversion.

PREDICAMENT OF C-54-J WELL

From initial drilling it appeared that, since the top of Triassic was not penetrated at the anticipated depth, the well trajectory had missed the apex and had paralleled the flank of the anticline. The drilling was stopped and the VSP data acquired, processed and interpreted. At the same time a suite of logs, including a dipmeter, was acquired. Based on all this information the most likely location of the apex of the anticline was inferred. When drilling resumed, the trajectory of the wellbore was deviated towards the new target.

RUDIMENTS OF VSP MIGRATION

The VSP provides information not contained in a surface seismic image. Firstly, the positioning of receivers (geophones) in the wellbore allows for deriving a reliable function relating the seismic velocity and depth from the traveltime of first arrivals. Secondly, the positioning of reflectors with respect to the wellbore can be inferred from the traveltime of reflected waves. Proper location of reflectors in a complex geological regime, e.g., non-planar reflectors, is greatly aided by multiple sources and receivers yielding a large number of raypaths. Since the VSP data set is in the time-depth domain, construction of an interpretable image in offset-depth domain must involve a process of mapping between the two domains.

Currently, there are two commonly used methods for transforming the VSP data into the offset-depth domain, namely VSP-to-CDP-Transform and Kirchhoff Migration. Our modelling studies, performed prior to the present study, show that the former is very dependent on accurate model of the subsurface, including proper location of interfaces, while the latter one requires only a reasonable velocity field for the algorithm. If the subsurface model is well known (as is often the case for the seismic data acquired on the plains) the VSP-to-CDP-Transform would often yield a sharper image without undesirable, yet intrinsic, artifacts of the Kirchhoff migration. If, on the other hand, the subsurface structure is not well known (as is often the case for the seismic data acquired in the foothills), the Kirchhoff migration can provide a reasonable image with a less accurate input model. Finally, it can be noted that both techniques may be used to arrive at the interpretation of the subsurface, with the VSP-to-CDP-Transform serving as a convenient verification for the model derived from the interpretation of the migration results. In the present study, the migration algorithm was used on its own.

The Kirchhoff migration of VSP data stems from the concept that if a point source, a point receiver and a point scatterer are contained in an infinite homogeneous, isotropic medium the location of the scatterer can be inferred from the traveltime of the signal taken to travel the path "source-scatterer-receiver". The distance travelled by the signal is the product of the traveltime and the speed of the signal in the medium. Thus it follows that the scatterer must be located on the ellipse whose string-length is equal to the distance travelled by the signal. Each source-receiver pair yields an ellipse corresponding to a single scattering point as shown in Figure 2. In a medium consisting of different velocity layers the term "ellipse" is used rather loosely, since a perfect ellipse corresponds only to a constant velocity medium.

A large number of source-receiver pairs allows the scatterer to be more accurately located. For example, Figures 3a and b show reflections from a planar dipping interface generated from a single source and captured by multiple receivers. In the migrated image, high amplitudes correspond to segment of the interface illuminated by the source. The high amplitudes are created by the superposition of many ellipses. The migration "smiles" are an inevitable by-product of the process with limited number of sources and receivers. Only in the case of very many sources and receivers will the migrated VSP image be comparable to a high-fold surface seismic image as illustrated by the synthetic study of Payne et al. (1994).

EXPERIMENTAL CONSIDERATIONS

In a geophysical application involving a complex subsurface, a limited frequency bandwidth signal, and other experimental limitations and errors, the generation of VSP migration requires careful acquisition, processing and interpretation. A crucial element in useful acquisition involves some knowledge of the study area to allow optimal deployment of sources and receivers.

The selection of suitable source locations faces the challenge posed by the rugged topography, and environmental considerations. The fortuitous location of the "lease road" in

