Fold-Thrust Interactions in the Canadian Rocky Mountains Revisited - A New Kinematic Model and its Implications for Other Shallow Fold-Thrust Belts*

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Abstract

We show that the ramp-flat models are not the general case in the Rocky Mountains and present an alternative. Most folds in the Rocky Mountains are interpreted as a product of thrusting. Three fold-thrust scenarios are recognized which, in some circumstances, represent subsequent stages in the development of ramps and flats: detachment folds, fault-propagation-folds, and fault-bend folds. Another, apparently rarer fold-thrust interaction, the break-thrust fold, comprises an antiform-synform pair with a common limb that is thrusted. Most of the ramp-flat folds are interpreted in seismic profiles but they are rarely actually observed. The subsurface interpretations may be biased by model-driven seismic processing owing to poor footwall imaging, possibly enhanced by unsuited acquisition parameters designed for undeformed Plains strata. We base our interpretation on structures that are either well exposed or, if subsurface data are good, seismic images controlled by wells. The result is a more realistic interpretation of antiform-synform pairs. One of our examples from the Front Ranges, the exposed Mt. Allan syncline in the footwall of the Rundle thrust, gives evidence based on small structures such as cleavage and parasitic folds that folding predated thrusting. This is inconsistent with a ramp-flat model. In another example, the geological subsurface model of the Brazeau thrust zone in the Foothills needs to be revised from a fault-propagation fold to a thrusted anticline-syncline pair. We propose a kinematic interpretation consistent with the anticline-syncline geometry as well as with the general deformational environment. The model is applicable to any fold-thrust belt. A similar kinematic picture has been observed in centrifuge experiments designed to represent a Rockies-type environment. The consequence of the new model for hydrocarbon exploration lies in the footwall geometry: layering there is not automatically flat-lying and undeformed, but dips at various angles and is likely to be overturned. In the future, improved seismic techniques may reveal a higher degree of large-scale folding in the Rocky Mountains Foothills than previously believed.

References Cited


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1. Introduction

2. Two Geometrical Models of the Brazeau Thrust Zone

3. Examples of Thrusted Anticline/Syncline Pairs

1. Folding Mechanisms:
   • Folding without Thrusting (a New Model)
   • Folding by Thrusting and the Role of Structural Overprinting

2. Extension of Classic Fold Models and Integration in a Progressive Deformation

3. Concluding Remarks
“...In a world where so much emphasis seems to be put on faulting, it's always fun to look at folding...” Glen Stockmal, Geol. Surv. Can.

Rocky Mountains: Westerly dipping shallow fold-thrust belt Laramide orogeny

Foothills (subsurface; hydrocarbons): Interpretation > Observation Model driven

Front Ranges (exposed; small structures): Observation > Interpretation

Appalachian Ramp-Flat Model: Bedding-Parallel Flats joined by Ramps

Rich (1934)
Ramp-Flat Folds: 3 “End Members” (originated as kink-hinge folds)

A

Detachment Fold (Jamison, 1987): prior to ramp formation
“tip line fold”

B

Fault-Propagation Fold (Suppe & Medwedeff, 1984):
during ramp formation
“tip line fold”

C

Fault-Bend Fold (Rich, 1934; Suppe, 1983):
after ramp formation

Redrawn from Jamison (1987)

Hanging wall anticlines, footwall undeformed: no footwall syncline is developed in current geometrical or kinematic Models of FPF and FBF.

All of the fold-thrust models have a synclinal flexure forelimb of the anticline: tilting required!
What do we observe in the Front Ranges?

Overturned footwall!

Footwall syncline! Not desired!

FPF model: Overused in subsurface interpretations?

Break-Thrust Fold (Willis, 1894): fold overprinted by a thrust

Synclinal hinge, thickened: fold profile not concentric (no seismic)!

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Küblı & Langenberg (2002): no well information used for footwall interpretation

Mesozoic clastic sediments
Paleozoic carbonates (Cambrian, Devonian, Carboniferous)

- Staircase trajectory
- Hanging wall: anticline-syncline pair in Paleozoic and Mesozoic rocks
- Undeformed footwall
- Basal detachment in the Mississippian
Fault-Propagation Fold?

Küblı & Langenberg (2002)

Both seismic lines 1.5 km apart

Break-Thrust Fold?

Newson (2015)

Hinge in Devonian rocks

Differences:
- Overprinting relationship
- Location of detachment
- Footwall geometry
- K&L (2002) fault pattern looks constructed

- Well information used
- Overturned footwall syncline (ductile footwall)
- Ramp overprints fold pair
- Basal detachment in Cambrian

No vertical exaggeration
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Not exactly to scale!

