Workshop #6

Demonstration of Processing and Model Building Methods on a Real Complex Structure Data Set

Organizers: Christof Stork, Advance Geophysical; Charles Welsh, Talisman Energy Inc.; Andy Skuce, Husky Oil Ltd.

Chairman: Andy Skuce, Husky Oil Ltd.

Panelists: Charles Welsh, Talisman Energy; Larry Lines, Memorial University of Newfoundland; Graham Bowyer, British Petroleum; John Toldi, Chevron; Andreas Ehinger, IFP.

Objectives:

1) analyze the current state of technology for imaging in complex 2D structure,
2) highlight areas where improvement is needed for imaging in complex structure, and
3) establish this public real data set as an industry standard to aid the easy demonstration of new technology for imaging in complex structure.

Agenda:

1:30 Welcome & Overview of workshop, Andy Skuce, Husky Oil

1:35 Interpreters Perspective & Exploration History, Andy Skuce, Husky Oil, & Charles Welsh, Talisman Energy, co-owners of the data set.

1:55 Summary presentations of the poster sessions. Each poster gives a 2 minute summary of their poster.

2:25 Poster presentations. There will be 6 poster presentation sessions each of length 15 minutes. Each presenter will talk every other session.

3:55 Panel summary. Five industry leaders will comment on the current state of the art for imaging in complex structure.

4:20 Questions and comments from the floor.

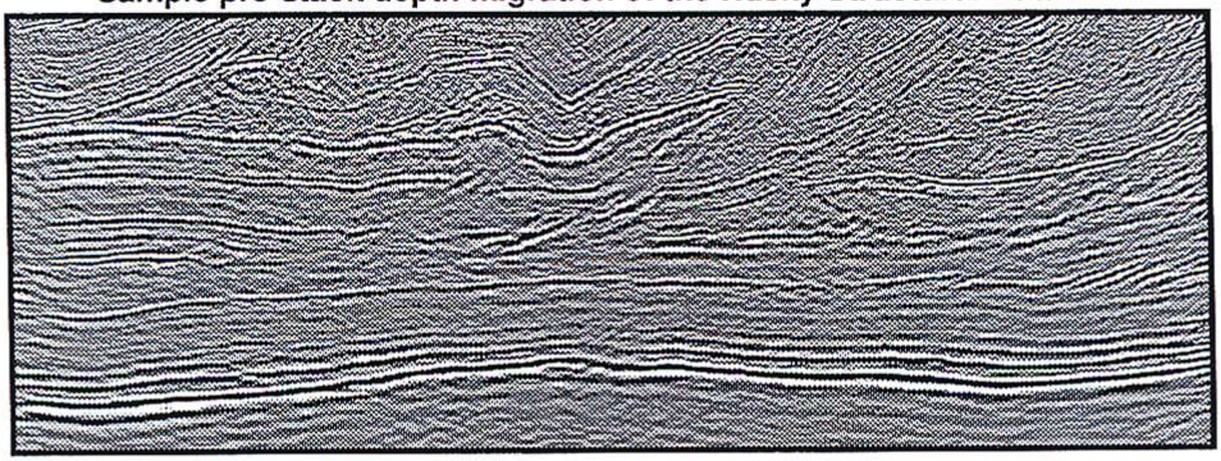
4:30 Additional poster presentations per interest.

Contents:

Dataset description:

The data set on which this workshop is based has been previously advertised in the SEG Leading Edge, the EAEG First Break, and the CSEG Recorder as the "Husky Structural Data Set from the Canadian Foothills". The data set has excellent signal quality, considerable associated geologic information, minimal 3D effects, a nearby VSP, and very interesting complex structure. Numerous potential processing, interpretation, and model building techniques can help resolve subsurface structure. In particular, with considerable associated geologic information, this data set can serve to demonstrate methods for integrating geologic information with seismic processing and model building.

Sample pre-stack depth migration of the Husky Structural Data Set:



Whereas imaging in complex structure frequently requires 3D seismic data, 3D methods can be developed and demonstrated on the much simpler and cheaper 2D case. The similarity of nearby seismic lines to this line, the analysis of nearby wells, and the success of 2D pre-stack depth migration methods on a neighboring line indicates that 3D effects are minimal for this line. Thus this line serves as an excellent test of methods for imaging in complex structure that are intended to be applied to 3D data as well as help address the 2D problem.

You can obtain a copy of the data by sending a check made out to Advance Geophysical for US$40 or 20 UK Pounds to: Husky Structural Data Set, c/o Christof Stork, Advance Geophysical, 7409 S Alton Ct., Englewood CO 80112, USA.

SEISMIC IMAGING IN THE CANADIAN ROCKY MOUNTAIN FOOTHILLS

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Introduction

Husky Oil and Talisman Energy are two independent, mid-sized companies that operate extensively and successfully in the overthrust belt of the Canadian Rocky Mountains, an exploration area that has always provided a challenge for seismic imaging. Both companies, who rely on independent contractors for their seismic technology, have, in recent years, made several attempts to apply new pre-stack depth imaging techniques to Foothills seismic data. Success in getting a good depth image was found to be elusive: we suspected that problems such as topography, statics, anisotropy, noise, sideswipe, irregular geometries and an unknown solution were rendering the problem insoluble. Many of the successful depth migration examples that we were shown dealt with problems and environments (e.g., synthetic models, extensional tectonics, marine data, sub-salt imaging) that were substantially different to the conditions that we were facing in the thrust belt. Because of our perception that Foothills seismic data were not getting their fair share of attention from the research community, and acting upon a far-sighted suggestion from Christof Stork, Talisman and Husky decided to release, virtually free of charge, a Foothills data set, the "Benjamin Line", complete with geological control, so that it could become adopted as a type example for land 2D seismic data in areas of complex structure. To stimulate maximum interest and research, we wanted to circulate the data as widely as possible, so we placed few conditions upon its destination or its use. The released data are located in the Southern Alberta Foothills, near 51° 30'N, 115°W.

Foothills structure and stratigraphy

The Canadian Rocky Mountain Foothills occur in a belt 40-80 km wide and 1500 km long, lying between the Canadian Rocky Mountains and the Plains in Alberta and British Columbia. The Foothills Belt is characterized by overthrust structures of great geometric variety, ranging from classic fault-bend folds on low-angle thrust faults in southern Alberta to detachment-fold dominated structures in NE British Columbia with all possible in-between types of structure found everywhere. See Price (1994) for a full treatment of the evolution of the Canadian Cordillera.

The stratigraphy of the Canadian Foothills can, at least for geophysical purposes, be crudely subdivided into two main units: carbonate-dominated Paleozoic rocks that were deposited on a shallow marine platform; and Mesozoic clastic rocks, mostly shales, deposited in a foreland basin that formed during the mountain building. Broadly speaking, carbonates have velocities in the 6000-6500 m/s range and clastics in the 4000-5000 m/s range. The basically simple two layer velocity structure is greatly complicated by the compressional tectonics of the Laramide episode.

We are fortunate in Western Canada because the kinds of lithologies and structures found underneath the Foothills are very well exposed in the adjacent Rocky Mountains, providing analogues that help us in our interpretation of subsurface geology. One classic locality is the McConnell Thrust on Mount Yamnuska, where Cambrian carbonates have been moved more than 35 km eastwards and upwards through most of the sedimentary section to lie on top of Upper Cretaceous shales and sandstones. The thrust fault itself is almost a knife-edge contact that ought to form a strong and coherent seismic reflector. A thrust fault similar to this, the Burnt Timber Fault, is present on the test line, transporting Paleozoic carbonates over Cretaceous clastics.

The fold-fault style of the Southern Alberta Foothills is mostly that of the classic ramp-flat or staircase geometry, where simple folds are formed as a geometric necessity over the steps in the fault plane. Generally, the flats occur in incompetent weak layers in the sedimentary pile, usually shales or coals, and the ramps form through the stronger, more competent units such as carbonates and sandstones. Simple fault-bend folds typically are broad, gentle structures with dip changes of around 20°: they are relatively easy to image on seismic data. Fault-bend folds can produce much more complicated structures where they are superimposed to form structures such as duplexes and antiformal stacks.

However, there is more to the structure of the Foothills than just this simple fold style. Structural complications occur in the footwalls of thrust sheets, as seen in the overturned syncline on Mount Allan. Hints of a syncline in the footwall of the Waiparous Thrust are seen on a depth migrated version of a line located a few kilometres south of the Benjamin example and it may be that there are un-imaged footwall synclines on the test line. Tight folds, often referred to as detachment folds, can also occur in the hanging walls of thrust sheets, as seen in exposed examples at Moose Mountain and Mount Kidd. Clearly, structures like these are going to be difficult or impossible to image on seismic data, but we have every reason to believe that they exist in the subsurface. In the Benjamin example, we have not yet been able to image the steep eastern limb, at Devonian levels, of the detachment fold drilled by the well in the middle of the section.

Basement is generally assumed to dip gently to the southwest under the Foothills. No major structures in the basement have ever been proven by drilling in the thrustbelt and most of the major basement time structures observed on seismic data are explicable in terms of velocity artifacts. Small basement structures are, however, sometimes seen in the Plains where we can confidently assume that there are no significant lateral velocity changes. Therefore, we cannot rule out the possibility that similar, maybe even larger, structures exist under the Foothills. Nevertheless, the burden of proof rests upon those who propose that such structures exist.