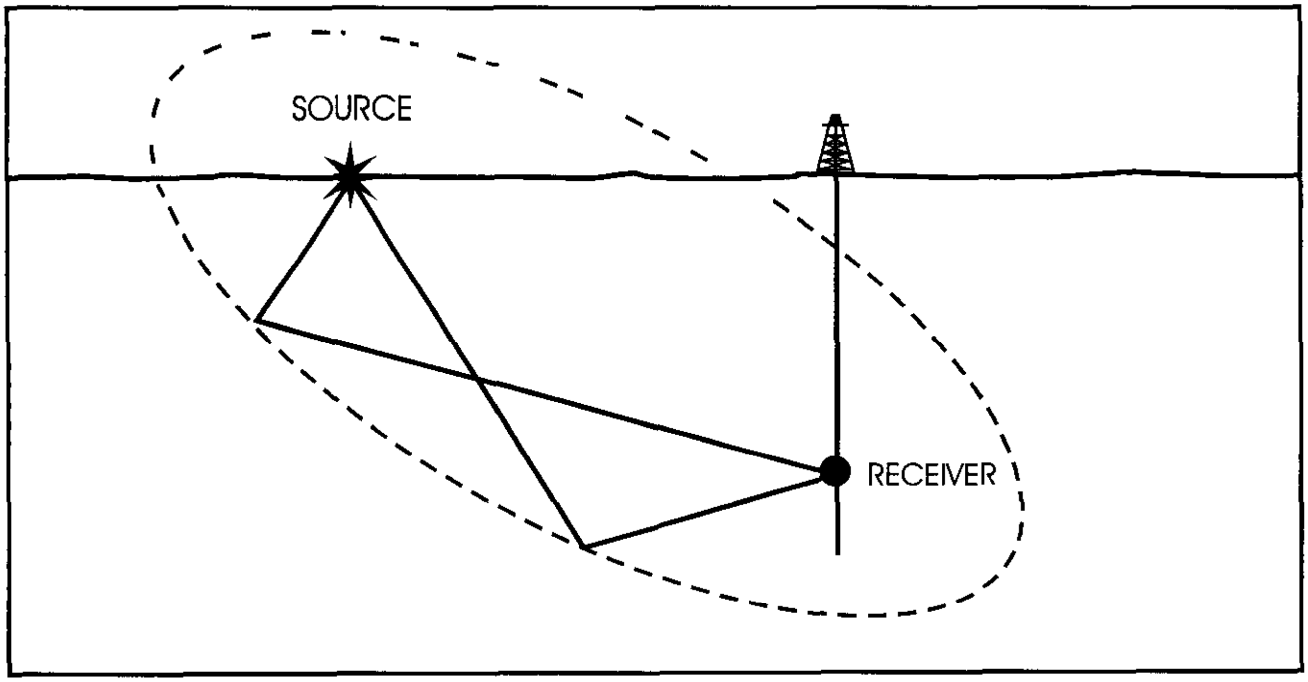

Fig. 2. Locus of all possible reflection points in a uniform velocity field for a given source-receiver configuration given the distance travelled by the signal, i.e., the product of traveltime and speed. The source and receiver constitute the focal points of the ellipse.

the vicinity of c-54-J which paralleled the dip direction, played an important role in the feasibility of this study. Although it would be unreasonable to expect such a convenient situation in all cases, one should consider the construction of a "lease road" with a possible "walk-away" VSP in mind.

Proper consideration of limitations imposed by both physical and economic constraints must be taken into account for optimal acquisition. It is important to realize that there are numerous cases where either of the above-mentioned factors rules out the usefulness of the VSP survey. Obviously, it is preferable to assess the usefulness of a tool prior to investing a significant effort.

PRE-SURVEY PLANNING

Several considerations had to be taken into account in order to limit the time of acquisition while still acquiring a useful image. Firstly, one must consider the expected distribution of reflectors in the subsurface, including depth to target, reflectors dips and approximate seismic velocities in order to optimize the acquisition by properly locating sources and receivers. To answer some of the questions, pre-survey modelling is very useful.

Since the available algorithm for Kirchhoff migration operates in the two-dimensional space, it is important to acquire the data in such a way that all sources, receivers, and raypaths are coplanar. This is possible if rapid changes in the structural picture are confined to a single azimuth, i.e., dip direction. In the context of the present study a road coinciding with the regional dip direction provided proper location for the deployment of sources.

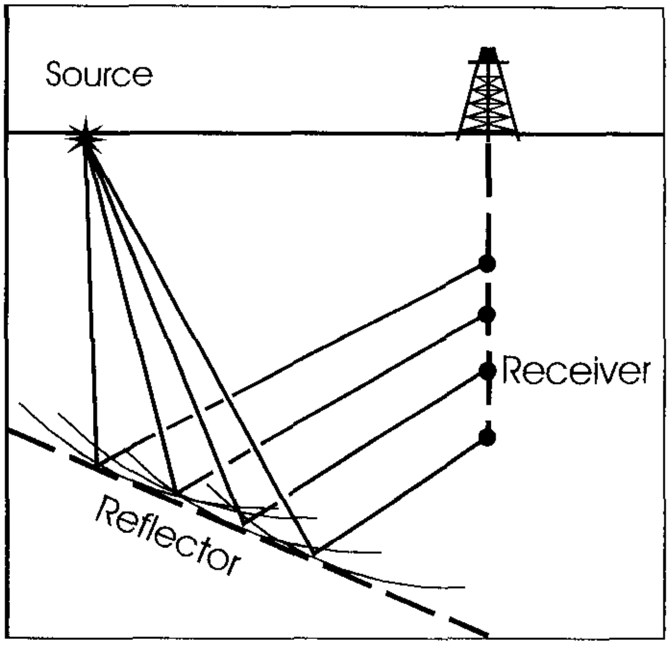

Fig. 3a. Schematic diagram illustrating rays reflected from a planar dipping interface.

The axis of the anticline inferred from the surface seismic data was expected to be perpendicular to the lease road allowing the data acquisition in the dip direction. Based on the geological knowledge of the area, the northeastern flank of the anticline was expected to be much steeper than the southwestern flank. The wellbore was believed to be located to the northeast of the steep flank of the anticline. Therefore,

