Moving Toward Palinspastic Reconstruction of Velocity Models in Prestack Depth Migration

Joanne C. Archer and Don C. Lawton, Dept. of Geology and Geophysics, University of Calgary, Calgary

2004 CSEG National Convention

Introduction

In order to produce an accurate depth migration of a seismic line, one needs an accurate velocity model. This model should reflect the lithology and lithostatic load that the rocks have experienced through burial and deformation. If we understand the geometry of these rocks, and their behaviour upon deformation, we can produce a more accurate velocity model. Performing palinspastic restoration of a depth-migrated seismic line can be used to assess the geologic validity of the velocity models and can lead to improvements in these models, particularly in the fine-scale velocity structure of exploration targets.

A seismic line from the Rocky Mountain Foothills in NE British Columbia was interpreted. This line is located on the eastern edge of the Foreland Fold and Thrust Belt in the Canadian Cordillera within the structural transition zone. This transition zone represents a change in structural style from fault-dominated structures in the south to fold-dominated structures in the north.

Because concentric folds account for much of the displacement in this region, we are able to assume constant volume with no movement in and out of the plane when restoring our cross-sections (Dahlstrom, 1969; Hossack, 1979; Wilkerson and Dicken, 2001). Two methods were used for balancing, namely line length and area balancing. Balancing of the interpretation of the seismic section was performed with two different software programs: 2D Move version 3.1d (Midland Valley Exploration, 2001) and LithoTect version 1.08 (Geo-Logic Systems, 2002).

Geology

Within the Foreland Fold and Thrust Belt of the Canadian Rocky Mountains, there is a south-north transition between structural styles. Structures range from a thrust-dominated style in the south to a concentric, fold-dominated style to the north, as a result of a transition in lithology. To the south, rock units tend to contain thick competent carbonates and sandstones, which are resistant to folding, and result in the predominance of faulting that is seen in the area. To the north, thinner and much shalier units dominate. These shale packages act as detachment horizons and deform more easily, resulting in folding, rather than the faulting seen to the south (McMechan and Thompson, 1989). The structure of the transition zone is dominated by folding at the surface with thrust faults playing a more dominant role in subsurface deformation (Wright et al., 1994).

A study of the structural geometry of the Carbon Creek area to the northwest (McMechan 2002) was used to aid in the interpretation. The interpretation of the structural style and locations of detachments in the Carbon Creek area is similar to those seen in this study area. The structural interpretation of the Carbon creek area (McMechan, 2002) was made based on surface, well and seismic data. Two major detachments were identified, one within the Late Devonian Besa River Formation and the other within the Cretaceous Shaftesbury Group. The Besa River serves as the basal detachment of the fold and thrust belt. Near 54° 45’N, Besa River shales form a regional detachment separating faulted folds in Carboniferous carbonates from underlying, undeformed or thrust imbricated, middle Devonian strata (McMechan and Thompson, 1989). This detachment level changes from the Jurassic Fernie to the Triassic section as you move to the north. The Fernie Group separates different fold geometries above and below this detachment (McMechan and Thompson, 1989). In the seismic section interpreted for this study, three detachment horizons were identified. The first was within the Cretaceous Shaftesbury, the second within the Jurassic Fernie group and the third within the upper Devonian Exshaw shales.

Seismic Section

The seismic section used in this interpretation was processed, including anisotropic prestack depth migration, by Veritas Geoservices Inc.. This depth section allowed for structural balancing to take place as thicknesses of units in the section represent the actual unit thicknesses found in the subsurface reasonably well.

