Seismic Imaging of the Overturned Limb of a Footwall Syncline in the Alberta Foothills of the Canadian Rocky Mountains and Its Impact on Exploration*

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Abstract

The deformation model for the Alberta fold and thrust belt has frequently been interpreted as being a fault bend fold model. Based on an interpretation of a modern seismic line we would suggest that some parts of this structural domain deviate from this interpretation. We will show an interpretation that has an early detachment fold that has been later modified by a major thrust fault. In an effort to better understand the Alberta Foothills a seismic line was acquired in 2005. It is 52 km long and runs SW to NE across the structural strike of the surface geology. A regional section from the Alberta Geological Survey runs parallel with the seismic line 3 km to the NW. On this section a major thrust, the Brazeau Thrust is interpreted with approximately 25 km of dip slip movement on it. This thrust carries Paleozoic Carbonates in the hanging wall which outcrop at the surface. The footwall cutoff is interpreted to be at 5 km depth in the regional Paleozoic. The deformation model for this interpretation can best be described as following a fault bend fold style of deformation. An interpretation of the seismic line has provided a substantially different model for the Brazeau Thrust. In this interpretation we show a sub thrust overturned fold limb of Paleozoic Carbonates imaged in the seismic section. This new interpretation would radically revise the deformation model for this part of the Brazeau Thrust. The new model would have a detachment fold with amplitude of 2 km occurring early on in the evolution of the structure. Subsequent to the folding a thrust initiated and carried the back limb of the fold to the NE by 10 km. The Brazeau Thrust is 120 km long and is well explored. Many of the interpretations to date have invoked fault bend folding as a deformation model. The early detachment fold modified by a late stage thrust model is based on the interpretation of the new seismic and well data. The modified detachment fold appears to have developed along strike from Limestone Mountain, a major gas field formed in a duplex of Paleozoic Carbonates in the footwall of the Brazeau Thrust. As such it represents a rapid lateral change in the deformation model of this particular domain. This information will increase the risk of drilling a successful commercial gas well on the NW extension to the Limestone Mountain Field.

Introduction

A regional seismic line (LOFF8) was shot and processed in 2005 (Colombo, 2005). It was part of a high intensity, long offset seismic program acquired across part of the Alberta Foothills (AF) of the Canadian Rocky Mountains. This line was reprocessed and reinterpreted in 2015 using the latest processing techniques by Thrust Belt Imaging (TBI) and Moose Oils Ltd (MOL) in Calgary. LOFF8 shows examples of three types of oil and gas plays that are typical for the AF. The examples seen on the line are a Mississippian carbonate duplex, a Cretaceous clastic triangle zone, and a possible Devonian sub-thrust reef play.

The interpretation of LOFF8 in time and depth is reviewed in this paper. The tools used for the integration of the surface and subsurface geological and geophysical data are described and a new deformation model for this area is presented.

Regional Geology

The stratigraphy for this part of the AF is summarised on the stratigraphic column (Figure 1). The structural style for this area is dominated by the Brazeau Thrust. Which is a large displacement, low angle thrust fault. This is illustrated by the regional cross section D-D’ published by the Alberta Geological Survey (Langenberg et al., 2002) (Figure 2). The LOFF8 line is within 5 km and runs subparallel to D-D' (Figure 3).

LOFF8 Seismic Acquisition Parameters

This seismic line was shot in August 2005 using high intensity, long offset acquisition parameters in a typical fold and thrust belt environment.

Shot Interval:	90 m	Minimum Offset:	15 m
Group Interval:	15 m	Maximum Offset:	12,000 m
# Channels/Shot:	1600	Nominal Fold:	133
Length:	52.8 km	Charge Size:	10 kg
Source:	Dynamite	Shot Depth:	1 x 18m

Pre Stack Time Migration (PSTM)

Surface Geology

A total of 652 square kilometers of published geological mapping were used to provide the surface control for the LOFF8 seismic line. This information included geological outcrop data along the surface trace of the seismic line as well as the bedding data used for calculating the down plunge projection. (Groshong, 2008).

Well Data

The well data in Western Canada is all in the public domain after a variable confidentiality period. For this project the public well data was used to extract location, deviation survey, and a TD depth for each well. The public data base for this area was searched and analysed using GeoScout. Initially 27 wells were checked for quality and consistency and then used in the PSTM interpretation. The horizon/formation tops of key wells were picked and cross checked against the public database. In addition, all the available dipmeter data was quality controlled and analysed for dip and plunge.

Velocity Model

In the early stage of the PSTM work flow, an anomalous area of high-velocity rock was identified by the processor. This area was in the footwall of the Brazeau Thrust where the cross section D-D' had predicted low-velocity Mesozoic formations. The velocities being used in the PSTM were more compatible with higher velocity Paleozoic carbonates (Figure 4).

PSTM Work Flow

The seismic imaging work flow focused on static corrections (field and residuals), S/N ratio improvement, and the definition of robust velocity functions. This was followed by the Kirchhoff PSTM. (Geosystems, 2006).

Pre Stack Depth Migration (PSDM)

Surface Geology

As a result of the velocity anomaly it was decided to increase the geological study area. Both the surface geology and the wells were examined in detail over a larger area. 82 wells and 1600 square kilometers of surface geology were incorporated into the geological model.

Down Plunge Projection

During the review of dipmeters and wireline logs for the expanded area one well stood out. It was a very deep test with a TD of 5985 m. The well's name is AQUIT CDCOG Shunda 7-13-39-15 (7-13) drilled in 1981. This well had an exceptionally good wireline logging suite that included good quality dipmeter data.

Both the surface mapping and well data show that the Brazeau Thrust sheet is a major structural feature with a very consistent trend and plunge in this area. Based on this information the direction and amount of plunge in two structural domains was determined (Groshong, 2008). The northern domain extended from LOFF8 NW for 8 km and the southern one extended from LOFF8 to the SE for 15 km. Within these two domains, large scale features could be safely projected many kilometres.

All the surface geology data and well data (including dip vectors) were loaded into the Move software. This allowed the dip data to be analysed and projected interactively onto the plane of section using a down plunge projection direction of 1.060 at 3170 AZ (Figure 5).

Dipmeter Analysis

The 7-13 well had 5985 m of wireline logs, deviation surveys, dipmeter, and top data. The entire wireline log data was checked for quality and consistency; this included a detailed review of the dipmeter data. The geological tops were re-picked for consistency with the other 82 wells. This data was loaded into the RDA dipmeter-analysis software for calculating down plunge projection.

A detailed dip analysis was carried out using the 7-13 well data. In this process, points were picked in the well bore using the SCAT display (Statistical Curvature Analysis Technique) to highlight dip domains (Bengston, 1981). These were then interpreted using the gamma correlation log from the wireline logging suite to determine the stratigraphic up direction (Figure 6).

Based on this process the well was divided into three large domains. The dipmeter data and geological tops in the hanging wall of the Brazeau Thrust were designated as an upper domain called BR. This data was imported into the dipmeter analysis package with the stratigraphic top of the dipmeter data pointing up. The data in the footwall of the Brazeau Thrust were found to be in one of two distinct geological domains. Bedding from the Brazeau Thrust down to 4250 m was overturned, based on the gamma correlation log. This domain was called the OT domain and the dipmeter data was loaded with the stratigraphic top of the dipmeter data pointing down. The third geological domain was the data from 4250 m to TD which was called the R domain and it was loaded with the stratigraphic top of the dipmeter data pointing up.