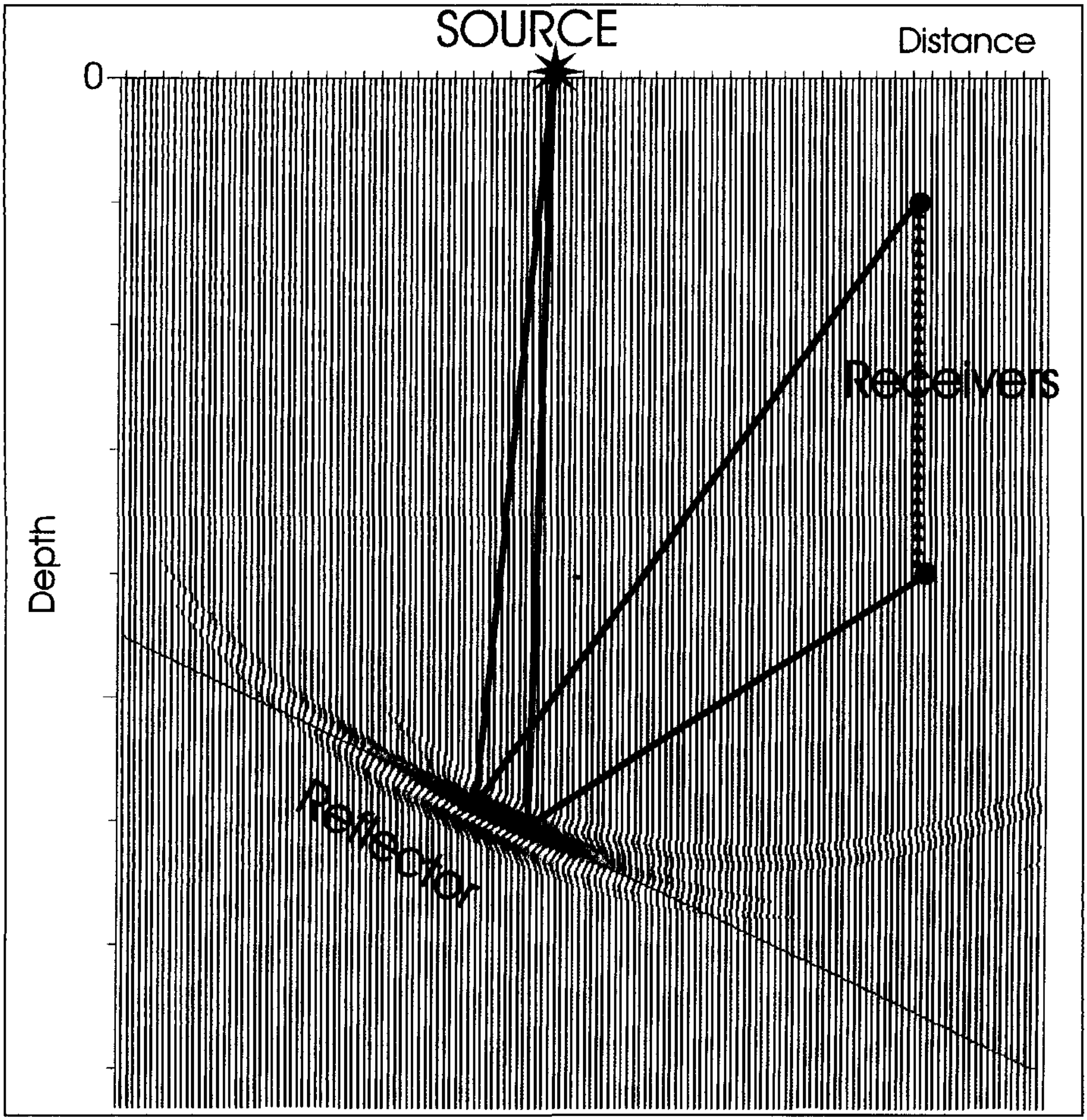

Fig. 3b. Migration of synthetic data obtained from a planar dipping interface. Note the excellent correspondence of high amplitude with the dipping interface. Also note the "elliptical smile" resulting from the construction of the image.

in view of those factors, the sources were placed closer together above the SW limb of the anticline, while a wider aperture was applied over the NE limb to capture, at a larger distance, the rays from a steeply dipping reflector. Also, by raytracing a simple model based on the current estimate of the geologic structure, the optimal locations of receivers in the wellbore were established. This raytracing process indicated that a range of receivers spaced 20 metres apart over the bottom 500 metres of the well would adequately image the target.

Vibrators were selected as the energy source due to the excellent repeatability of the signal and a relative ease and rapidity of operation. A linear "up-sweep" from 8 Hz to 60 Hz was chosen as previous VSP studies in this area indicated a significant loss of higher frequencies in the signal, and it was inferred that signals with frequencies higher than about

60 Hz would not be recorded. To increase the energy generated by the source, a pair of synchronized vibrators was required at each source location.

DATA ACQUISITION

Based on the pre-survey planning the receivers were deployed in the bottom portion of the well from 1940 metres to 1400 metres at a 20 m spacing. This interval was considered the minimum interval necessary to obtain a useful image.

Three pairs of vibrators were used to minimize the acquisition time. One pair was vibrating while the other two were moving to another source location and preparing to generate the signal. Twenty offset locations were acquired. Nineteen were used for imaging and one was used for velocity information. Seven offsets were located NE of the wellbore and spaced about 200 m apart to image the steeply dipping flank of the anticline. The remaining twelve offsets were located SW of the wellbore and spaced about 100 m apart to image the more gently dipping flank (Figure 1). For each source-geophone combination, four sweeps were used. The signal, as observed during the initial stages of acquisition, appeared to have a good signal-to-noise ratio; hence, four sweeps per receiver level were considered sufficient in view of the overall time constraint.