Seven horizons were chosen and interpreted. Each horizon corresponds with a distinct reflectivity character; these tended to be changes from a series of parallel reflectors to regions of little reflectivity (Figure 1). The horizons picked were the Cardium, Dunvegan, Shaftesbury, Falher, Baldonnel, Mississippian and Wabamun. The Cardium and Dunvegan were the only horizons carried upon a large thrust fault (Fault A) found in the southwestern portion of the section. This thrust fault ramps and appears to be the result of a secondary, or late stage, tectonic event. The Shaftesbury through Baldonnel horizons were involved in what appears to be concentric box folding. What is not clear is whether the box folds are continuous or if the leading edge of the fold is cut by a fault. This led to two separate interpretations, a “fault interpretation” (Figure 2) and a “fold interpretation” (Figure 3). The fault interpretation involved a third fault with a detachment above the Mississippian (Fault B); this fault cuts through the leading edge of the fold. The Wabamun and Mississippian appear to have been affected by an early series of thrust faults (Fault C) in both interpretations, which cut the Wabamun and terminate as blind thrusts within the Mississippian where displacement is taken up as folds. These late Paleozoic faults seem to influence the structure above them through to the Shaftesbury.

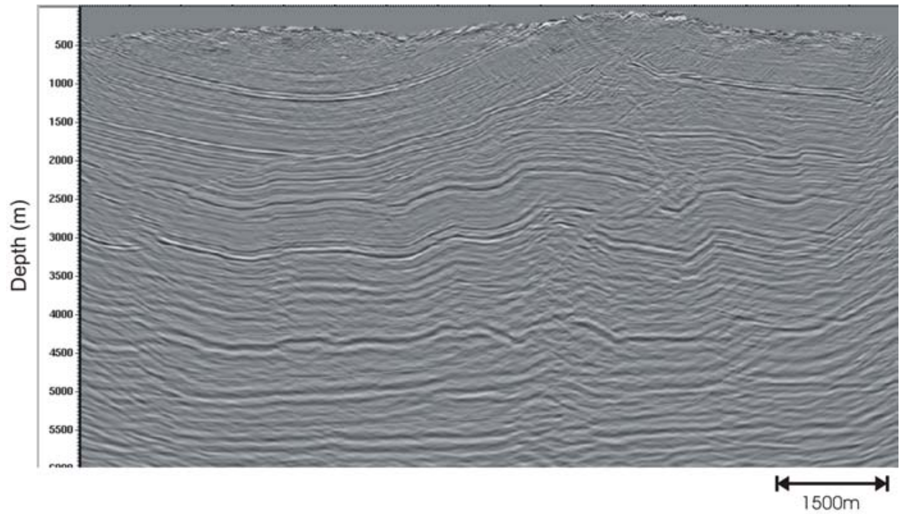

Figure 1: Original, uninterpreted seismic section used for balancing of cross-sections. Different reflectivity packages can be easily identified in addition to fault zones. This section is oriented SE-NW.

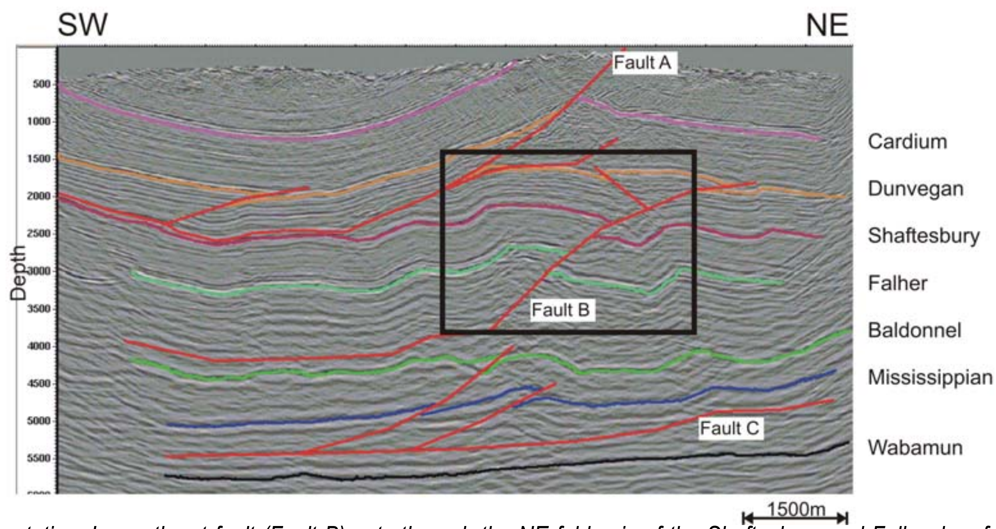

Figure 2: Fault interpretation. Large thrust fault (Fault B) cuts through the NE fold axis of the Shaftesbury and Falher box fold; this displacement continues through the Dunvegan and creates a pop-up structure. The box highlights the differences between the fault interpretation and the fold interpretation.