The geological tops, domains, and dip vectors were incorporated into the revised structural interpretation of the formations penetrated in 7-13. The Paleozoic stratigraphy can now be seen to be the right way up in the hanging wall of the Brazeau Thrust, overturned in the immediate footwall of the Brazeau Thrust and the right way up again in the regional part of the section. This data was then projected onto LOFF8 using a down plunge projection. The resulting interpretation in depth clearly illustrates that the velocity anomaly is caused by Paleozoic carbonate in the overturned limb of a fold, in the footwall of the Brazeau Thrust (Figure 7).

Geological Modeling

The depth model in Move was palinspastically restored and then forward modeled to test for balance (Dahlstrom, 1969). This was carried out using the Move's flexural flow algorithm. As a result of this restoration of the Paleozoic, some changes in the footwall interpretation of the Brazeau Thrust were made to maintain ramp geometry (Figure 8).

Geophysical Modeling

The balanced cross section derived from the PSDM of LOFF8 was used as the input model for simulating synthetic seismic shots records using the Tesseral 2D software (Figure 9).

2D synthetic seismic shot records were simulated from this model using a finite-difference numerical representation of the wave equation that included P-wave primaries and interbed multiples but not converted shear wave or surface multiples. The resulting data was then run through a Kirchhoff PSDM with a 7000 meter aperture. The travel times were obtained by solving the eikonal equation using finite differences.

The geophysical modelling supports the concept that an overturned limb of the footwall syncline could be imaged in LOFF8 (Figure 10).

Revised Velocity Model

Based on the geological modelling from the 7-13 well, the velocity model for the LOFF8 was revised. An overturned limb of Paleozoic carbonates was added into the LOFF8 PSDM velocity model. (Figure 11).

PSDM Work Flow

To better image the seismic events, a PSDM approach was used. The depth processing section was characterized by the application of a wide-offset workflow. For the shallower section (2.5 km from surface) this consisted of the definition for an initial interval velocity field derived from the interpretation of pre-stack time migration, conversion of RMS velocities field within the interval velocity fields, the sonic log information and tomographic velocities (turning rays). This was followed by an iterative loop of pre-stack depth migration and velocity updates in a layer-stripping fashion from top to bottom of the model.

The velocity update during the depth migration workflow relied on iterative geologic consistent velocity scans for the portions with low S/N ratio and Common Reflection Point (CRP) tomography. The selection of the appropriate velocity parameters was confirmed by a relative improvement of the stacking power on the seismic section and the flattening of migrated events in the Common Image Gather panels (CIG). The combined time/depth migration workflows allowed the definition of good structural details.

Conclusions

1) The interpretation of LOFF8 provided an ideal platform to illustrate a workflow for integrating geology and geophysics in a processing stream for fold and thrust belts.

2) The high intensity, long offset seismic acquisition parameters of LOFF8 in conjunction with the PSTM and PSDM work flows improved the image of the overturned limb in the footwall of the Brazeau Thrust Sheet (Figure 12). This work flow can be applied to other fold and thrust belts, especially where the sub thrust target is obscured by higher velocity geological formations at the surface.

3) This process was successful in identifying a new deformation model for the Brazeau Thrust. It showed that a large fold with an amplitude of 2 km occurred early in the evolution of the structure. This was followed by the initiation of a thrust that carried the back limb of the fold to the NE by 10 km.

4) The Brazeau Thrust is 120 km long and it is well explored with numerous wells and seismic lines. Many of the interpretations of this thrust to date have invoked fault bend folding as a deformation model. In this interpretation of LOFF8 we see an early detachment fold that has been modified by a late-stage thrust. This detachment fold model has been interpreted to exist 60 km along strike from the Limestone Mountain gas field. This is a duplex of Paleozoic carbonates formed by fault bend folding in the footwall of the Brazeau Thrust. The sharp contrast between these two very different deformation models is remarkable and has implications for exploring for commercial structures beneath the Brazeau Thrust.

Acknowledgments

Geological Interpretation

- Moose Oils Ltd, Calgary, AB, Canada

Seismic Processing

- Thrust Belt Imaging (TBI) Calgary, AB, Canada

Software

- geoScout data base management software, geoLogic Systems Ltd, Calgary, AB, Canada
- Move structural geological modelling software, Midland Valley, Glasgow, Scotland, UK
- RDA dip analysis software, ResDip Systems, Houston, Texas, USA
- Tesseral 2D seismic wave form modelling, Tesseral Technologies Inc., Calgary, AB, Canada

Seismic Data

- LOFF8, Seis Ventures Res. Ltd, Calgary, AB, Canada

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Langenberg, C.W., A.P. Beaton, and H. Berhane, 2002, Regional Evaluation of the Coalbed Methane Potential of the Foothills/Mountains of Alberta (Second Edition): EUB/AGS Earth Sciences Report 2002-05.