In spite of the large scale of the acquisition, the entire operation took less than 36 hours. The data were acquired by Schlumberger of Canada. Upon completion of the acquisition the data were transferred to Calgary for rush processing in the offices of Western Atlas Logging.

DATA PROCESSING

The data from each offset were edited, summed and the first arrivals picked to produce nineteen total wavefield datasets. Editing and summing of the data indicated that four sweeps provided a marginally adequate signal-to-noise ratio. Typical borehole surveys in this area use six to eight sweeps when time is not such a severe constraint.

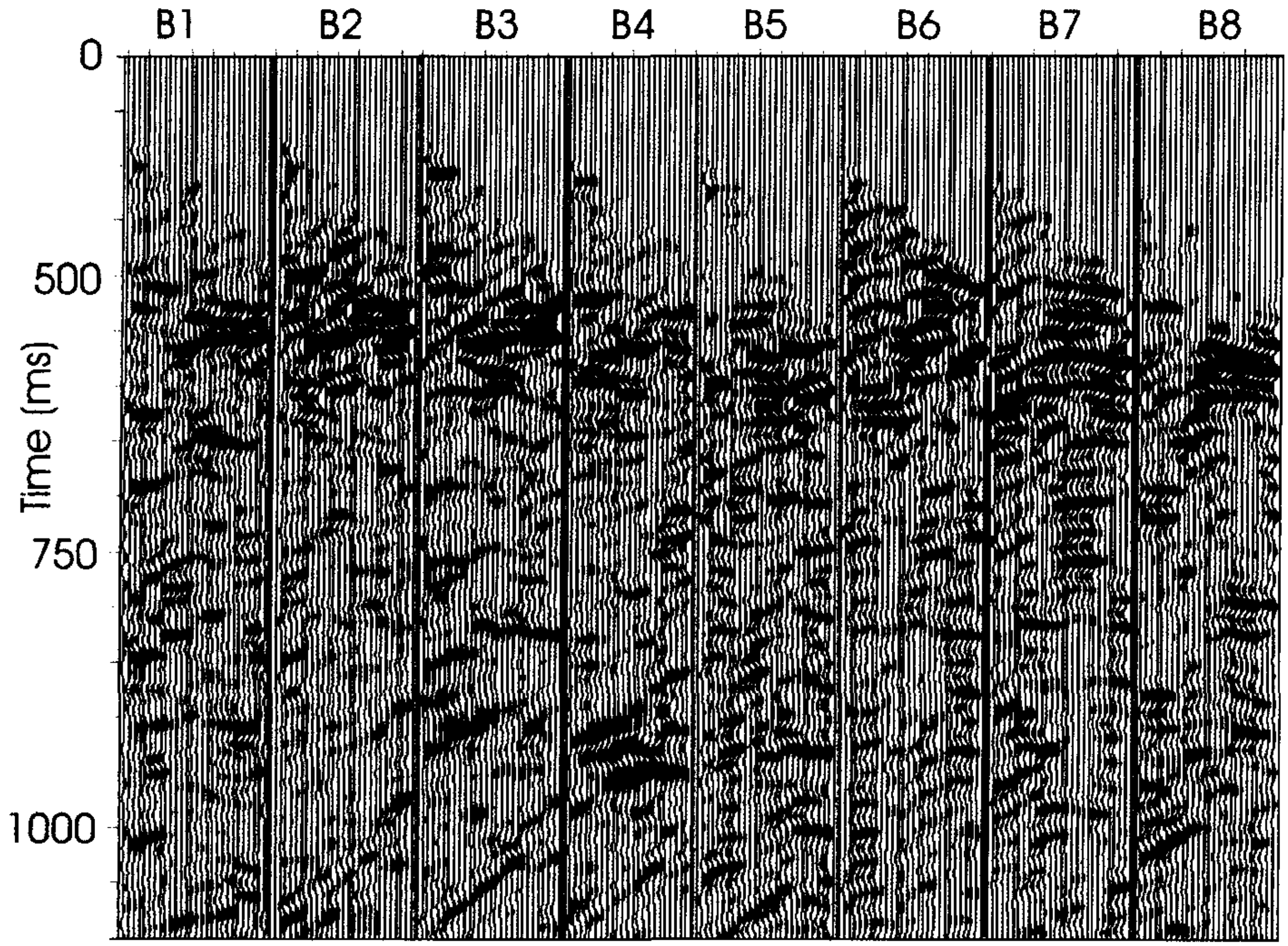

Fig. 4. Selected deconvolved reflected wavefields from the SW source array constituting the input to migration.