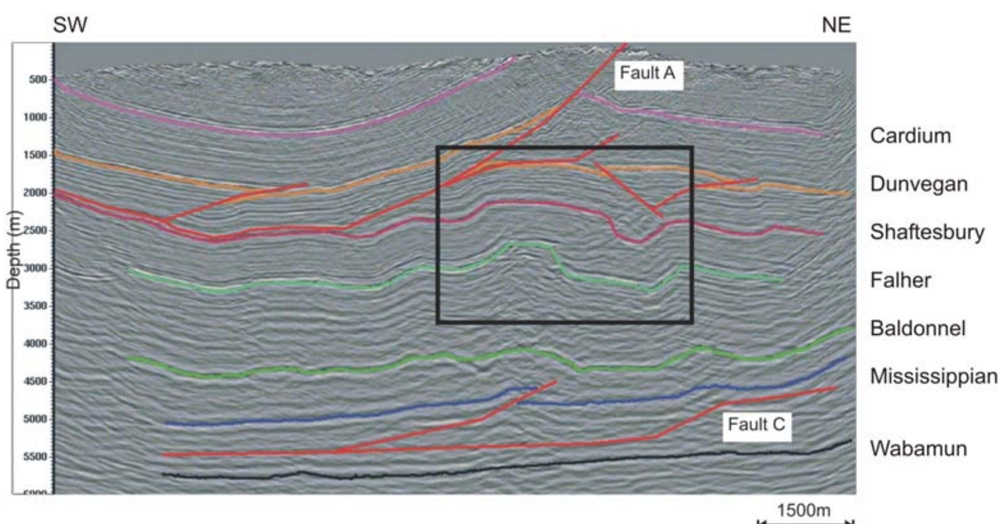

Figure 3: Fold interpretation. Shortening of the Shaftesbury and Falher formations is taken up as concentric, angular box folds with little, to no, faulting. Box shows location of differing interpretation between the fold and fault interpretations.

Balanced Cross-sections

The best method to determine if a cross-section interpreted from seismic data is correct is to test if it can be restored palinspastically without mass excess or deficiency. This implies that the beds can be restored to their pre-deformational, depositional geometry without introducing any anomalous bed length changes (Dahlstrom, 1969). Wilkerson and Dicken (2001) identified four criteria, taken from Dahlstrom, 1970, that are needed in order to create a balanced cross-section: (1) Interpreted structures must reflect those seen in the area of interest; (2) the resulting pre-deformational strata and fault geometries should be reasonable once unfolding and removal of slip has taken place; (3) mass is conserved between the deformed and restored section, or has been reasonably accounted for; and (4) the development of structures from the undeformed to deformed state is kinematically possible.

The length of the seismic section involved in this study was 11.85 km. However, the edges of the section show some migration artefacts and only the central 11 km were used for the interpretation.

Both the fault and fold interpretations were restored and the degree of shortening was calculated for both (Figure 4). Both interpretations show a similar degree of shortening but the fold interpretation was shortened less than that of the fault interpretation. The upper two units, the Cardium and Dunvegan, underwent the greatest amount of shortening with a 15-23% reduction in length. The middle four units experienced similar amounts of shortening with both interpretations near 10%. The Wabamun experienced minimal shortening, as was expected, as most of the deformation was above this unit.