Exploration in the Foothills; the Benjamin prospect

Hydrocarbon exploration targets in the Foothills mainly consist of structural traps in Mississippian and Devonian carbonate rocks. Generally, gas is the main hydrocarbon found, although the oldest field in the area, Turner Valley, is an oilfield. Most of the obvious large structures have now been drilled and it is the task of the seismic specialists to locate the smaller and more complex features, often in areas of poor data quality. In just about every prospect we drill we are pushing the seismic tool to the limit of its capability.

The acquisition of seismic data in the Foothills involves major effort and expense. Nearly all operations are now heliportable, using a dynamite source. Costs range from Can$20,000 to $30,000 per kilometre. In an effort to minimize the environmental impact, the seismic cutlines are cut narrower and narrower: the lines we are cutting now are just wide enough to walk along. Trees and bushes are cut carefully to avoid disrupting the forest canopy, so that our seismic lines are nowadays barely visible, even from a helicopter flying directly above. This style of shooting has been called *stealth seismic*. We are able to acquire data over the most rugged topography and, in the worst cases, we have had to hire climbers to lay out our cable. The main limiting factor on data quality is the presence of exposed carbonate rocks at the surface: in these areas we get poor geophone coupling, little signal penetration and considerable amounts of source-generated noise. There are no exposed carbonates on the Benjamin line and the data quality is better than average.

Talisman and Husky shot their first data over the Benjamin prospect in 1991. The data were pre-stack time migrated and then interpreted. The Burnt Timber Thrust Sheet is well imaged, carrying a section of Cambrian and younger rocks over Cretaceous rocks. Several unsuccessful wells had already been drilled into the sheet but a small bump in the middle of the section had remained untouched. We drilled this structure as our first prospect. We interpreted this feature as a transported fault-propagation fold, but we found upon drilling that the rocks in the footwall of the minor thrust cutting the fold were folded into a syncline, forcing us to revise our interpretation to a faulted and transported detachment fold. Gas was discovered in this well, which is currently on production at a rate of 20 million cubic feet a day. Talisman later sold its share of the field to Husky. Subsequently, Husky went on to drill a well a few kilometres to the east to test the leading edge of the thrust sheet. The first attempt just missed the cut-off of the Mississippian and the well was plugged back and directionally drilled. The whipstock found the leading edge but was unable to test any commercial quantities of gas due to a lack of permeability in the reservoir.

Husky's approach to seismic imaging; p-wave anisotropy

At Husky, our routine approach to seismic imaging in the Foothills is to perform pre-stack time migration. We find that the imaged geometry of structures is very sensitive to small variations (less than 5%) in the velocity field. We generally try to pick the velocities that give the best image without worrying too much about the absolute values of the velocities. We are fully aware that time-based migrations do not work in theory where there are lateral velocity variations but we feel that we can partially compensate for these effects by using unrealistic velocities in a time migration, forcing a good image out of the data. Thus, even though time migration should not work well in theory, we find that it usually works sufficiently well for us in practice. We convert our time interpretations to depth using inverse image ray modelling, realizing that this too sometimes violates theory, but finding that in practice this exercise moves our events closer to their correct positions.

Our experience with depth migration is different. We are convinced that the process works in theory so we keep trying it, however, we normally cannot get it to work well for us in practice. To date, we have never made an exploration decision based on the results of a depth migration. The problem is that when we use geologically reasonable velocities, the resulting image is usually very poor. When we vary the velocities to improve the image, we occasionally, after much labour, achieve results comparable to a good time-migrated section, but the depths are all wrong and we find that we have learned little from the process and often wonder why we bothered.

Recently, we have started to become aware that one reason our efforts are failing is that we have neglected to consider p-wave anisotropy. More than half of the section in the Foothills belt is composed of shales. Recent experimental work by Johnston and Christensen (1995) has shown that bedding-parallel velocities in shales are 20-30% faster than bedding-perpendicular velocities. So far, however, none of this kind of work has been done on shales from the Alberta Foothills.

Simple modelling calculations done on a single homogeneous, but anisotropic (30%, anelliptic), flat-lying shale layer that show that NMO velocities calculated for the base of the layer can vary by as much as 20% compared to the actual, vertical depthing velocities. The velocities are offset-dependent. These results are consistent with our experience in depth migrating real data where we typically need to use higher velocities to image our data than we would measure from VSP's or sonic logs. This effect produces calculated depths that are erroneously large under shale sections: the same kind of effect was recognized in the North Sea more than ten years ago (Banik, 1984). Just south of the Benjamin line, another section that we have depth migrated using unconstrained tomography contains an apparent depth structure on its west side. This could be caused by a thinner section of shale being present there, pushing the deep events down less than on the east side of the line.

We find in practice that variations as small as 1% in the velocities can produce significant variations in the depth-migrated image. Modelling work by Sayers (1995) has shown that anisotropic effects are difficult to distinguish from effects introduced by velocity inhomogeneities. We suspect that tomographic approaches to depth migration probably compensate for anisotropic effects by inserting spurious inhomogeneities into the velocity field in a manner analogous to the way that we compensate for lateral velocity changes by using unrealistic velocities in time migrations.

Shales in thrust belts are not always horizontal: in the Foothills, we have recognized some pull-up anomalies that we think may be caused solely by dipping shales. As far as we know, there have been no studies done on the effect that dipping, anelliptically anisotropic rocks would have on velocity analysis and depth imaging. Given all these complications, it is hardly surprising that we encounter difficulties in the practical application of pre-stack depth migration when we neglect anisotropy, particularly if we look hard at the predicted depths and velocity distributions.

However, we are well aware of the practical difficulties involved in incorporating anisotropy in any pre-stack depth migration routine and we accept that it may be several years before this goal is achieved. It is our view that, until then, the main value of a depth migration is in the improved images that it might provide, yielding a more interpretable section and thus more geological information. Placing the features in correct absolute depths and positions is an important but secondary goal that can be approached by other means, such as seismic modelling and regional geological control.

Acknowledgments

I am grateful to many of my colleagues at Husky who have contributed a great deal to the thoughts expressed here: Lindsey Brady, Vince Cuschieri, Kel Johnston, Carol Laws, Larry Mewhort, Bill Rennie and Hugh Wishart. Christof Stork originally proposed this project and he is also to be commended for his efforts in organizing the workshop session. I thank the managements of Husky Oil Operations and Talisman Energy for giving permission for this data set to be released.

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Johnston, J.E. and Christensen, N.I. 1995. Seismic anisotropy of shales. *Journal of Geophysical Research*, **100**, 5991-6003.

Price, R.A. 1994. Cordilleran tectonics and the evolution of the Western Canada Sedimentary Basin. *In: Geological Atlas of the Western Canada Sedimentary Basin*. G.D. Mossop and I Shetsen (compilers). Calgary, Canadian Society of Petroleum Geologists, Alberta Research Council, 13-24.

Sayers, C.M. 1995. Anisotropic velocity analysis. *Geophysical Prospecting*, **43**, 541-568.

List of Workshop Posters:

Poster #1) Andy Skuce, Husky Oil Operations

2) Hugh Geiger, University of Calgary

3) Fred Kierulf & Florian Romanescu, Paradigm Geophysical

4) Larry Lines Memorial, University of Newfoundland

5) Wen-Jing Wu, Geo-X Systems Ltd.