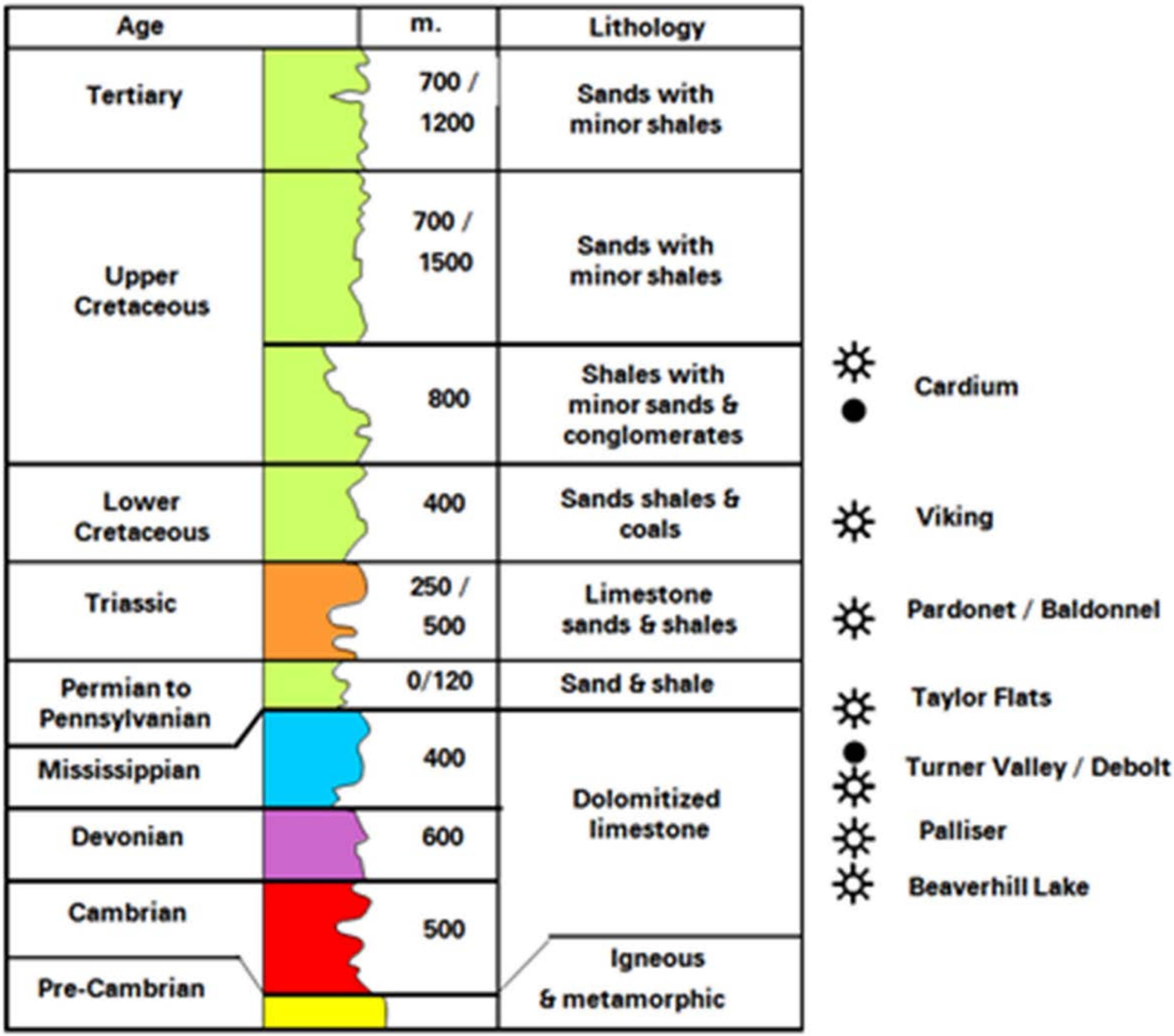

Figure 1. Stratigraphic table for the southern half of the AF with thickness, lithology and reservoirs.

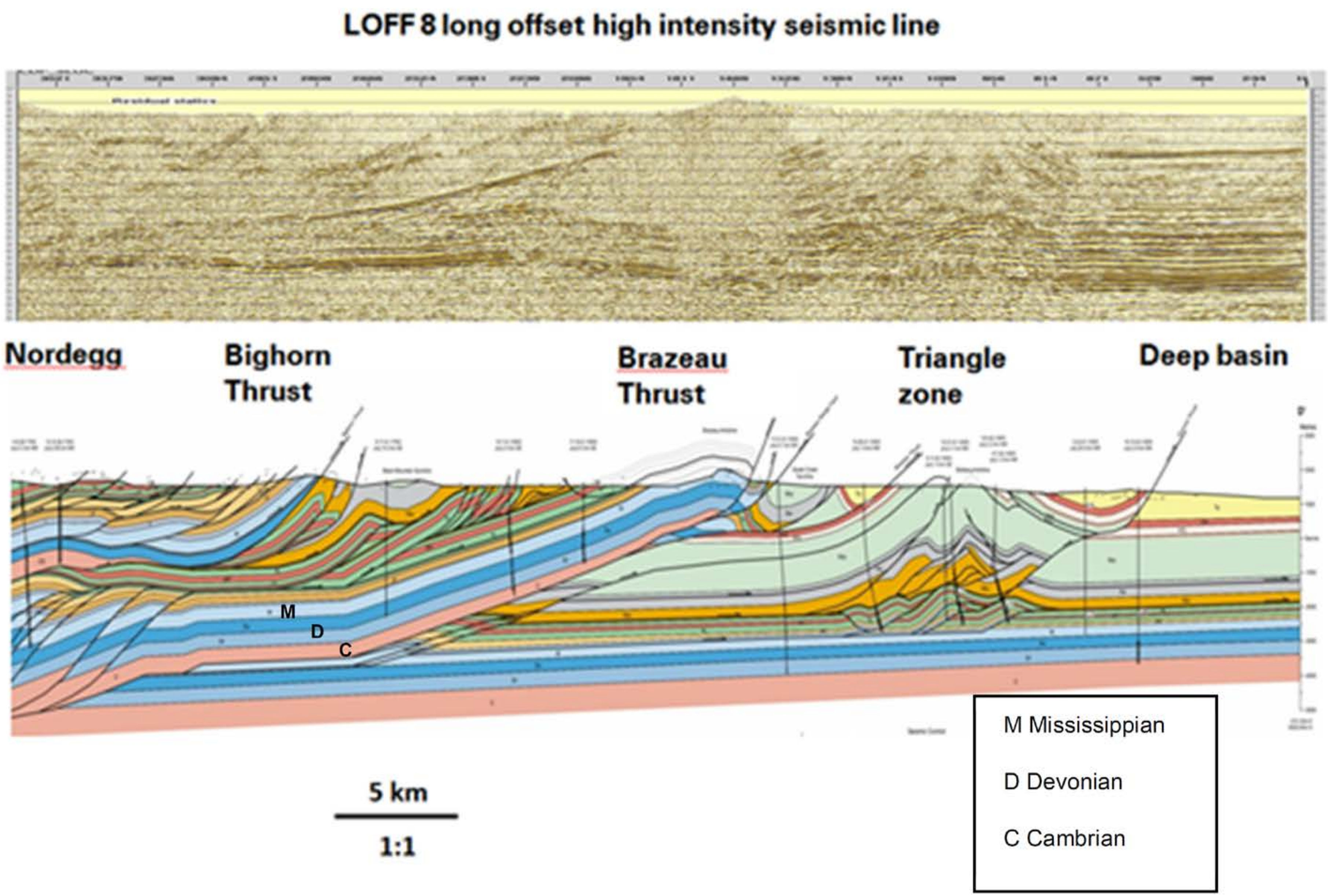

Figure 2. Initial time migration on LOFF8 in relation to regional section D-D’.