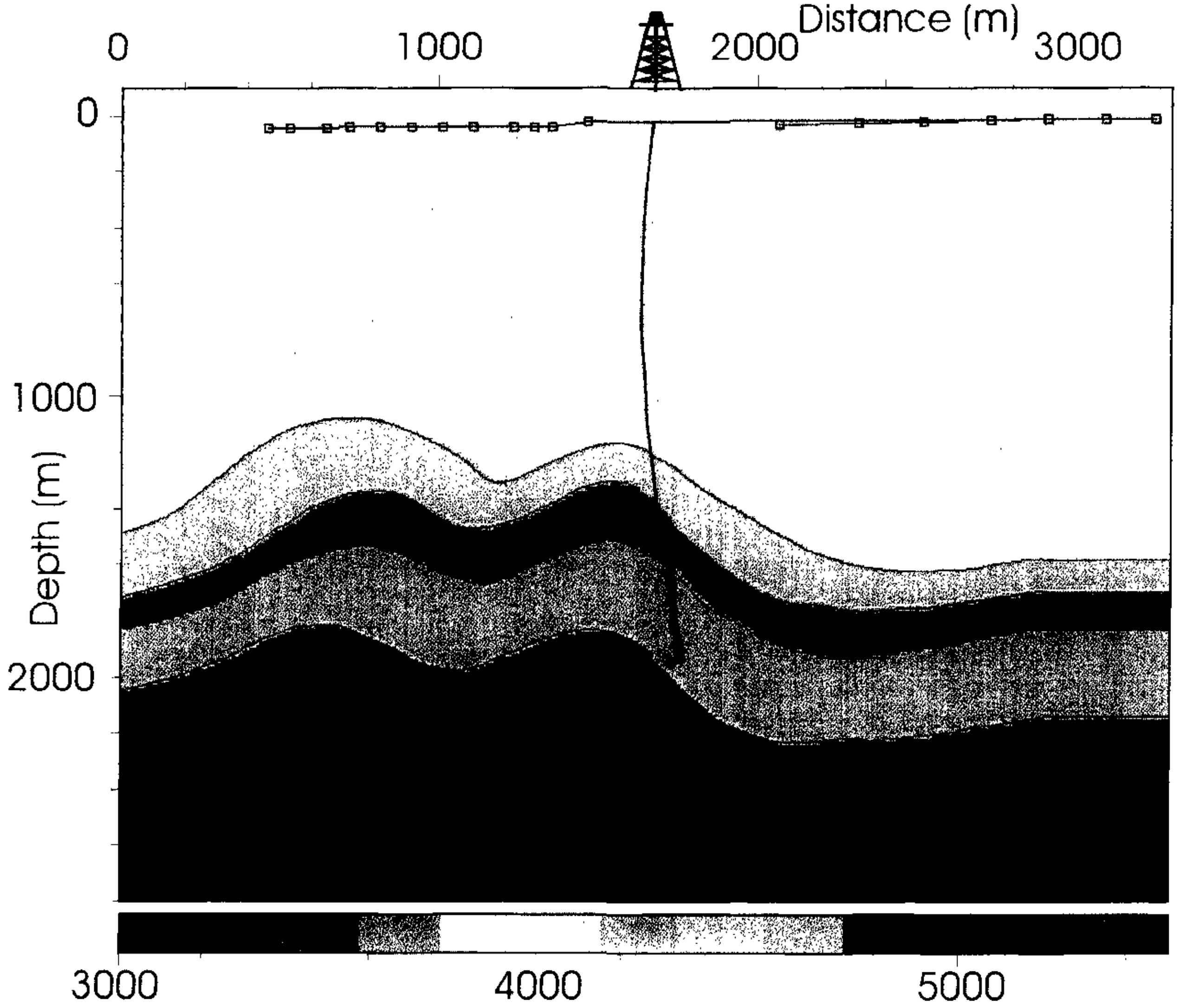

Fig. 5. Structural velocity model for migration. Velocities are derived from checkshots and regional information. Note the deployment of sources along the surface and receivers near the bottom of the wellbore.

Velocity information was obtained from the checkshot VSP data. In order to minimize processing time, the data from the NE offsets were merged in common-shot gathers in order to form a single dataset. Similarly the data from the SW offsets were merged together. The two merged datasets were processed independently using identical processing flows.

The appearance of the total wavefields was complicated by the presence of converted waves as well as reflected energy with moveouts similar to those of downgoing wavefield. The latter effect was due to the steeply dipping reflectors. Separation of the downgoing (direct) and upgoing (reflected) wavefields with opposite moveouts was accomplished by median filtering. The downgoing converted waves were attenuated by a second application of median filtering. Removal of reflected converted waves and reflections with downgoing moveouts could not be adequately treated without severely degrading the image.

Deconvolution yielding a zero-phase wavelet was performed. In VSP data such deconvolution consists of designing an operator from the direct arrival and applying it to the reflected waves. Since a direct measurement of the downgoing wavefield is recorded, the source signature and multiples from it are known and may be deconvolved to produce a zero-phase reflected wavefield.

Deconvolved data sets from the SW array and NE array were migrated independently using Kirchhoff depth migration. A partial display of the input data from the SW offset is shown in Figure 4.