6) Ron Schmid, Kelman Seismic Processing

7) Linda Worthy, CogniSeis Development Crop

8) Ray Dillahunty, GX Technology

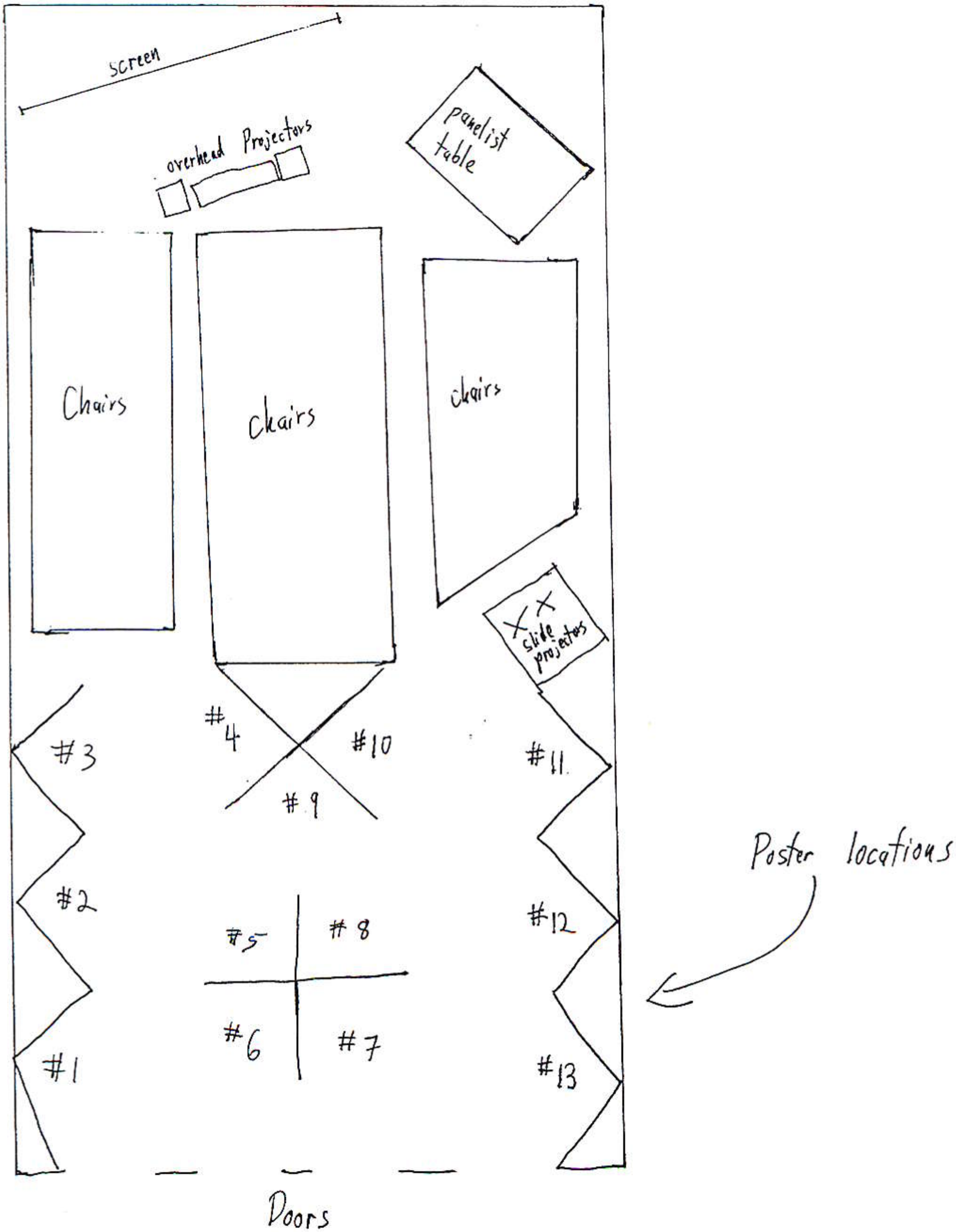
9) Dr. Vladimir B Pissetski, Ural Mining Institute

10) Christof Stork, Advance Geophysical

11) Craig Limbaugh, Advanced Data Solutions

12) Sami Kurdy, Integra GeoServices

Workshop #6 Floor LayouT



Equivalent offset Prestack Migration for Rugged Topography

John C. Bancroft and Hugh D. Geiger

Department of Geology and Geophysics, The University of Calgary, Calgary, Alberta, Canada

Equivalent offset prestack migration is a new migration technique that simplifies the process into the three steps of trace gathering, normal moveout, and stacking. This method has many advantages that range from reduced processing times, to accurate velocity analysis. The process has been modified to include processing from rugged topographies.

Traditional processing by stacking and post-stack migration is founded on flat reflectors, and common midpoint (CMP) position. The incorporation of dip moveout (DMO) into the processing sequence has improved the focusing of dipping events in areas with moderately complex structure. Prestack migration removes the CMP flat reflector restriction by assuming the energy is scattered from organized point reflectors (or scatter points), allowing each input trace to reconstruct energy directly at the scatter position.. Kirchhoff prestack time migration is bases on hyperbolic moveout and RMS velocities to form a migrated time section that represents a vertical array of scatter points. The data is approximately aligned on image rays traced on a depth section.

Equivalent offset prestack migration creates an intermediate step in the Kirchhoff process by creating a gather from all the input traces for each output trace. The input traces that are gathered for a given output location are sorted by an offset that is based on the distances of the scatter point from the source and receiver locations. The collection of input traces is referred to as the common scatter point (CSP) gather, and is similar in function to the common mid point (CMP) gather. Both are defined for an output location, and both contain input traces that are sorted with offset. However, the CSP gather contains many more traces than the CMP gather. The CMP gather only contains traces in which the source and receiver are equidistant and in opposite directions from the CMP location. In contrast, the CSP gather contains energy from *all* the input traces within the prestack migration aperture.

There is no time shifting of the input samples when they are sorted into the CSP gathers. Figure 1 illustrates the difference between a CMP and a CSP gather in a prestack volume. The figure has dimensions of CMP or CSP trace position, time t, and half source-receiver offset. The black dots on the top surface represent the position of traces similar to a stacking chart. The traces come from one sided source records with the source located at the zero offset position on the front surface. Source records are spaced at four CMP position intervals. The shaded area defines a CMP or a CSP gather. Note that only three live traces fall within the CMP gather. In contrast, the CSP gather will include all the neighboring traces. Circular lines on the top of the volume represent the possible paths of some neighboring traces as they are copied to the CSP gather. The particular offset assigned to the samples in the neighboring traces is referred to as the *equivalent offset*.

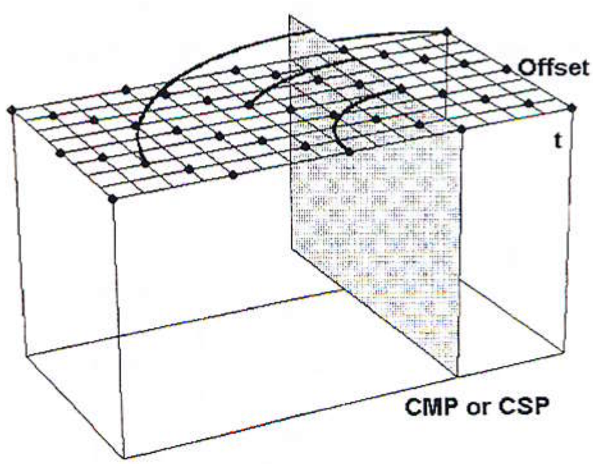


Fig.1 Formation of CMP and CSP gathers.

When the CSP gathers have been formed, each CSP gather may be scaled and filtered, or processed similarly to CMP gathers. Conventional algorithms such as noise and multiple removal, or velocity analysis, may also be used on the CSP gathers. Velocity analysis performed on the CSP gather will contain a more accurate velocity discrimination than those derived from NMO gathers. The improved discrimination results from using only one CSP gather, the high fold in the offset bins within the CSP gather, and offsets that are much larger than the source-receiver offset. Noise and multiples in the CSP gather now apply to the final prestack migration offsets, and not the offsets of CMP gathers in conventional processing.

Rugged topography requires the selection of a processing datum that may be either horizontal or follow the surface elevation. The equivalent offset is found by equating the travel times of a zero offset on the datum with the source-receiver travel time, as illustrated in figure 2.

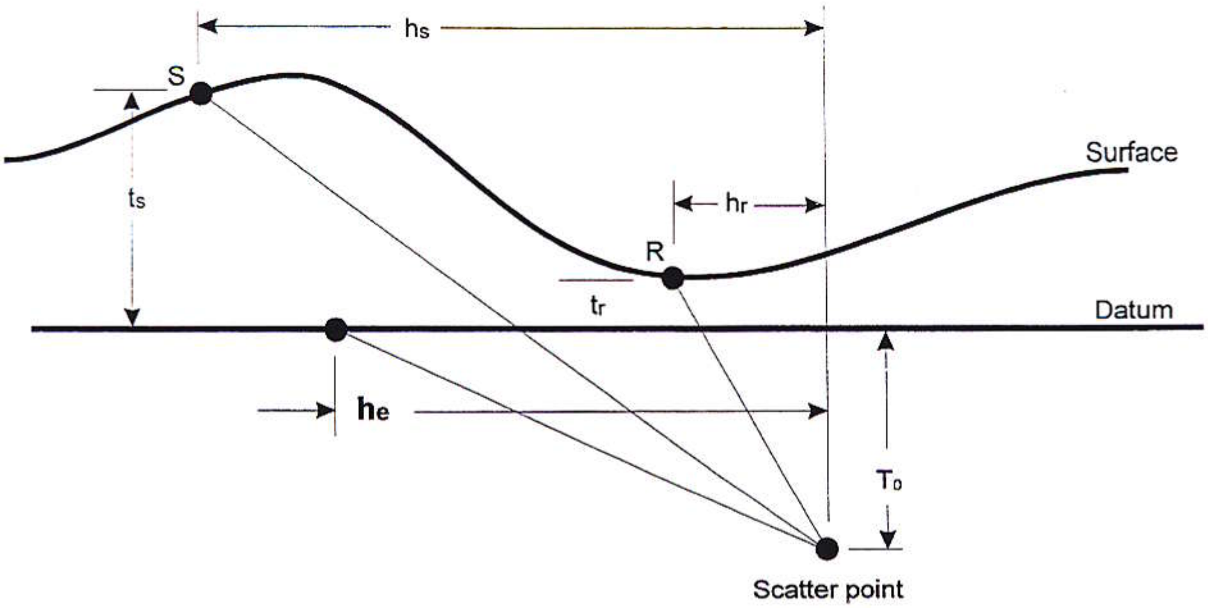


Figure 2. Ray paths, offsets, and travel times for computing the equivalent offset with rugged topography.