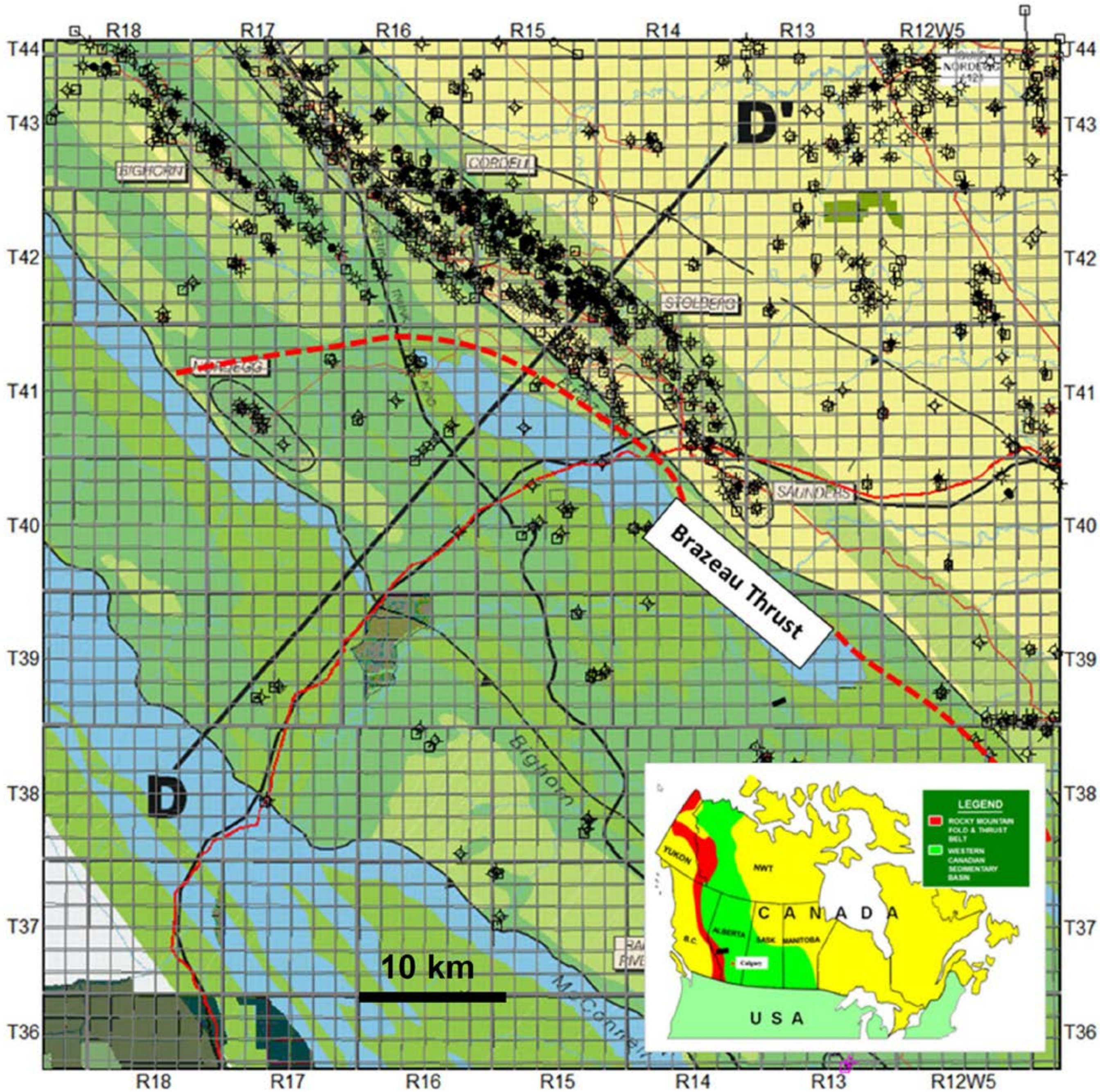

Figure 3. LOFF 8 runs close to and subparallel to the section D-D’. Approx. 100 km NW of Calgary.

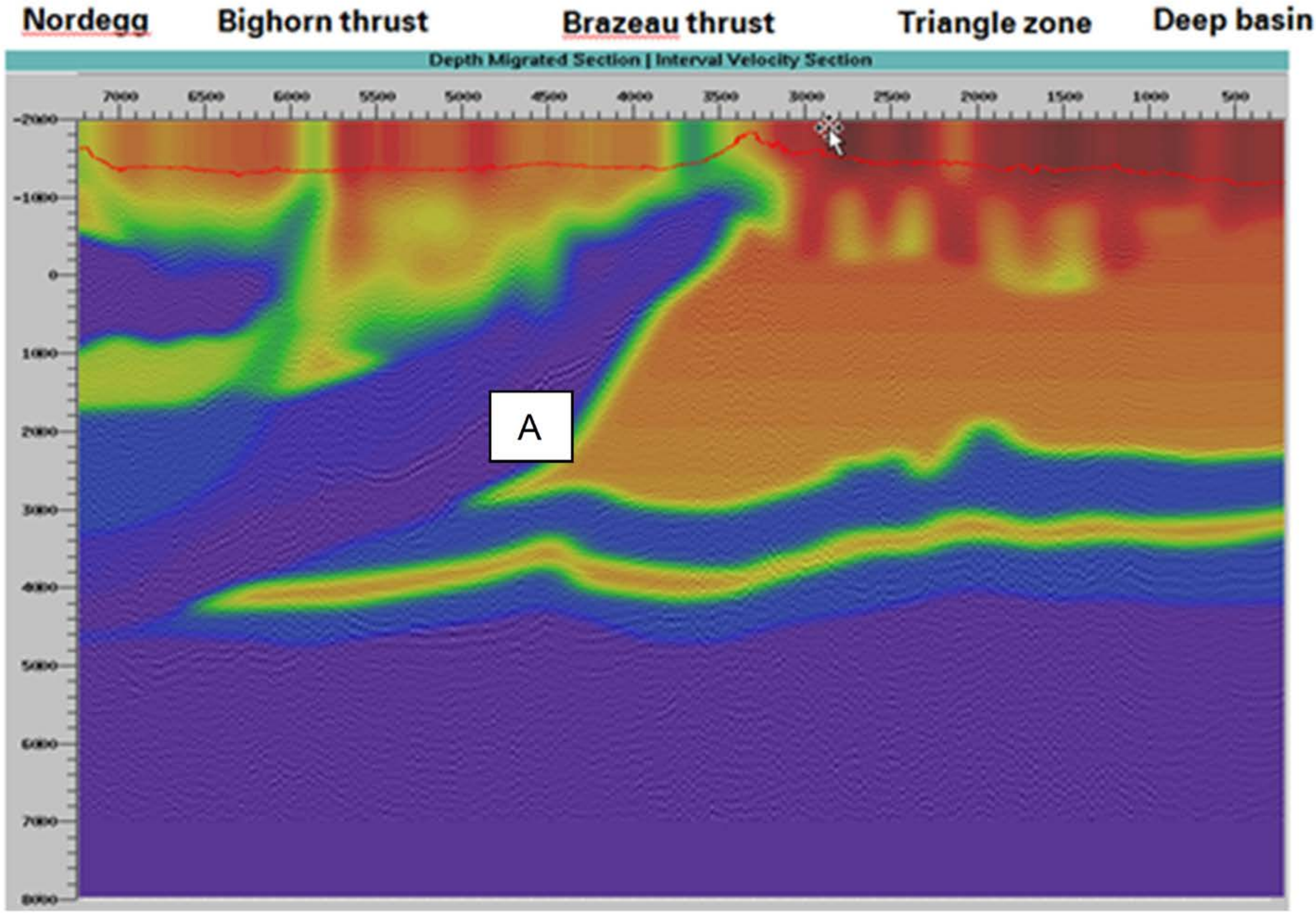

Figure 4. Initial velocity model showing the previously unidentified high velocity zone (A) in the footwall of the Brazeau Thrust.