The domain in which a migrated VSP image is displayed is equivalent to that of a normal geological cross-section spanned by horizontal and vertical distances, whereas the domain of the pre-migration display, spanned by depth and traveltime, does not have a simple pictorial geological equivalent. Thus, for VSP data, the process of migration consists of changing the domain in which the data is displayed. Prior

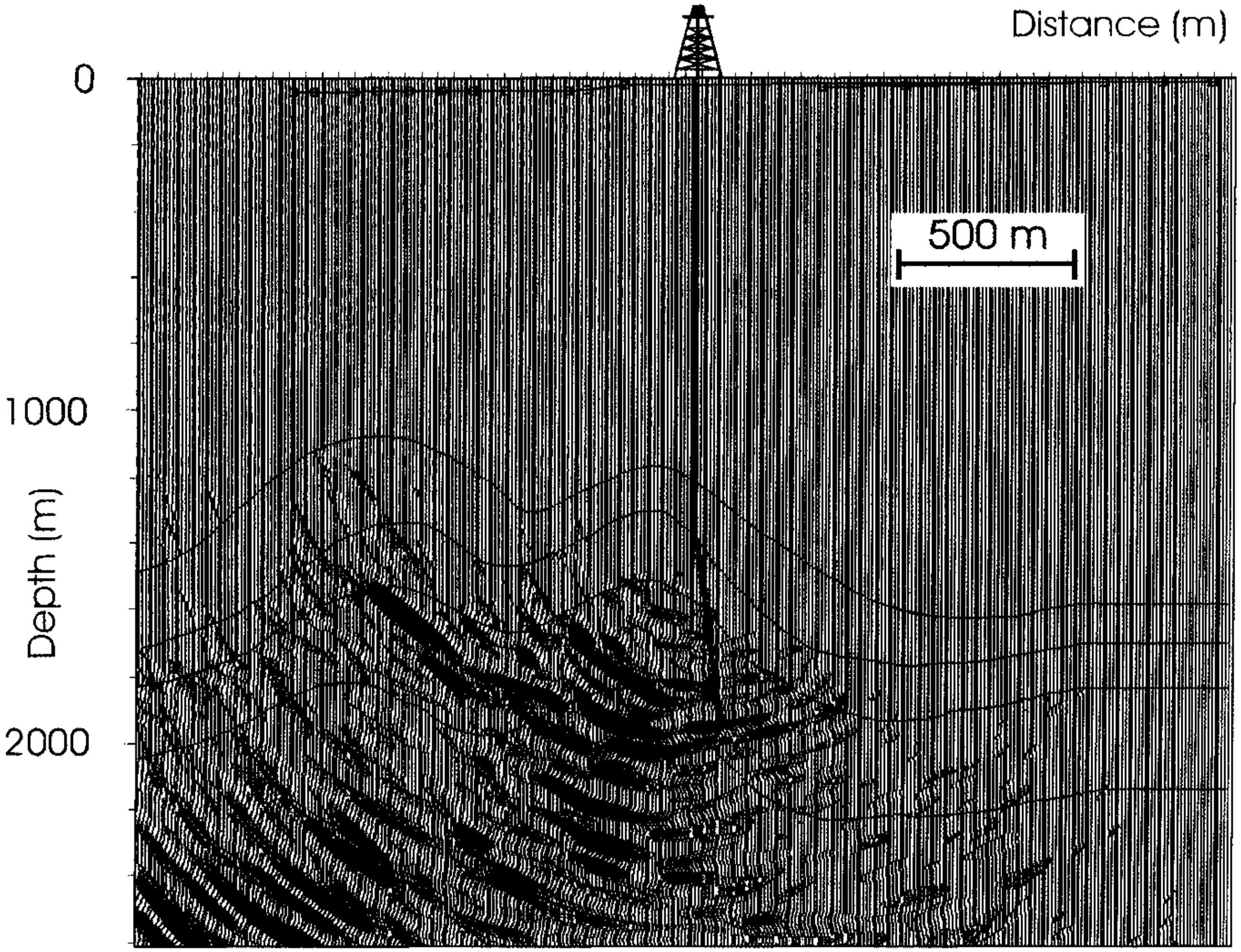

Fig. 6a. Migrated image with velocity model. High-amplitude zones indicate likely positions of reflectors illuminated by source-receiver configurations. Positions of sources near the surface and receivers near the bottom of the wellbore are shown.

to migration, the depth to a given receiver in the wellbore is placed on the horizontal axis, while traveltime is placed on the vertical axis. After migration, horizontal distance is placed on the horizontal axis, while depth is placed on the vertical axis.

A 2D-input model is required for VSP migration. The model defines the structure of the velocity field for traveltime calculations. The model, based on interpretation of the surface seismic, velocity information from the checkshot survey and regional velocity information, is shown in Figure 5. The sources and receivers are then projected onto the model with the wellhead being located at 1600 m on horizontal axis. The resulting migrated images from each array were analyzed and corrected for static differences and merged to create a single image as shown in Figure 6a. The entire processing sequence was accomplished in 18 hours so that a timely interpretation could be made in order to whipstock the well and minimize rig costs.

INTERPRETATION

The interpretation of VSP data suffers, like all seismic data, from the problem of non-uniqueness. The very construction of the image through the Kirchhoff algorithm generates many artifacts; most notably, the elliptical shapes which contribute to the construction of the image are still visible and might render the interpretation more difficult. The interpreter will, almost inevitably, be faced with ambiguous results. A relatively reliable interpretation can be achieved by applying geological constraints, as well as all available information, e.g., dipmeter, sonic logs, etc. Since the likely position of the reflector, or a scattering point, is indicated by a high amplitude on the image, it has been found that a colour-coded amplitude display provides more information and allows a more reliable picture of the subsurface to be deduced than when using a black and white, variable-area display.