The total travel times for the three ray paths are computed using the appropriate offset, zero offset time, and velocity. The RMS velocity is defined from datum to the scatter point V_{sc}, and is modified to the surface for each source V_{srs} and receiver V_{rec} using Dix forum. The following equation uses one-way travel times for T_0 to equate the equivalent offset time with the total source receiver travel time T giving,

$$T = \left((T_0 + t_s)^2 + \frac{h_s^2}{V_{srs}^2(T_0 + t_s)} \right)^{1/2} + \left((T_0 + t_r)^2 + \frac{h_r^2}{V_{rec}^2(T_0 + t_r)} \right)^{1/2} = 2\left(T_0^2 + \frac{h_e^2}{V_{sc}^2(T_0)} \right)^{1/2},$$

where t_s and t_r are the vertical travel times from source and receiver to the datum, and the offset h_s and h_r are the distances from the source and receiver to the common scatter point CSP.
The equivalent offset h_e may be computed from

$$h_e = V_{sc}(T_0)\left(\frac{T^2}{4} - T_0^2 \right)^{1/2}$$

where the total travel time T is computed for a given T_0.

The presentation will include examples of equivalent offset migration using data corrected to a horizontal datum, and data migrated from surface, corrected for refraction statics only.

POSTER # 3

AN EXAMPLE OF HOW PRE-STACK DEPTH MIGRATION CAN SHOW YOU THAT YOUR GEOLOGICAL CONCEPTS MAY BE WRONG

Florian Romanescu, Fred Kierulf & Brian Burgess of Paradigm Geophysical Corporation

We feel that it is important to consider the zone of interest during any complex structure imaging project and to understand the objective of the project. To that end we concentrated on the leading edge of the thrusted Mississippian sheet that was drilled by wells A, B and C.

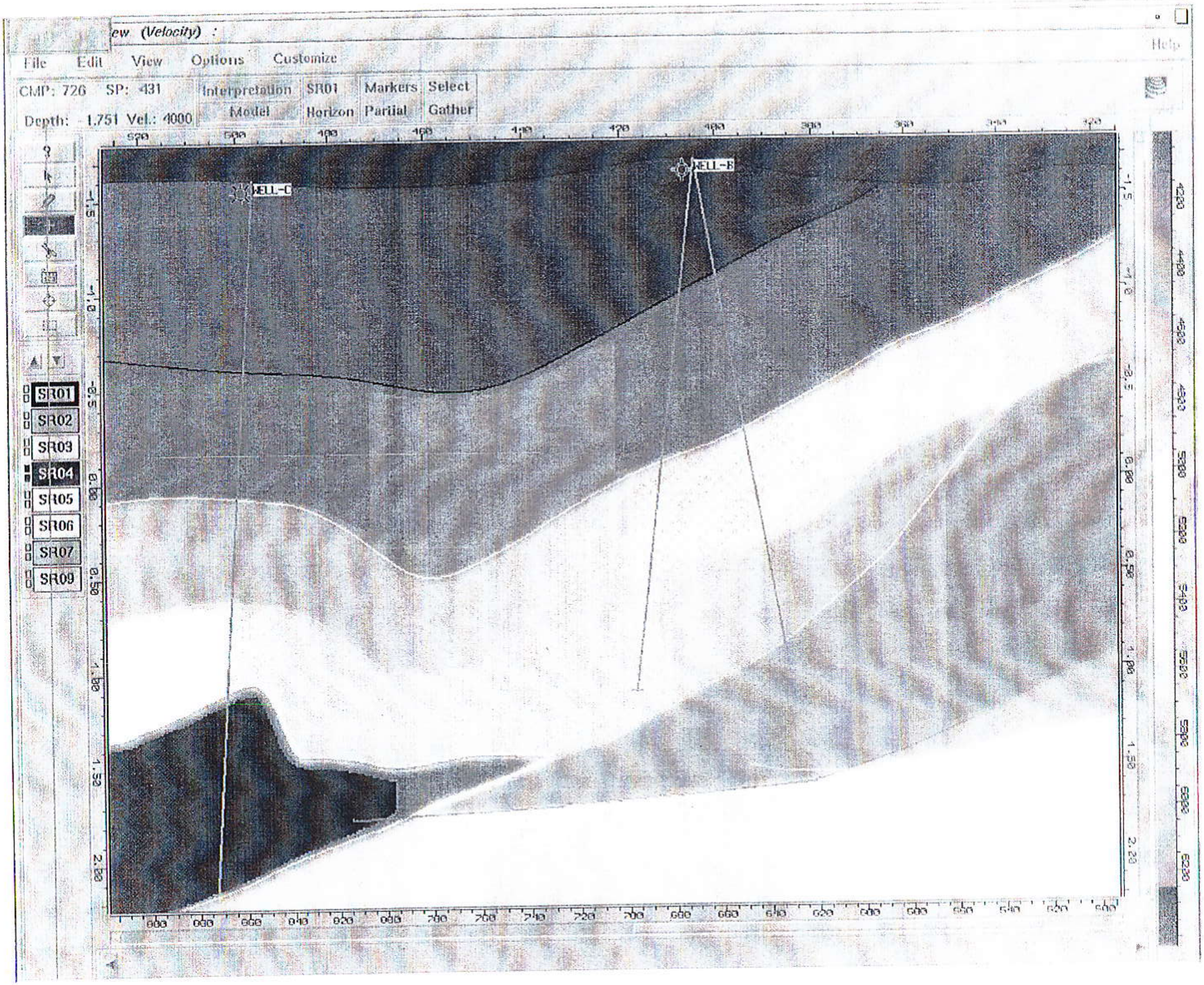
We show that wells A & B were drilled too far east on the sheet to penetrate a full section of the reservoir zone and that using modern velocity analysis and imaging tools we can influence the interpretation leading to better positioned wells.

Two key points we learned using these data are; first that longer offset records will assist with velocity analysis on deeper basement reflections and; second that a scheme needs to be developed to easily adjust the imaging velocity field for gross anisotropic corrections in order to tie well depths.

Our route to pre-stack imaging and model building began with time domain stacks and migrations using horizon keyed velocity analysis tools. Assigning interval velocities from the wells to the layers interpreted on a time migrated image and ray trace modeling the layers into the depth domain gave us our initial depth model. This is a common starting point for pre-stack depth imaging in our experience. The initial pre-stack depth migration to gathers was done using this constant layer velocity model. We then interpreted pre-stack residual depth corrections (delays). These delays were used by a tomographic matrix solver to calculate changes to the horizon depths and the layer velocities that minimize the delays.

The changes we found most intriguing were that the Mississippian unit at the leading edge of the structure creates positive depth delays that require a slower interval velocity in the unit to correct for. This suggests that there is less carbonate than initially interpreted at the leading edge. The figure shows the final velocity model over the leading edge units.

The pre-stack depth image is similar to that generated through pre-stack time migration but the information regarding slower interval velocities in the zone of interest layer comes through integrated analysis of depth migrated gathers and the interval velocity model. These changes can be used by interpreters to evaluate possible geological changes to their initial structural interpretation and better assess the risks of penetrating what they expect to drill.



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SR07
SR09
WELL-C
WELL-B

Prestack Depth Migration of an Alberta Foothills Data Set - The Husky Experience

by Wen-Jing Wu*, Larry Lines, Andrew Burton, Han-Xing Lu, William Jamison, Jinming Zhu, R. Phillip Bording; Memorial University of Newfoundland

Summary

We produce depth images for an Alberta foothills line by using a number of migration and velocity analysis techniques. Velocity models are estimated by a series of interpretive steps involving focusing analysis, common image gather analysis, traveltime tomography, and structural reinterpretation (using well information). We use both Kirchhoff and reverse-time prestack depth migration methods with the source and receiver at their correct surface elevations. Thus far, our preferred seismic depth section has been produced by using a pre-stack reverse-time migration algorithm developed by Wu et al. (1995).

Introduction

In recent years, industrial research institutions have participated in prestack migration contests for the Marmousi data, a synthetic data set designed at the Institut Francais du Petrole (Versteeg, 1994). Today we are pursuing similar experiments for structurally complex Alberta foothills data, using a seismic line provided by Larry Mewhort (Husky Oil) and Christof Stork (Advance Geophysical). This abstract summarizes the results obtained by the Memorial University Seismic Imaging Consortium.

Methodology

Velocity analysis coupled with prestack depth migration is generally an iterative procedure in which one constantly attempts to improve the focusing and consistency of the prestack depth migration. The common image gathers in the depth domain should show no dependence on offset if the correct velocity model is used. Hopefully, the velocity model and depth image also agree with available well information. The velocity model construction is based on a structural interpretation of this thrust-fault environment. In this iterative procedure, we started with post-stack depth migration for an initial model based on well velocity data. This step was followed by velocity model adjustments (structural re-interpretations) and pre-stack depth migrations.

Results

Initial migrations on stacked data produced results which were credible at depth yet showed significant image blurring of the shallow steeply dipping reflectors. This observation showed that it is preferable to use the sources and receivers at their correct topographic locations in a prestack migration algorithm. Iterative alteration of velocities coupled with prestack migrations added detail to the thrust faulting in our model. Both Kirchhoff and reverse-time algorithms were used in pre-stack depth migration. At this stage, our preferred depth migration is one obtained by reverse-time migration in Figure 1. The results also show that the reverse-time migration algorithms are quite robust and generally less sensitive than other methods to errors in the velocity model.

Conclusions

Our conclusions from the study thus far are two-fold. Pre-stack depth migration with correct source-receiver elevations is preferable over post-stack migration in areas of large elevation change. In using pre-stack migration on foothills data, velocity model adjustments should be done in an interpretive setting with several tools.