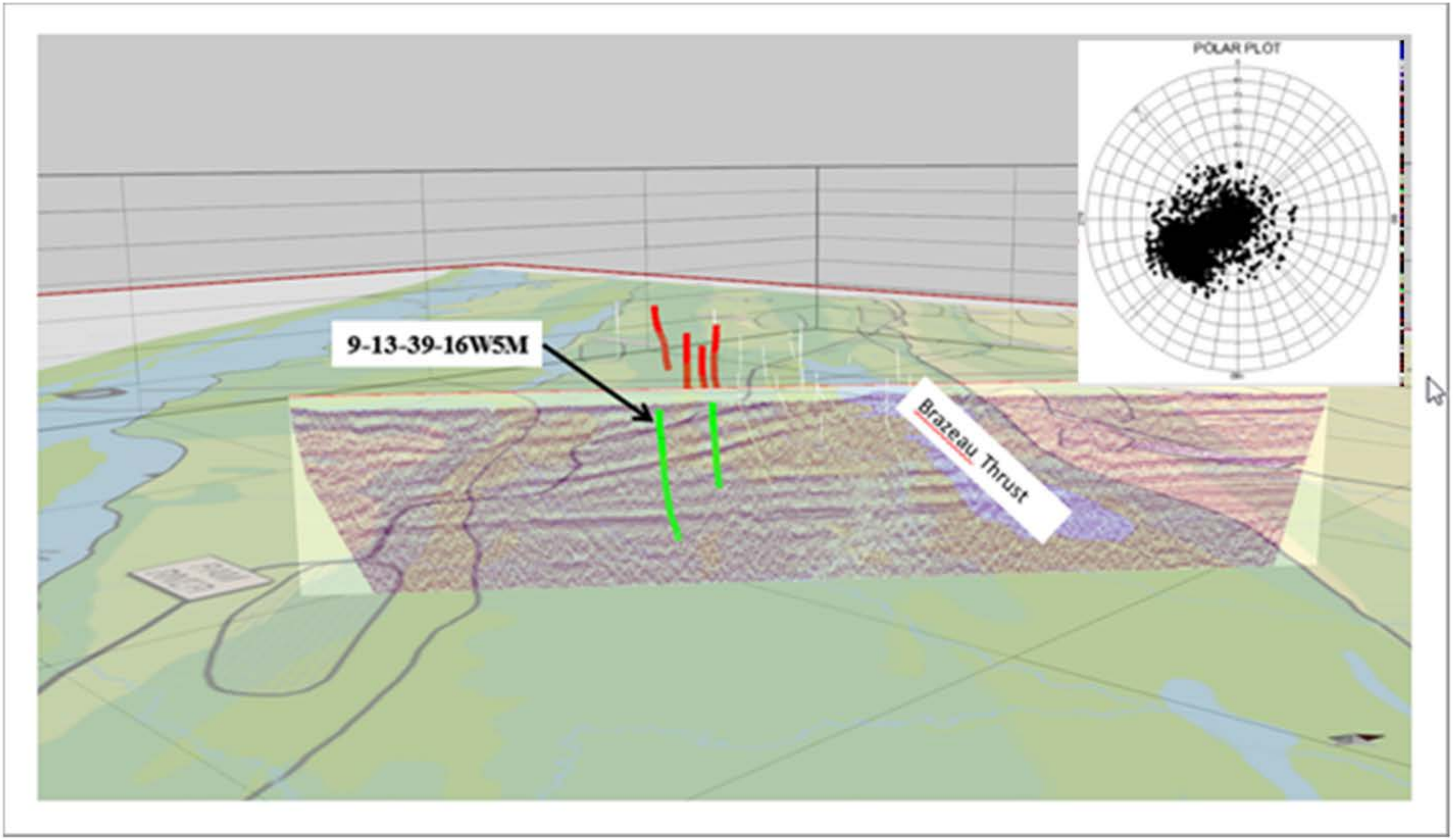

Figure 5. An oblique view in Move. Well data was projected along the calculated fold axis 1.060 at 3170 AZ.
(Upper Hemisphere Polar Plot Schmidt Net of bedding data.).

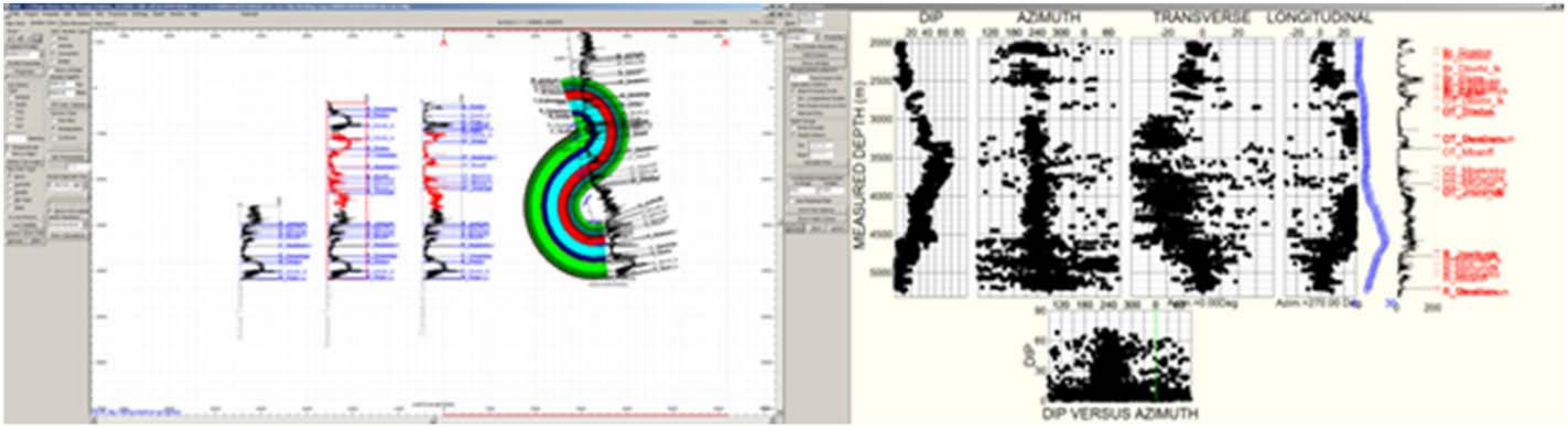

Figure 6. RDA dipmeter analysis software was used to carry out an interactive SCAT and vector section analysis.