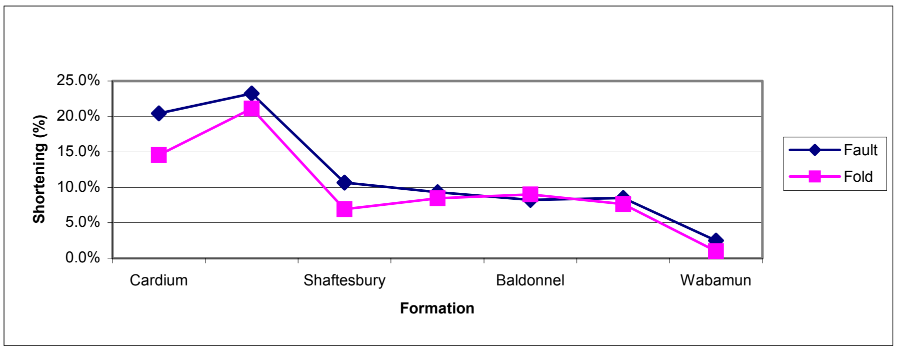

Figure 4: Graph shows the amount of shortening of each unit in the section with both the fault and fold interpretations. Both the Cardium and Dunvegan have undergone the greatest amount of shortening. The Shaftesbury, Falher, Baldonnel and Mississippian underwent a moderate amount of shortening while the Wabamun experienced the least amount.

Discussion and Conclusions

Both the fault and fold interpretations identify three detachments within each interpretation. However, the amount of shortening for the Cardium and Dunvegan is more pronounced in the fault interpretation when compared to the fold interpretation. This is to be expected as more displacement can take place over a fault than with a simple fold geometry.

The concentric parallel fold geometry produced a bed that followed the Falher geometry consistently to the southwest but no longer fit at the pop-up structure and east of it. The angular projection fit well along the Falher horizon to the southwest as well and this time, the shape of the fold in the syncline was similar to that of the projection (Figure 6). However, there was also a lateral shift of the syncline with this projection. The northeast limb of the syncline should be shifted to the northeast if the folding is assumed to follow simple angular parallel behaviour. Because this was not the geometry indicated by the seismic interpretation, there appeared to be a thickening of the bed within the fold, this became apparent upon restoration of the fold interpretation.

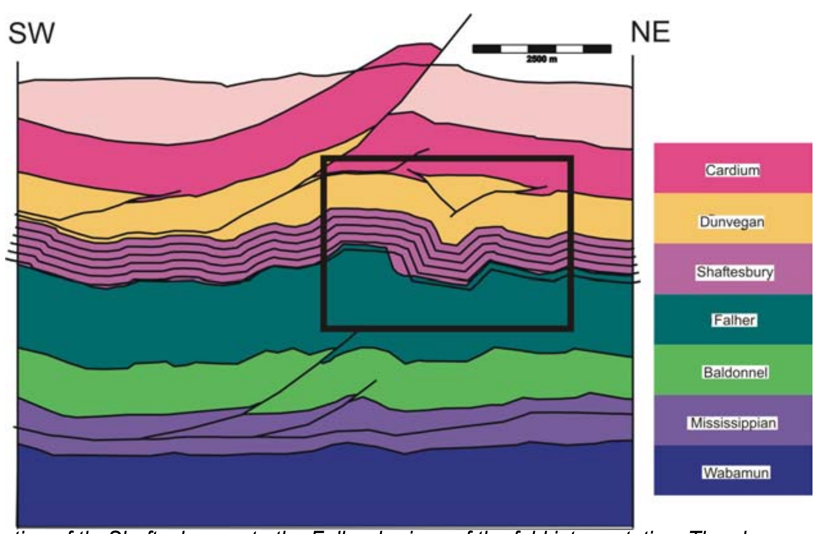

Figure 5: Angular parallel projection of theShaftesbury onto the Falher horizon of the fold interpretation. The shapes of the folds are similar but there is some error in the lateral positioning.

The Shaftesbury bed geometry was also projected onto the Falher in the fault interpretation (Figure 6). The shapes of the two beds were a better match with the fault geometry than was found with the fold geometry. These results indicate that the fault geometry is the more reasonable interpretation. The Shaftesbury and Falher most likely underwent box folding and these folds were subsequently cut by a fault with a detachment above the Mississippian and terminating above the Dunvegan. This fault interpretation provides a more reasonable explanation for the presence of the pop-up structure as well.