References

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Wu, W., Lines, L., Lu, H., 1995, Reverse-time migration with finite-difference solutions of the acoustic wave equation: extended abstract for 1995 annual SEG meeting in Houston, Tx.

*present address: Geo-X Systems Ltd., Calgary, Alberta, Canada.

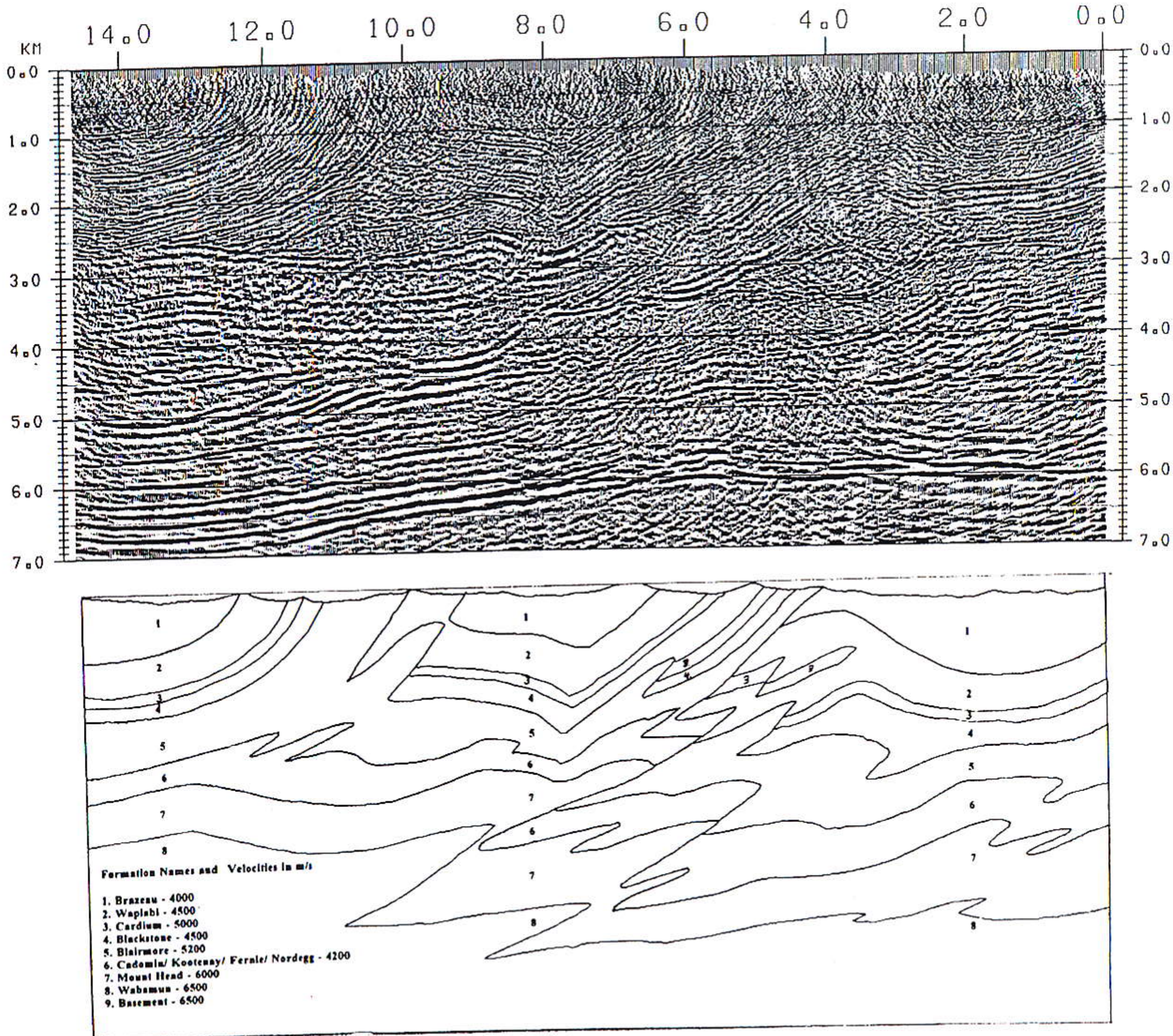

Figure 1. Prestack reverse-time depth migration (top) with updated velocity model (bottom).

USE OF MODEL BASED NMO WITH PRESTACK DEPTH MIGRATION - FOOTHILLS EXAMPLE (BENJAMIN)

SUMMARY

This paper concentrates on methods used to refine the velocity depth model between iterations of depth migration. We have chosen to exploit the technique of model based normal moveout. We feel this method meets the necessary requirements demanded of any updating procedure. Specifically, it addresses the issues of non-hyperbolicity, provides measures to indicate locations of velocity errors, and estimates of the magnitude of the velocity errors. Furthermore, confirmation that the correct model adjustments have been made is readily available. The method is fast, allowing for interactive visualization of the results. The consequence of this procedure is that fewer iterations of full prestack depth migration are required while ensuring that all reasonable geologic interpretations have been evaluated.

INTRODUCTION

Efforts to image seismic data under extreme lateral velocity variations have often lead to frustration. 2D prestack depth migration can generate the correct image (to the extent that the data is actually 2D i.e. no off-line reflected energy) if the detailed velocity field is provided. Processors have resorted to various techniques to correct for the delay time distortions that are not predicted by conventional NMO. Layer stripping works well on synthetic data, however on real data it suffers from accumulated errors due to an inability to accurately define layers above the zone of interest. Another approach is to use a tomographic depth model updating algorithm. This can be useful, however, small errors in picking residual moveout cause a large error in the velocity estimation. This problem becomes more serious as one moves deeper in the seismic section. The solutions are non-unique and must be carefully constrained by an interpreter's information. We begin by a review of model based NMO and examine its benefits over conventional NMO routines. Subsequently, we describe the position of model based NMO in the processing flow and conditions where it is expected to give useful results. Finally, results of the procedure are shown.

Conventional NMO Vs Model Based NMO

It is well known that non-hyperbolic moveout is induced when there are strong lateral variations in velocity. Non-hyperbolic moveout is also introduced by large rapid changes in surface topography. These have been the bane of traditional velocity estimation techniques. Model based NMO differs from conventional NMO in two fundamental ways.

1) It recognizes the fact that surface elevations and weathering layer variations result in non-hyperbolic NMO delay times and corrects for those affects.
2) It does not assume that the same stacking velocity for all traces within the CMP. Non-hyperbolic NMO caused by lateral velocity variations is corrected by sampling the depth model from the shot point to midpoint to receiver point.

Model based NMO is similar to conventional NMO in that it does sample the depth model using straight rays. It also calculates the curved raypath travel times using a Dix type formula which assumes locally flat layering. It shares the fundamental assumption that the reflection point is midpoint. This implies that the most useful imaging results are obtained from generally flat layers.

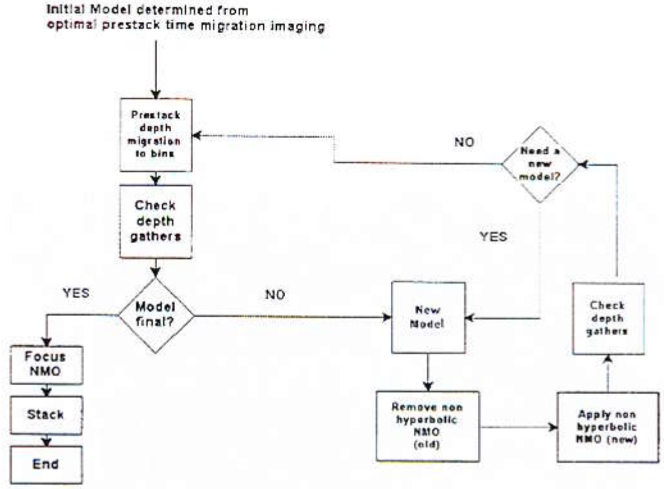

Figure 1: Position of model based NMO in the processing flow

Position of Model Based NMO in the Processing Flow

Figure 1. illustrates the use of model based NMO in a typical processing flow. The starting point is an analysis of the best time migration available. This is usually a prestack time migrated section. If the image test of using geologic velocities fails to image a particular zone of interest, then depth migration to offset bins is required. The layer boundary positions from the time processing and assignment of best guess interval velocities comprise the initial starting model for depth migration. Prestack depth migration is performed and the resultant depth gathers are analyzed to assess the consistency of events within the CRP. If the model is deemed to be final, then focusing NMO velocities can be used to fine tune the image prior to final stack. If the consistency of the events is less than desired, then a new model can be derived by the following procedure.

First the non-hyperbolic NMO associated with the old model is removed. Then non-hyperbolic NMO associated with a newly proposed model is applied. A new set of depth gathers and resultant stacked section can be re-evaluated. Any number of model hypothesis can be assessed. The technique is effective and fast - especially when used with interactive tools, since after all we are only performing an NMO correction. Note that our model updating criteria is one that stresses the observation of the real data image response as opposed to the observation of generated model horizon. This technique requires intensive interpretative input to guide and constrain the model development. During the model updating procedure, there will be a point when no further improvements can be made to the depth image. At this time another iteration of depth migration is performed.

Real Data Example

This real dataset was chosen because it has the features typically encountered in the Western Canadian foothills environment. These features are:

1). Generally flat layers beneath complex faulting and folding that results extreme lateral velocity variations.