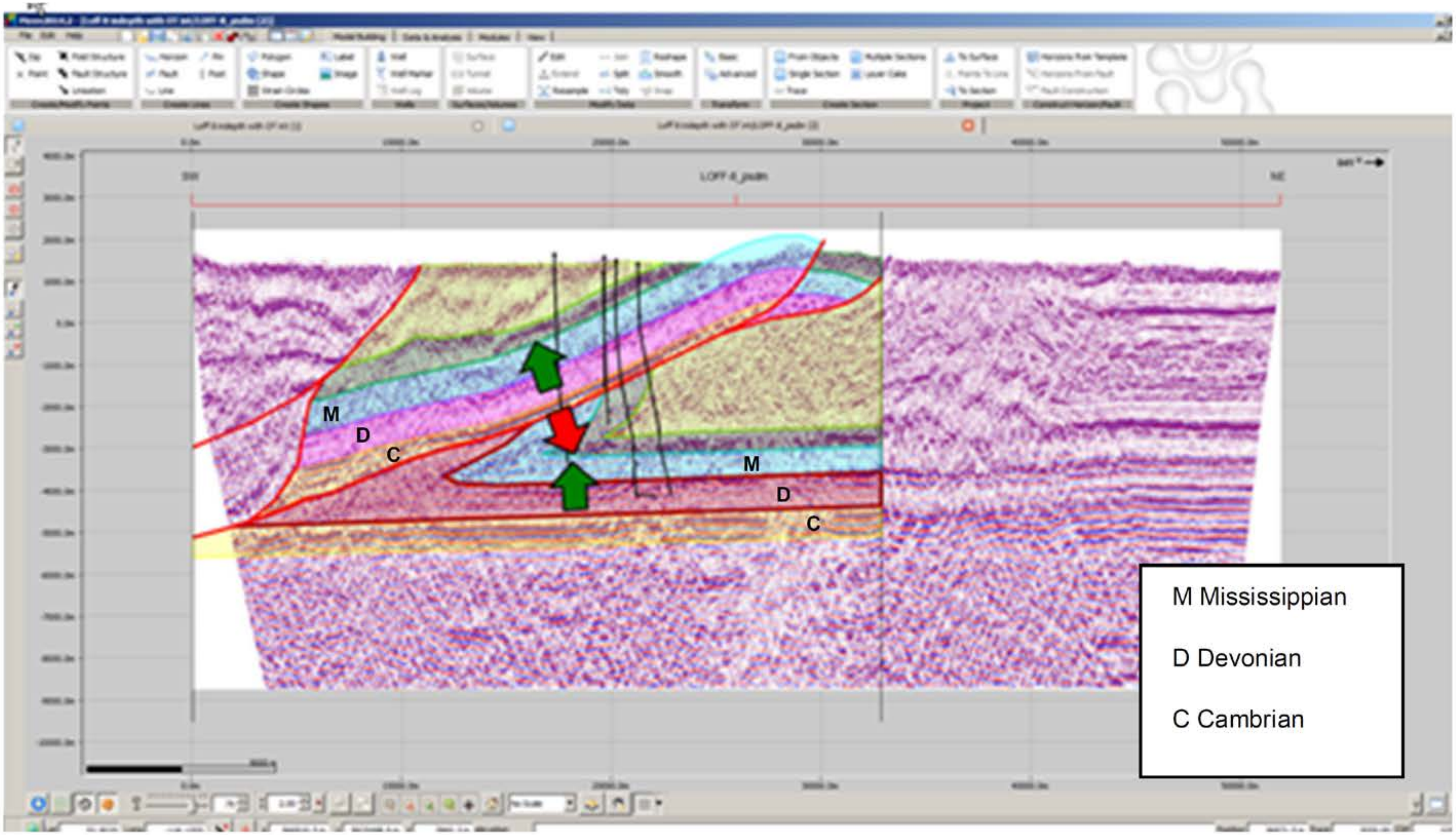

Figure 7. Move allowed for the incorporation of the revised geological model of 7-13 to be projected down plunge on to LOFF8. Arrows show the stratigraphic up direction.

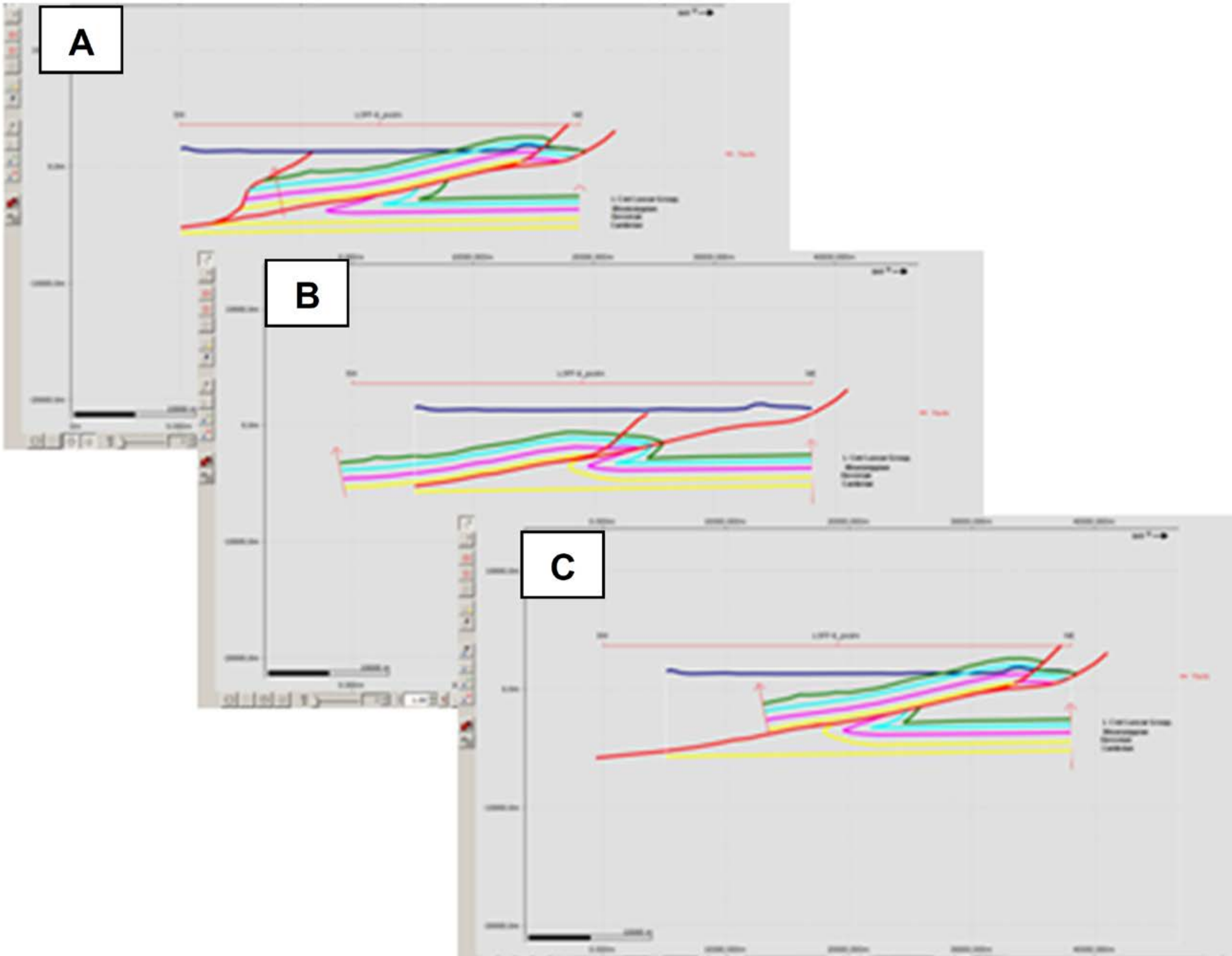

Figure 8. Three steps in balancing the geological input into the PSDM using Move. A: Geological interpretation in depth. B: Palinspastic restoration and editing of fault cutoffs. C: Forward modelling to present day geometry.