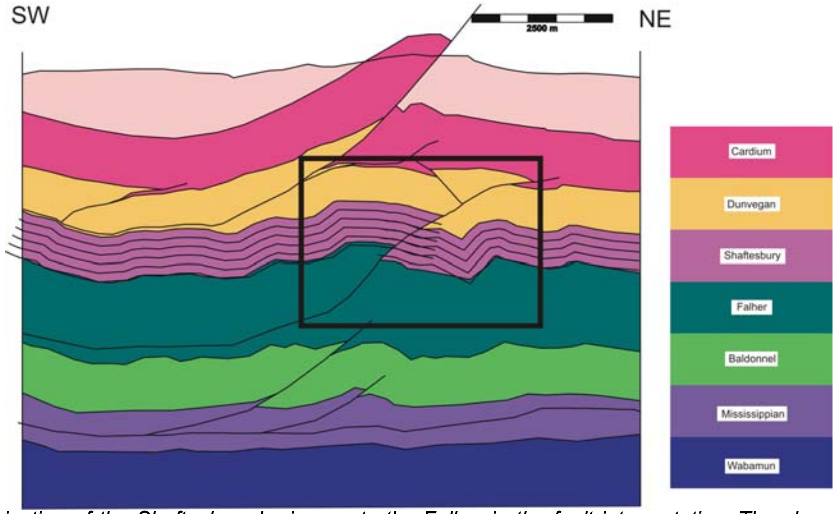

Figure 6: Angular parallel projection of the Shaftesbury horizon onto the Falher in the fault interpretation. The shape of the Falher in the footwall matches with the predicted shape using an angular fold geometry.

Implications

Based on balancing principles, the depth migration velocity model will be refined in an attempt to refine the structural interpretation of the depth-migrated image. If we decide that the fold interpretation is a more reasonable model, and folding is angular parallel to the northeast, the upper and lower boundaries of the bed should follow the same fold geometry. This geometric relationship will be used to drive the construction of velocity models for use in pre-stack depth migration.

Accurate depth migrations require accurate velocity models. Understanding the geometry of geologic units and structural principles should aid in determining the integrity of a model. An iterative approach will be taken to depth migration in which velocity models will be modified to produce a geologically reasonable seismic section that can be restored. Lateral positioning errors common to depth migrations should be reduced with this approach.

Acknowledgments

We wish to thank El Paso Oil & Gas for the donation of the data used in this project, and to the sponsors of the Fold-Fault Research Project for their financial support.

References

Dahlstrom, C. D. A., 1969, Balanced Cross Sections: Canadian Journal of Earth Sciences, **6**, p. 743.

Dahlstrom, C. D. A., 1970, Structural Geology in the Eastern Margin of the Canadian Rocky Mountains: Bulletin of Canadian Petroleum Geology, **18**, p. 332-406.

Hossack, J. R., 1979, The use of balanced cross-sections in the calculation of orogenic contraction; a review: Journal of the Geological Society of London, **136** Part 6, p. 705-711.

McMechan, M. E., 2002, Structural geometry in the Carbon Creek area of the Rocky Mountain Fold and Thrust Belt, northeastern British Columbia: Bulletin of Canadian Petroleum Geology, **50**, p. 407-418.

McMechan, M. E., and R. I. Thompson, 1989, Structural Style and History of the Rocky Mountain Fold and Thrust Belt, in B. D. Ricketts, ed., Western Canada Sedimentary Basin: A case history, Canadian Society of Petroleum Geologists, p. 47-71.

Wilkerson, M. S., and C. L. Dicken, 2001, Quick-look techniques for evaluating two-dimensional cross sections in detached contractional settings: AAPG Bulletin, **85**, p. 1759-1770.

Wright, G. N., M. E. McMechan, and D. E. G. Potter, 1994, Structure and Architecture of the Western Canada Sedimentary Basin, in G. Mossop, and I. Shetson, eds., Atlas of the Western Canadian Sedimentary Basin, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 21.