2). Thrusting of older carbonate sections into the younger clastic section.

3). Extreme surface elevation and weathering layer changes that complicate the near surface model.

As the migration/model updating procedure continued, imaging clues revealed new structural details which were enhanced with subsequent model changes.

CONCLUSIONS

While working through the procedures outlined above, the interpreter was simultaneously processing and interpreting the dataset. They were able to test a wide range of geological hypothesis quickly and inexpensively. They also gained an understanding on the sensitivity of the data to each model assumption. In these datasets, model based NMO was successfully used to update the velocity model between iterations of depth migration. The process emphasized the importance of studying the depth migrated image. A logical question to ask at this point is "Will it work in 3D?" As yet we have not completed the development of a 3D version of this tool. We are however, optimistic of its potential.

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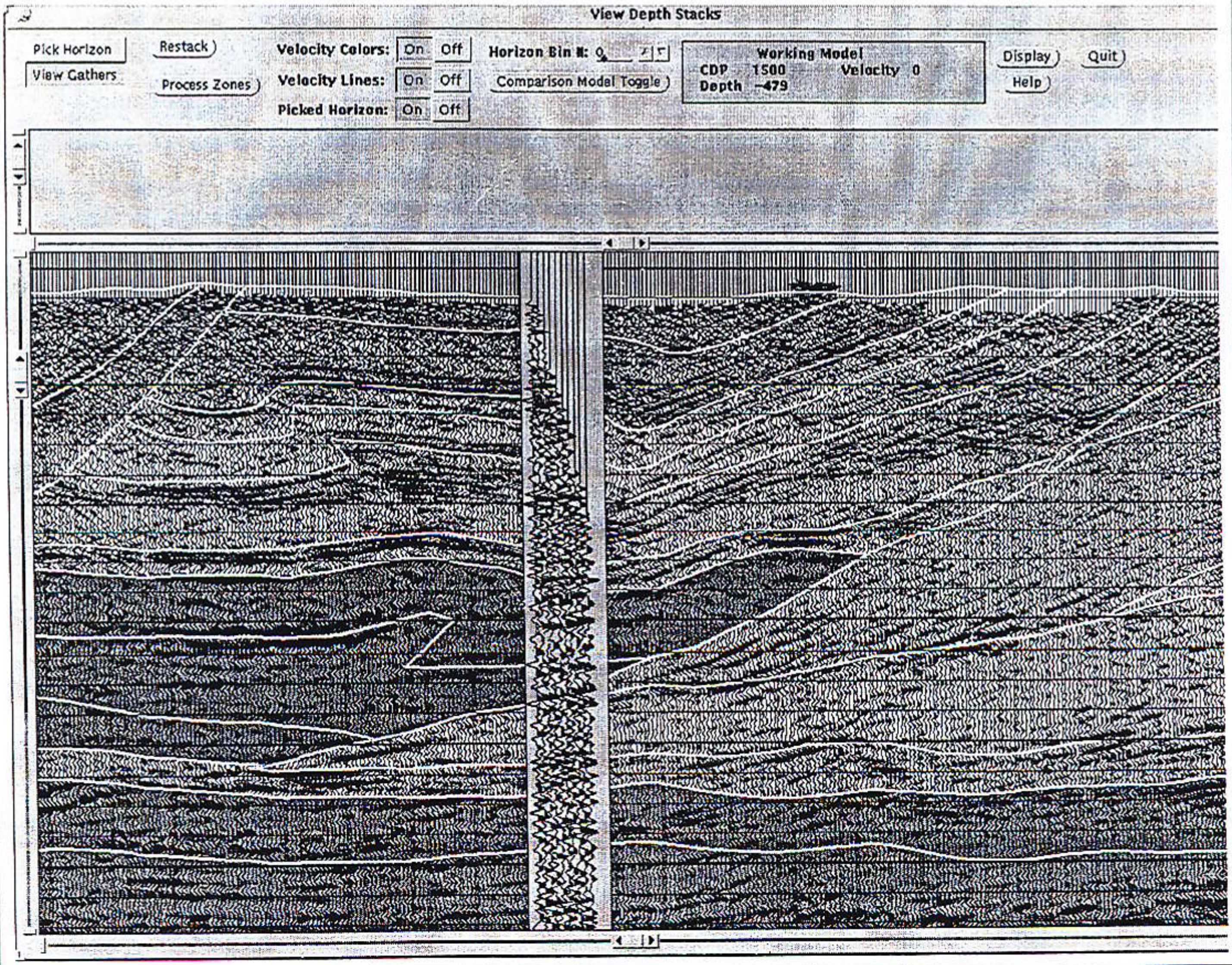
Figure 2: Model based migration velocity analysis - Benjamin Example



Prestack Depth Migration and Structural Restoration of the Benjamin Creek Dataset

CogniSeis, Houston, Texas

Structural geometries of velocity depth models used for seismic depth migration should be consistent with the structural formations of the geology. We use the constant velocity half space method to simultaneously estimate the velocity model and generate the prestack depth migrated image (Figure 1). Common image gathers constructed from depth migrated shot records were used to determine the migration interval velocities. The structural geometry of the model was tested for kinematic validity using geologic restoration and balancing.

Velocity depth model development proceeded recursively, with layer stripping following the main geological units (Figure 2). Velocity gradients were used, where appropriate. Image gather event alignment was used to check the velocity of the overburden as the model was developed.

Production processing sequences containing shot preprocessing and shot record migration were parallelized on a multi-cpu shared memory SGI Power Challenge to accelerate the iterative process of migration velocity analysis, prestack seismic imaging, and velocity model updating. A systems approach to parallelization was used to automatically partition job flow sequences into parallel and sequential segments. With this procedure, prestack migrations for the entire seismic profile could be generated in about 1/2 hour on a 12 cpu Power Challenge.

Fault prediction algorithms and forward geologic modeling were used to constrain the final velocity depth model. Regional detachment levels were used as a guide in checking the structural development of the restorations. Restoration and balancing of the model produced a late stage out of sequence fault as well as a normal fault (Figure 3). The late stage out of sequence faults are of interest because they are associated with intense fracturing and with production decisions. Restoration results encourage future work in iterating the restoration and velocity model building process.