A simple interpretation of the anticlinal structure is illustrated in Figure 6b. Note the high amplitude denoted by

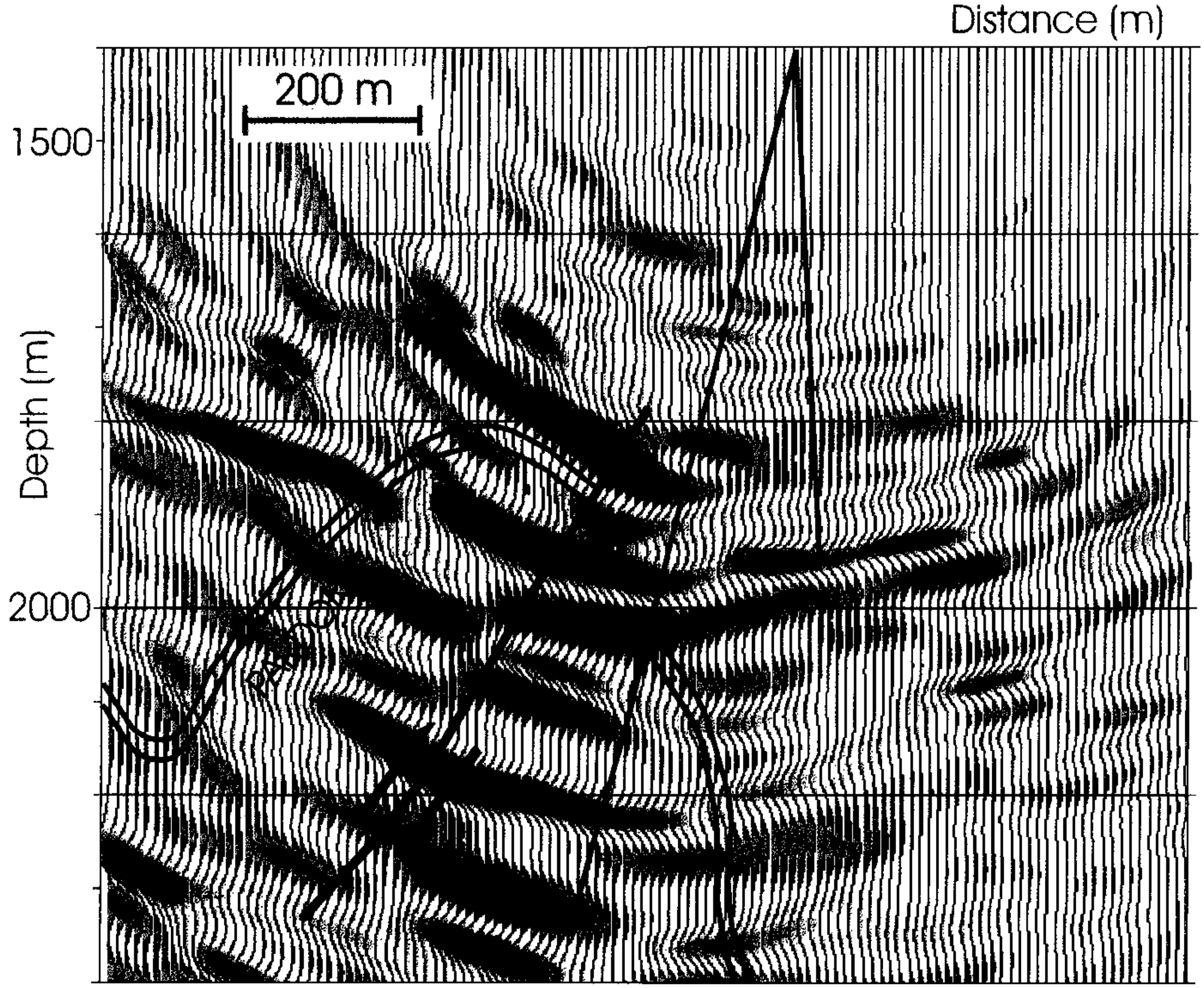

Fig. 6b. Magnification of the part of the image shown in Figure 6a. The interpretation suggests a Triassic anticline disturbed by a reverse fault whose existence is also inferred from well-logs. The position of the downthrown block was confirmed by drilling.

purple interpreted as the location of the reflector which can be compared with the image illustrated in Figure 3b. The "smiling" shape of the image is not a function of the geometry of reflectors but an inherent result of image construction by superposition of ellipses. One must learn to interpret the migrated VSP image in spite of this misleading artifact. The presence of the reverse fault is inferred from both the VSP image and the interception of the fault plane by the wellbore as indicated by well logs (see Figure 7).

In the Kirchhoff migrated image from all the offset locations, the zones of high amplitude were located behind the wellbore. This feature indicated that the crest of the anticline was situated to the southwest of the well trajectory. The presence of several zones of high amplitude suggested that the structure was not a simple anticline but rather an anticlinal uplift which consisted of several imbrications separated by faults. The lack of a clear location corresponding to the single apex entailed several complications as well as opened several options. The final decision concerning the selection of a rather moderate deviation with respect to trajectory of the original well was based on several factors. Firstly, the position of the adjacent well (c-45-J) had to be considered in view of the spacing unit. Secondly, by drilling further away from the aforementioned well, the likelihood of encountering and draining new reserves was increased.