Price & Mountjoy (1970)

Rundle Thrust

Mt. Rundle

Canmore

Three Sisters

Rundle Thrust

Mt. Kidd
Mt. Rundle, Rundle Thrust, and Mt. Allan Syncline at Banff


- Overturned footwall syncline cored by Jurassic rocks
- Penetrative ductile strain features (cf. Cant & Stockmal 1999):
  - Parasitic folds around synclinal hinge
  - Cleavage in hanging wall and footwall
  - Shear sense in the immediate footwall opposite to Rundle Thrust
  - Rundle Thrust overprints folds
Reconstruction: Mt. Rundle Anticline/Syncline Pair
Cross section by Price & Fermor (1984)
Re-drawn by Fitz-Diaz et al. (2011)
Three Sisters, Rundle Thrust, and Mt. Allan Syncline at Canmore

Prominent easterly verging faulted anticline-syncline pair
Folds are neither concentric or kinks, Devonian hinges thickened
Folds overprinted by the Rundle Thrust
Footwall of Rundle Thrust overturned

JKk: Jurassic Koutenay fm
Mlv: Mississippian Livingstone fm
Mbf: Mississippian Banff fm
Dpa: Devonian Palliser fm
Dax: Devonian Alexo fm
Dfa: Devonian Fairholme fm

Geology added according to Price & Mountjoy (1970)

zooming out →
Footwall syncline:
Cannot be a classic fault-propagation fold

Three Sisters and Mt. Allan Syncline

Price & Mountjoy (1970)
Three Sisters: parasitic folds, one magnitude smaller than Mt. Allan syncline
Both predate Rundle Thrust
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Constant Volume Model produces folds with left-dipping axial surfaces and variably dipping bedding.

Shortening component approximately parallel to bedding: folds are initially symmetrical.

May be overprinted by thrusts.

Model 1: Folding without Thrusting - no Detachment needed

Rocky Mountains as a shear zone: “Layer-parallel Simple Shear”

- Lengthening domain
- Shortening domain
- SW
- NE
- Undeformed

A

B $\gamma = 2$
25% shortening

C $\gamma = 8$
85% shortening

- Horizontal layering
- Penetrative homogenous simple shear
- Top to the NE sense of shear
- Variation in the orientation of layering: slight deviation from the shear plane

- Rocky Mountains as a shear zone: “Layer-parallel Simple Shear”
- Lengthening domain
- Shortening domain
- SW
- NE
- Undeformed
Model 2: Folding by Movement along a Fault

“Variation of the Detachment Fold Model”

- Thickened hinges
- The anticline causes deflection of the flat into a ramp
- Both models may lead to the same geometry
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<table>
<thead>
<tr>
<th>“End Members”</th>
<th>Progressive Deformation: “Stages”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 0: Fold Pair (no fault)</td>
<td><img src="image" alt="Classic DF" /></td>
</tr>
<tr>
<td>Stage 1: DF</td>
<td><img src="image" alt="Classic FPF" /></td>
</tr>
<tr>
<td>before ramp</td>
<td>Rare?</td>
</tr>
<tr>
<td>during ramp</td>
<td><img src="image" alt="Brazeau case 2 (Newson)" /></td>
</tr>
<tr>
<td>after ramp</td>
<td><img src="image" alt="Classic FBF" /></td>
</tr>
<tr>
<td>Stage 2: FPF</td>
<td><img src="image" alt="DF or FP" /></td>
</tr>
<tr>
<td>No Footwall Syncline</td>
<td><img src="image" alt="“BTF”" /></td>
</tr>
<tr>
<td>Footwall Syncline</td>
<td><img src="image" alt="A/S in hw" /></td>
</tr>
<tr>
<td>No Footwall Syncline</td>
<td><img src="image" alt="Overprinting!" /></td>
</tr>
</tbody>
</table>

- **Transient structures:** folds travel with tip line
- **“Hanging wall folds evolve”**
- **“Hanging wall syncline”**
All Three Cases:

Footwall: Detachment Fold or “Fold Pair”

Hanging wall: Fault-Propagation Fold, evolved from Detachment Fold or “Fold Pair” (“Pre-Ramp folds”)
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CONCLUDING REMARKS

• All structures in the Rockies can be explained by progressive deformation
• Different strain paths can lead to the same geometry
• Our two folding mechanisms lead to observed structures
• Not all folds in the Rockies are the product of thrusting
• Many ramps appear to be the consequence of folding
• The current geometrical and kinematic fold-thrust models are insufficient
• True classic fault-propagation folds may be rare in the Rockies; they are frequently interpreted only
• There is ample evidence of material thickening and volume loss: rigour is needed when performing quantitative cross section construction
• All of the above applies to any fold-thrust belt
• Improved seismic imaging will reveal more thrusted A/S pairs: Caution is advised when drilling footwall structures
THE END – THANK YOU

This Presentation benefitted from Discussions with:

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Greg Soule
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