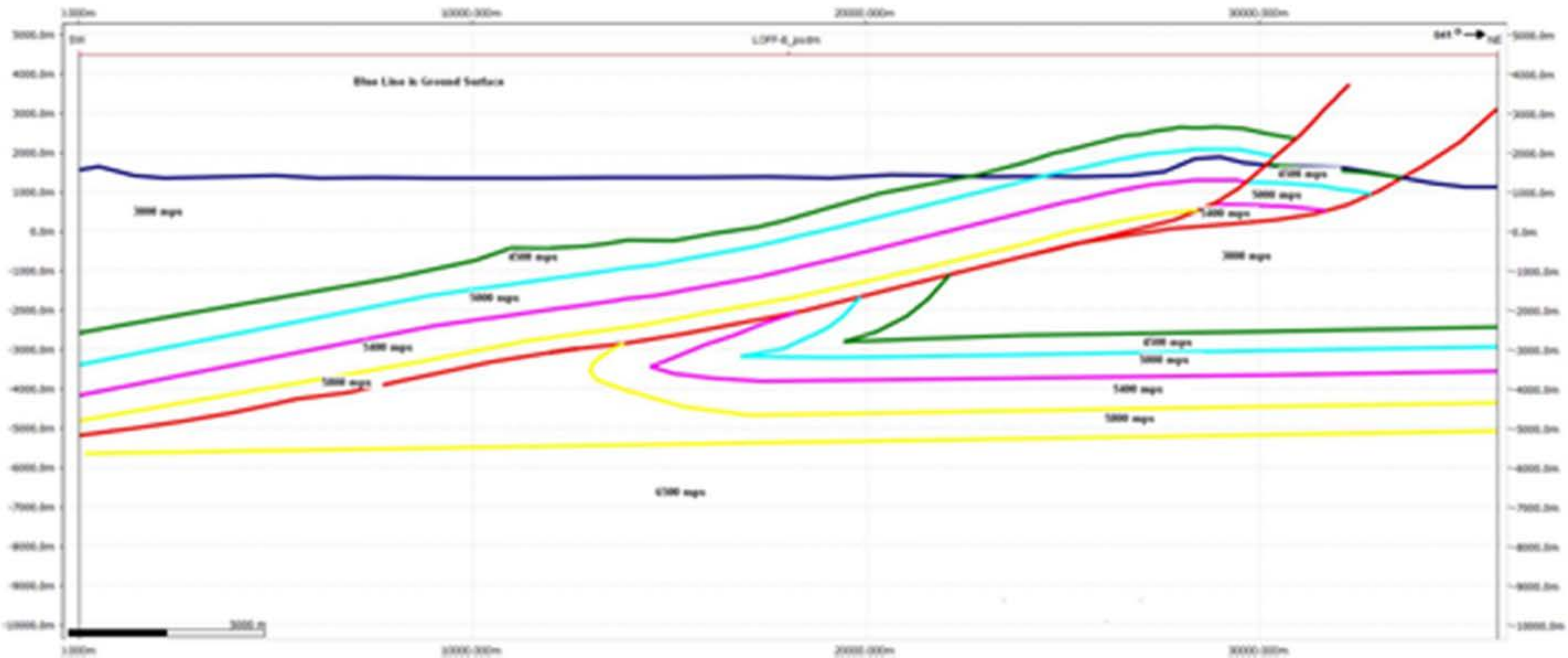

Figure 9. Velocity model derived from Figure 8 C.

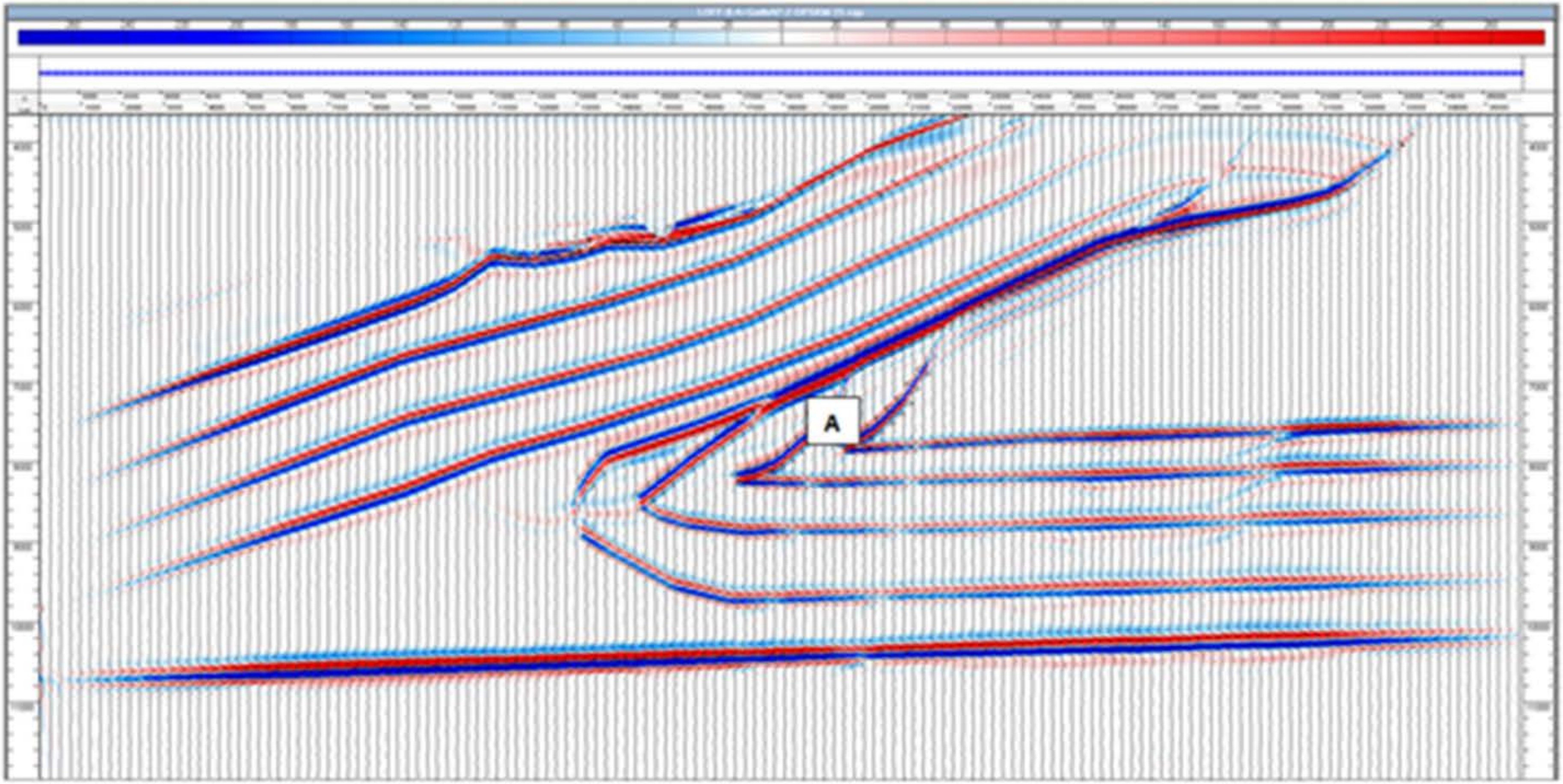

Figure 10. Full wave form model derived from the geological model. Note the overturned fold limb at A.