PreStack Depth Migration

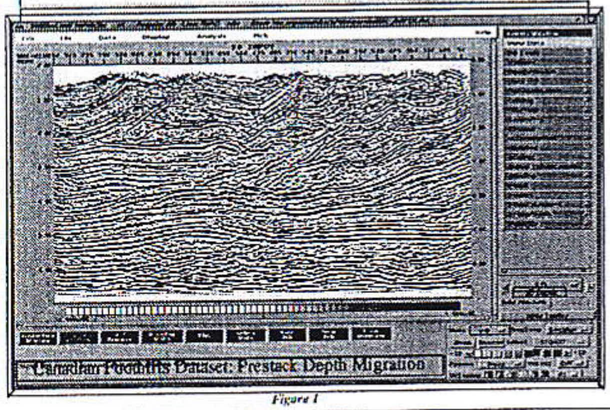


Figure 1

Velocity Depth Model

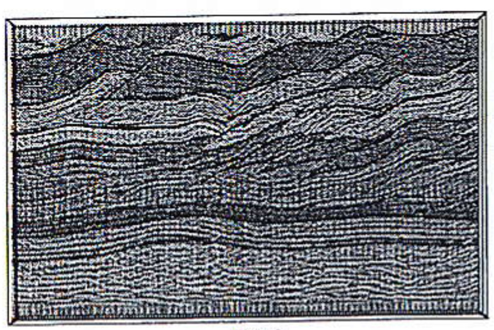


Figure 2

Geologic Restoration

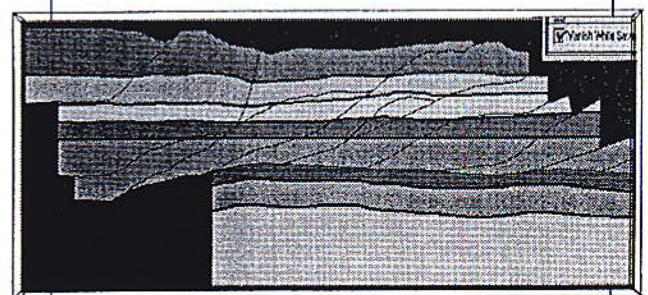
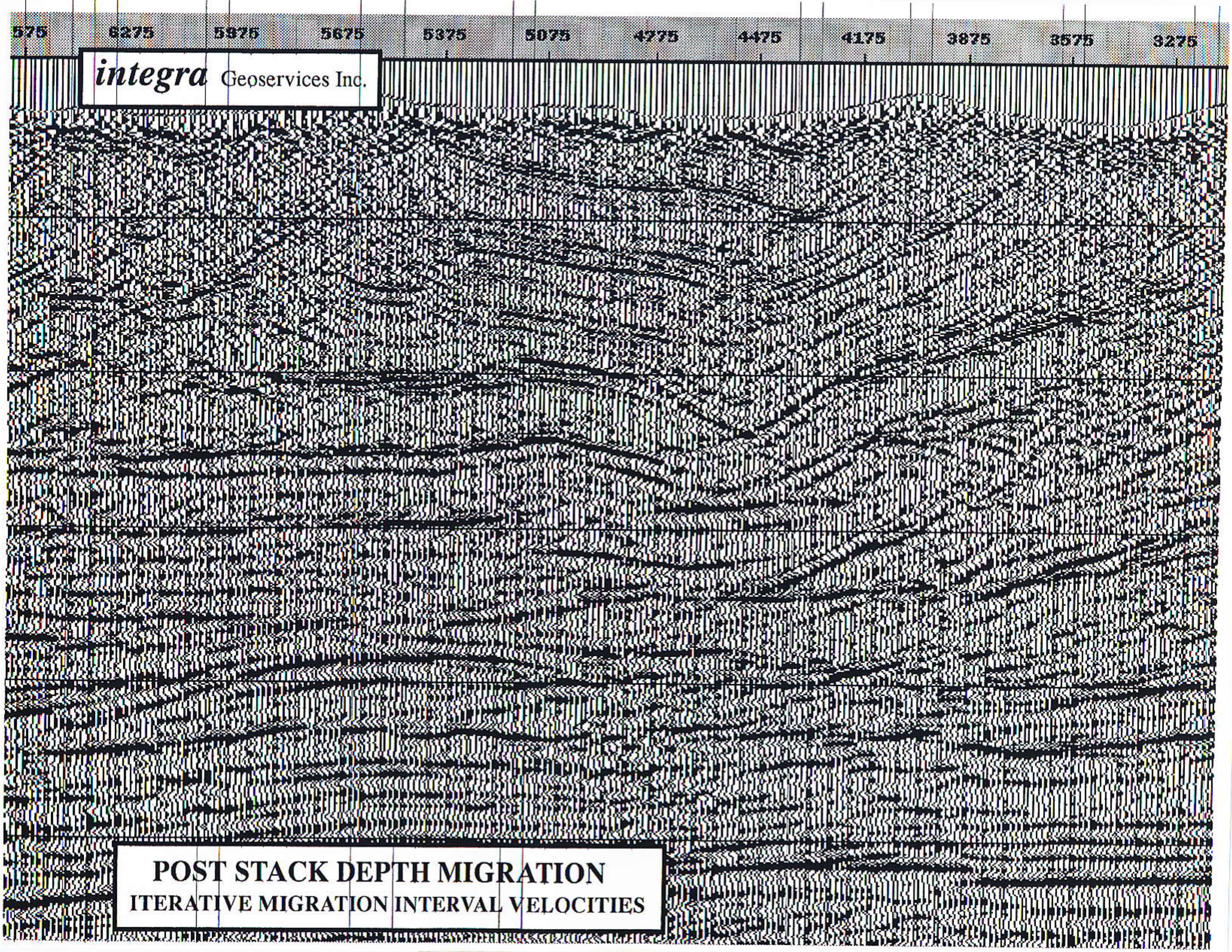


Figure 3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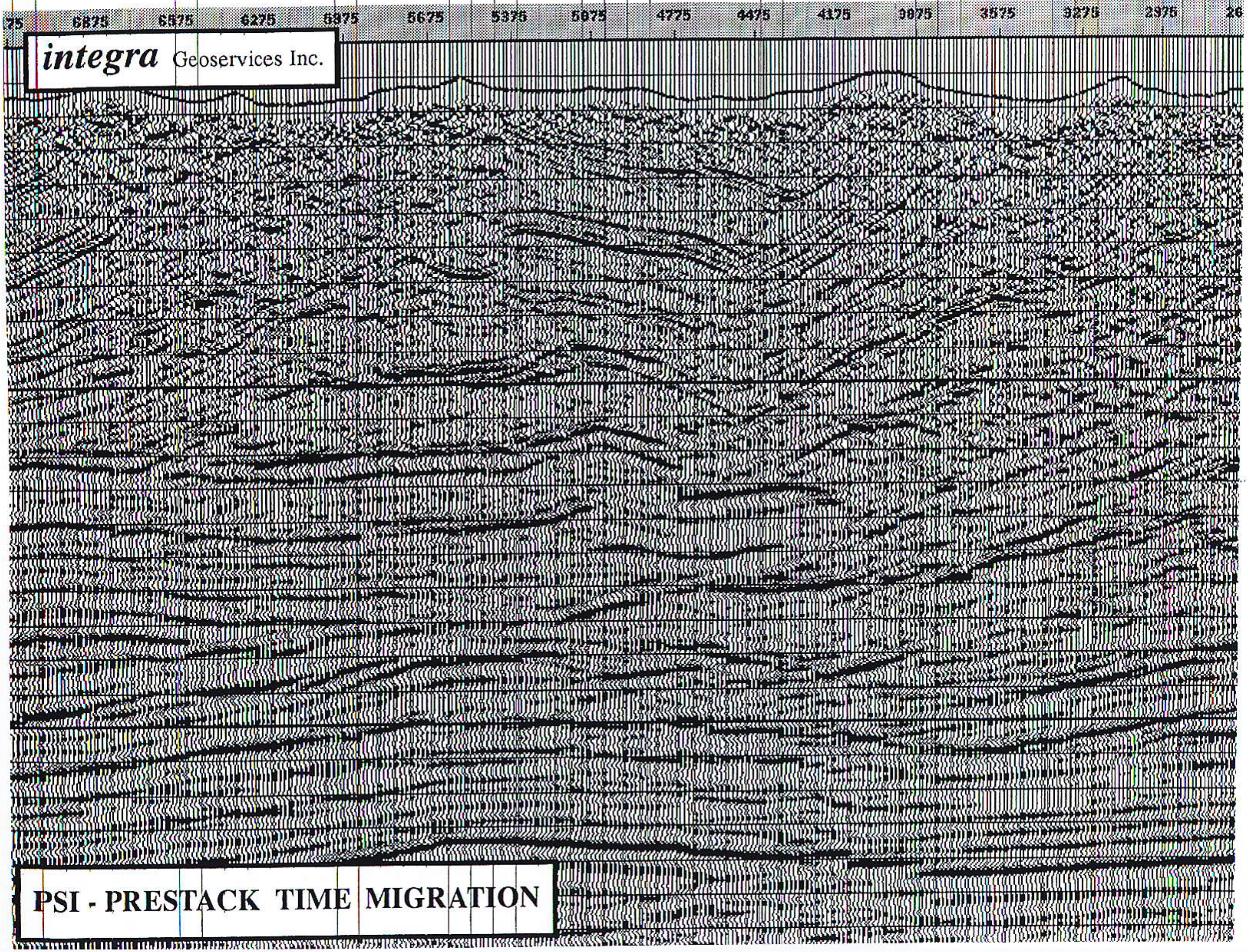
POST STACK DEPTH MIGRATION
ITERATIVE MIGRATION INTERVAL VELOCITIES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integra Geoservices Inc.
PSI - PRESTACK TIME MIGRATION

Poster #10, Christof Stork & Buzz Davis, Advance Geophysical

The technique of MVA tomography with a flexible model definition is well suited to interval velocity analysis on this data. MVA Tomograpy is a global inverse method produces velocity models consistent with the pre-stack data from the top of the model down to the bottom. We measure consistency by the flatness of events on CRP gathers.

A flexible velocity model definition aids the velocity model building process of this data because although this data has many events, they don't clearly delineate the geologic units. Numerous horizons occur within geologic units and sometimes they don't occur at geologic unit boundaries such as faults. One doesn't want to limit the development of a velocity model by an a priori specification of geologic shape that may be wrong. One doesn't want to be limited to using horizons on the edge of geologic units.

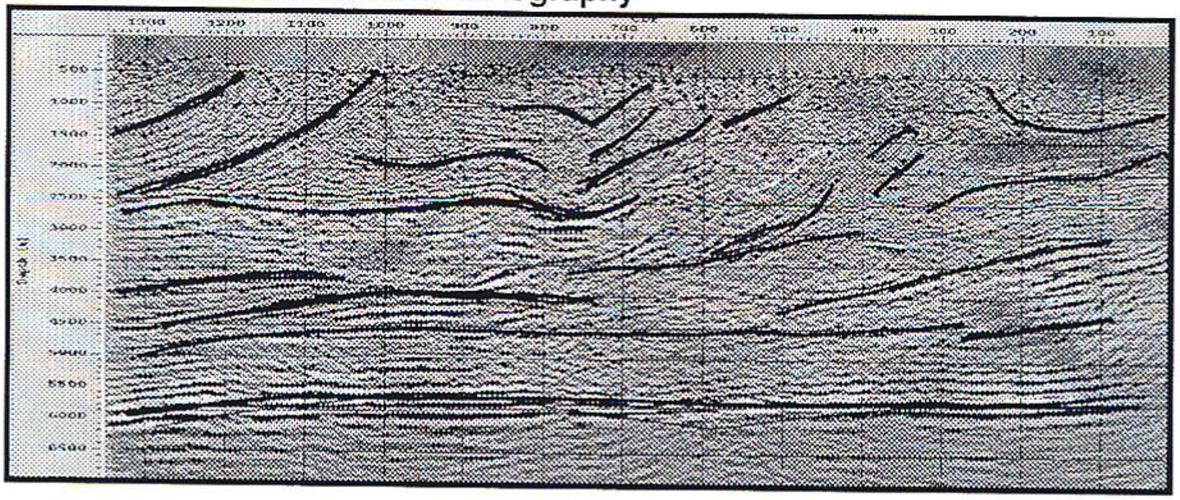
Despite the fairly good signal quality and the abundance of reflectors in this data, it is probably impossible to find a "correct" interval velocity model using the seismic data alone. Numerous velocity models, some significantly different, can be consistent with the pre-stack data as indicated by flat events on the CRP gathers.