DISCUSSION AND CONCLUSIONS

The modified well trajectory penetrated the structure and economic hydrocarbons were found. After all information was gathered a final interpretation was performed. New information, derived mainly from the dipmeter log in the new wellbore was, in its general outline, consistent with the original interpretation. Certain adjustments, referring to the exact spatial position of reflectors, were necessary as a result of the discrepancy between the actual and modelled velocity

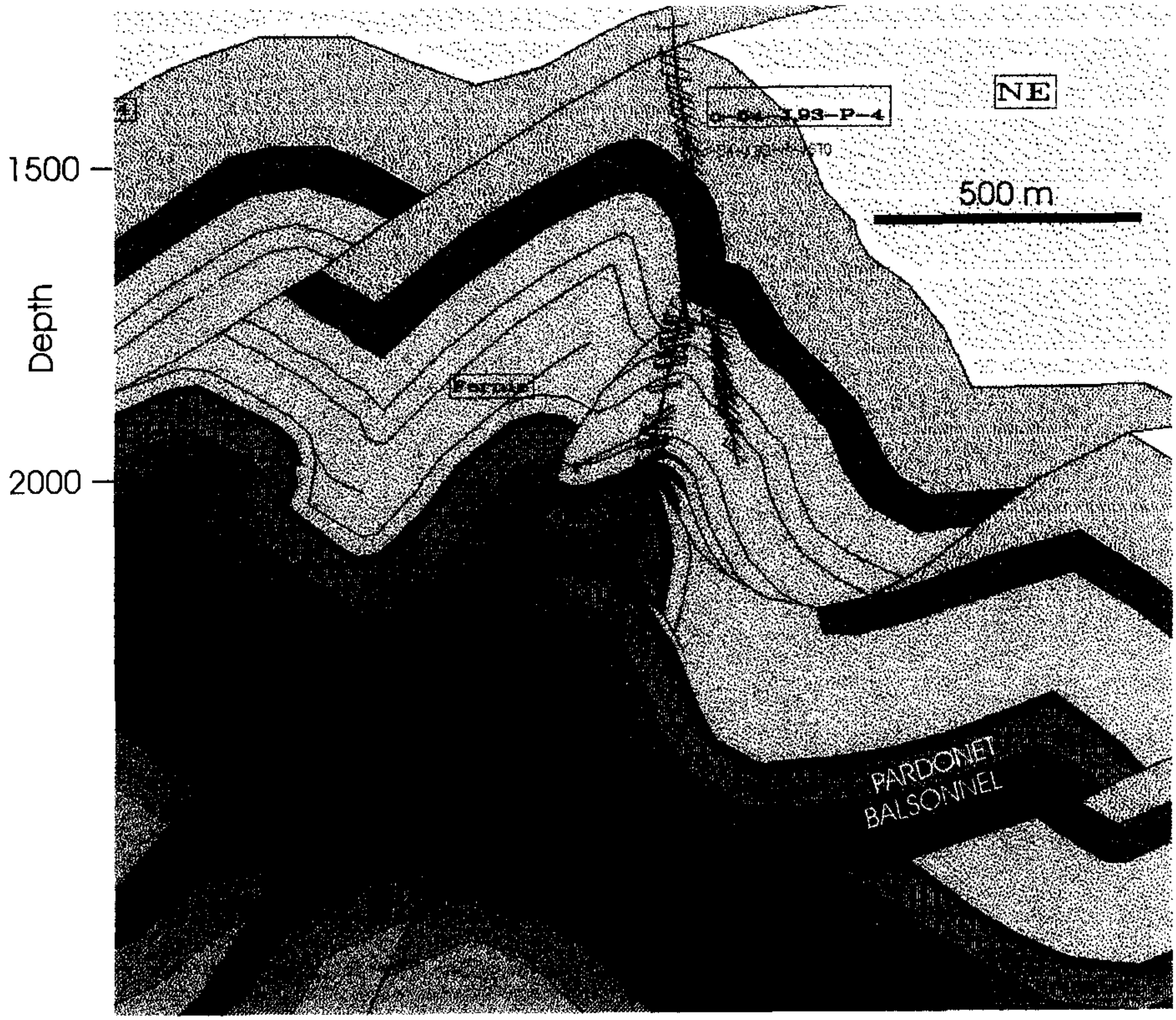

Fig. 7. Final interpretation of the subsurface based on all available information. The original and final (deeper) trajectories are shown. The adjacent well c-45-J (not shown) penetrates the anticlinal structure to the southwest of c-54-J.

fields. The high-amplitude zone visible in Figure 6b at approximately 1800 metres in depth, most likely corresponds to the highest point on the Triassic structure, while the high-amplitude zone at about 2000 metres in depth corresponds to the downthrown block.

The VSP proved to be a useful tool; it provided a timely result which was used in combination with other geological and geophysical information, to constrain the solution and make a decision on the deviation of the well. The image derived from the VSP has been subjected to only partial verification by drilling, which tested one zone marked by a high amplitude interpreted as a downthrown block. Another high-amplitude event, interpreted to be the crest of the Triassic anticline remains untested.

The importance of the VSP study performed on the Talisman/Ocelot c-54-J well goes beyond its use for this particular well. It contributed to the understanding of several important aspects of pre-survey planning, acquisition, processing and interpretation. This study is an example of the VSP as an exploration tool and shows the importance of using multiple sources in imaging complex structures.

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