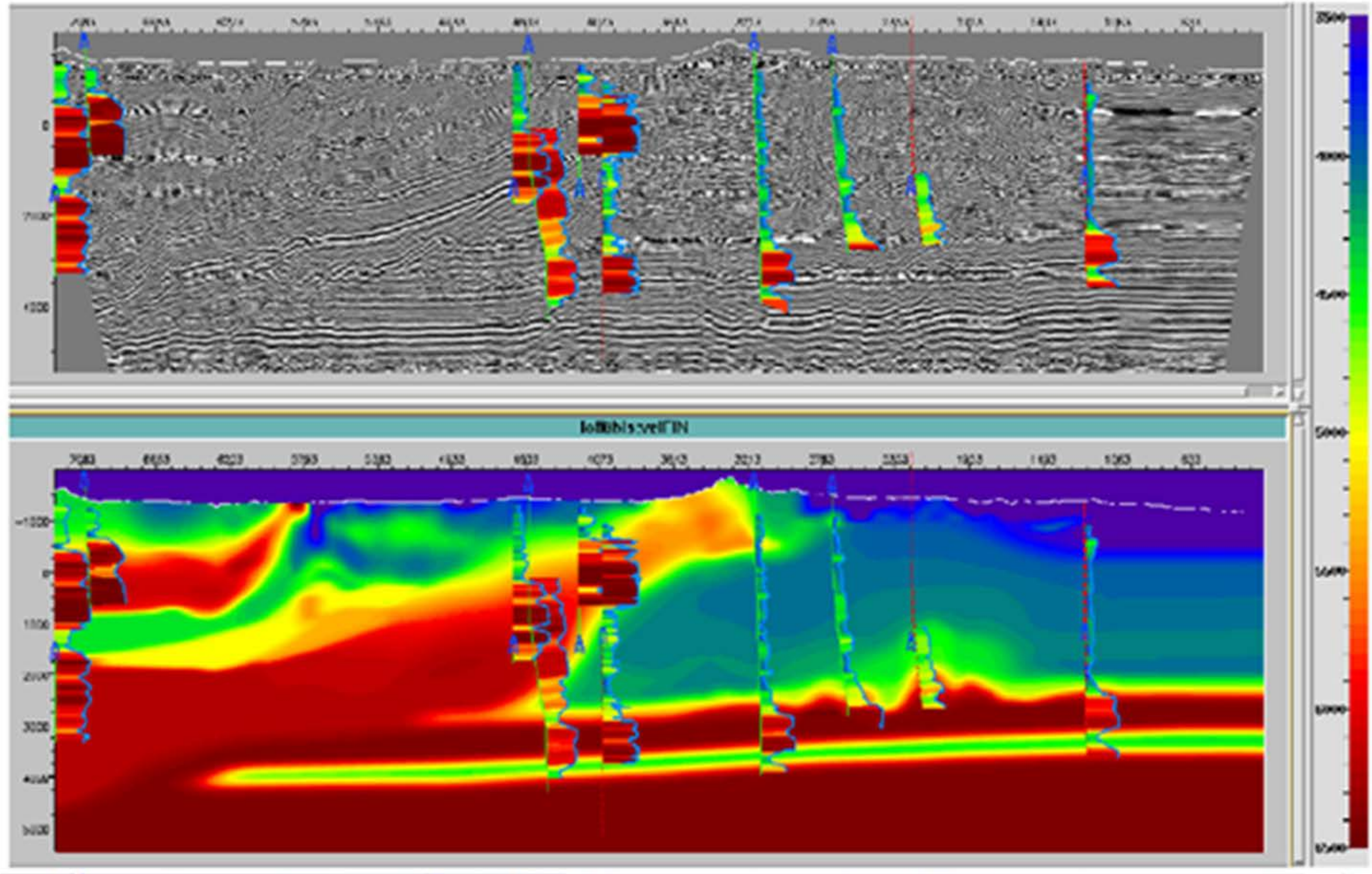

Figure 11. Revised velocity model used for the PSDM.

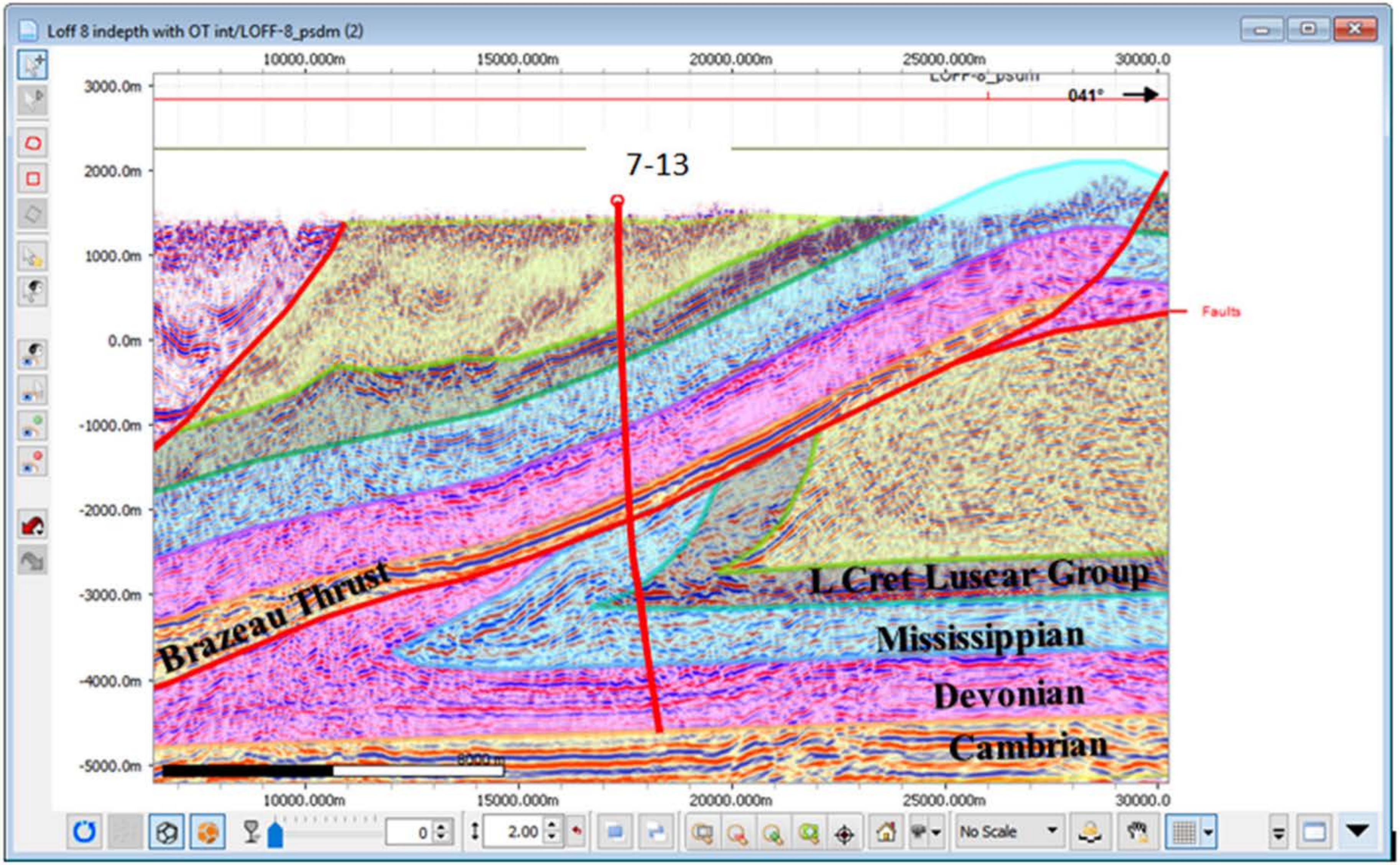

Figure 12. Final PSDM with 7-13 projected down plunge on to the plane of section.