The best velocity model must be determined by the judgement of an interpreter and the available geologic information. A key approach to making a judgement on the best model or a range of acceptable models is to produce numerous solutions that are consistent with the pre-stack data and geologic information yet differ in some significant manner. To interpret, you want to see the possibilities! Providing mechanisms for the interpreter to easily steer the generation of models in MVA Tomography lets him explore the solution space and make his judgement.

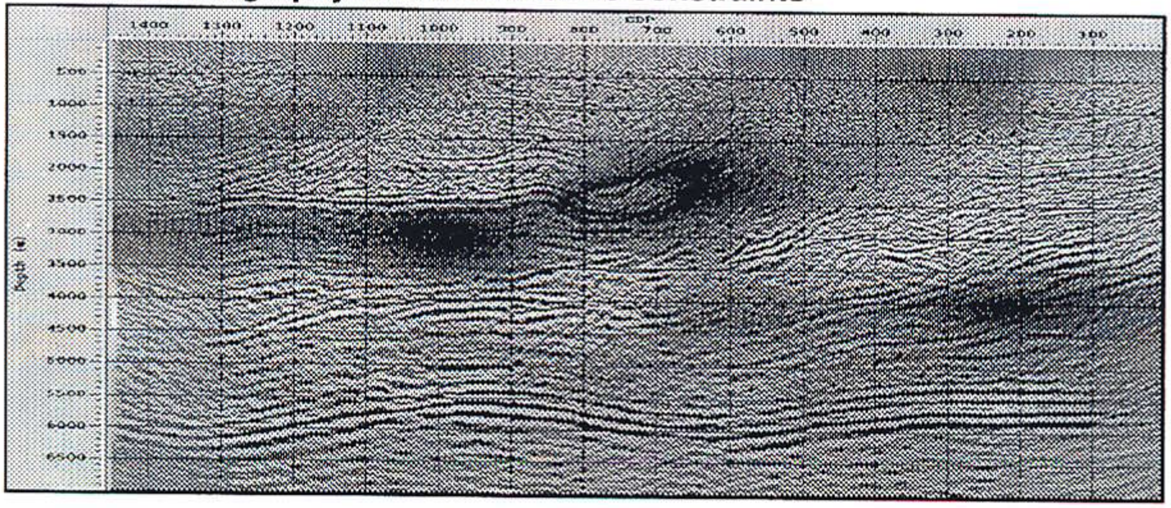
Velocity and reflector constraints are one such mechanism for steering the generation of velocity models. Velocity constraints limit velocity variations by general smoothing, to create geologic units where they can be interpreted with confidence, or to disallow velocity variations that a clearly unlikely.

Reflector constraints allow the interpreter to design a velocity model that will produce a desired reflector shape on migration. While this capability is open to abuse by a disreputable interpreter, when the structure on a time section is clearly wrong, as is the case with the basement reflector of this dataset, this constraint provides a key control for exploring possible velocity models. In this case, it appears that the constraint to make the basement reflector flat has helped produce a reasonable velocity field.

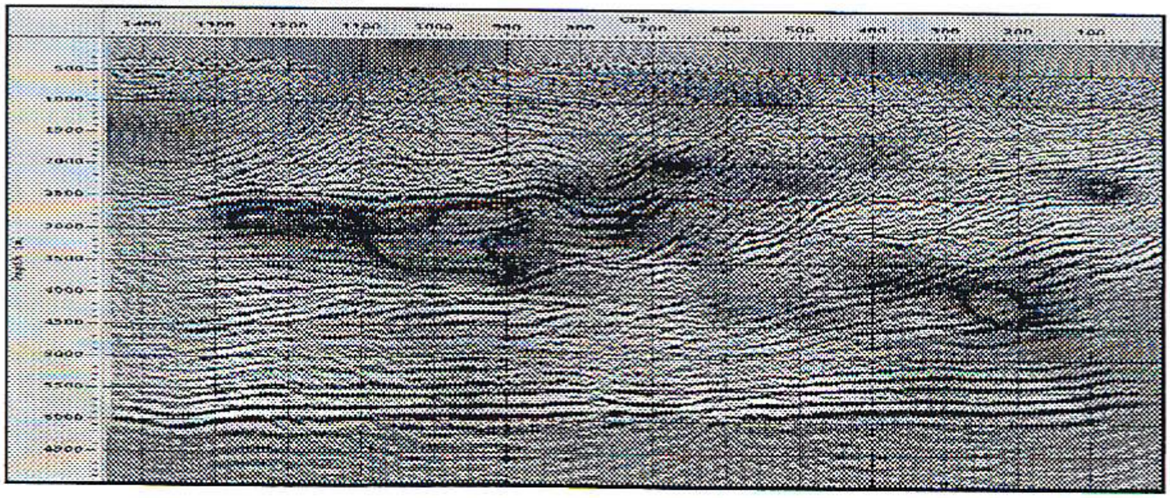
Horizons used for MVA Tomography



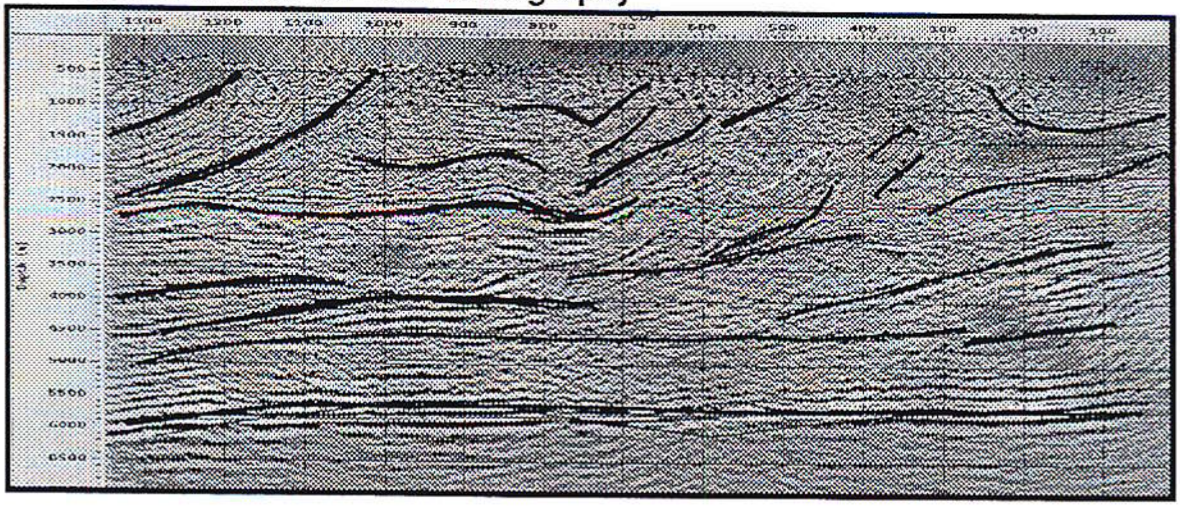
MVA Tomography Inversion with no constraints



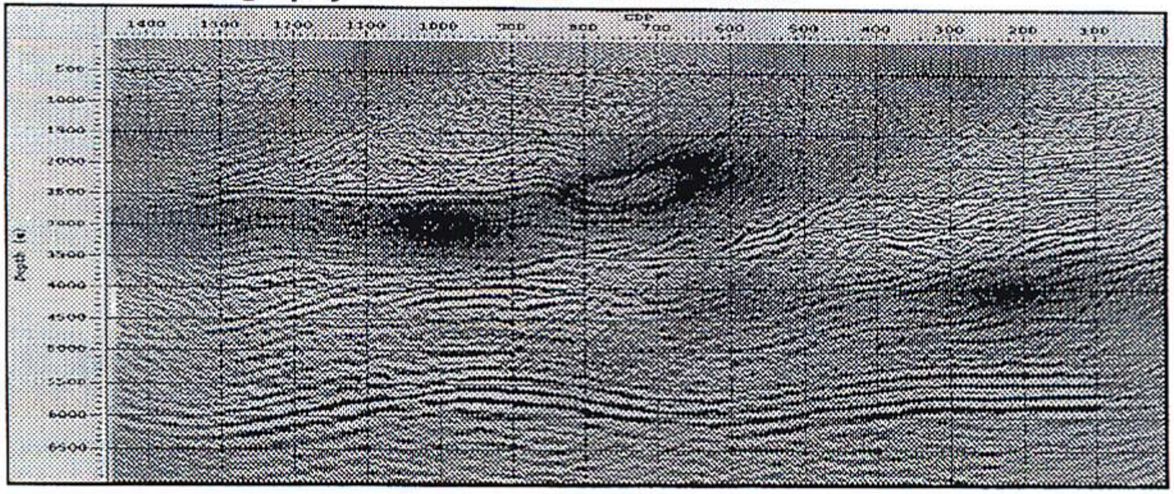
MVA Tomography Inversion with reflector constraints on basement reflector



Horizons used for MVA Tomography



MVA Tomography Inversion with no constraints



MVA Tomography Inversion with reflector constraints on basement reflector