Acadian Sliding: Anatomy of Styles for Gravitational Fault Development and Hydrocarbon Migration in the Western Appalachian Foreland Basin of Pennsylvania and West Virginia*

Robert Jacobi[1,2], Joel Starr[1], David Jackson[3], Travis Warner[1], and Craig Eckert[1]

Search and Discovery Article #41126 (2013)
Posted June 17, 2013

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

[1]EQT Production, Pittsburgh, PA (rdjacobi@buffalo.edu)
[2]UB Rock Fracture Group, University at Buffalo, Buffalo, NY
[3]ARKeX, Cambridge, United Kingdom

Abstract

We often think folds and faults in the Appalachian Basin are exemplified by the Chestnut Ridge Anticline in southwest Pennsylvania. After all, it is one of the sites where “thin-skinned tectonics” first was recognized (Gwinn, 1964), and well logs and seismic have contributed to our view of this structure over the years (e.g., Beardsley, et al., 1999; Scanlin and Engelder, 2003). However, other structures in the western Appalachian Foreland Basin of Pennsylvania (PA) (western Allegheny Plateau of PA) may better illustrate structural elements that we can fashion into a complete structural and hydrocarbon migration model.

In northwestern PA, seismic lines display back rotated fault blocks that have the appearance of slump blocks (Figure 1). They appear similar to slump-block images in seismic reflection profiles off Labrador and off the coast of Norway (e.g., Loseth et al., 2011). The slump blocks are directed toward the hinterland, with a zone of removal on the (paleo) upslope side and an easterly directed thrust on the (paleo) downslope side of the block (Figure 1); many of the thrusts ramp up from the Onondaga or Tully (e.g., Figure 1). The primary decollement (glide plane) is below the Silurian F salt and is in the Silurian Vernon Formation—it is not in the Salina “F” salt. The zones of removal in the salt and Vernon section resulted in drape or collapse synclines above the glide plane. Onlapping the limbs of the collapse syncline, and in-filling the collapse syncline are Upper Devonian sediments, including the Upper Devonian Bradford and Elk sands. Thus, these structures initiated in the Late Devonian. They were not initially Alleghanian structures; rather, they were (neo) Acadian structures. Several seismic lines in NW PA demonstrate these slump block features with a Late Devonian age.

In PA one of the EQT 3D seismic areas displays spectacular folds and faults. Here too are fault blocks with the distinctive upslope zone of removal, downslope anticlines constructed from a thickened salt and Vernon section, and the east-directed thrust at the downslope border of the fault block (Figure 2).

Flattening on the Silurian Rose Hill reflector reveals that the zone of removal results primarily from the removal of section below the Salina F

salt down into the Vernon. Note that in the flattened section it is apparent that the F salt does not change thickness significantly across the zone of removal (Figure 3). The thick F salt here is NOT the unit that is causing the thinning—it is thin salts and fine-grained units in the Salina and Vernon below the F salt. Immediately downslope from the zone of removal are spectacular box fold sets and kink bands along a dramatic decollement, indicating that the section above the decollement slid downslope away from the zone of removal (Figure 4). At the downslope portion of the fault block system is a small anticline with associated thrust ramp. This anticline is different from the broad anticline in that its thickness increase results from not only the units underlying the F salt, but also from a slight thickening of the F salt in the core of the fold. Additionally, unlike the zone of removal, which shows almost no effect on the thickness of the F salt, the syncline downslope from the associated thrust-fault does show a thinning of the F salt, consistent with older concepts of withdrawing the (F) salt from adjacent regions for increased accumulation in the anticlines.

An isochron (isopach) map of the Rose Hill to base-of-the-F-salt interval shows the same contrast between structural features: significant thinning in the zone of removal, little thickening in the core of the anticline, and some thinning in the syncline adjacent to the thrusted anticline. In contrast, the base-of-the-F-salt to Onondaga isochron (isopach) map shows a dramatic thickening in the thrusted anticline but negligible thinning in the syncline.

Although the collapse syncline and fault block are hypothesized to be slump-related, the 3D seismic survey shows that the faults and zone of removal are not appreciably U-shaped in map pattern (unlike the upslope parts of many sediment slides and slumps); rather, the structural elements are constructed of linked individual segments that are extremely straight. The overall trend reflects the faulted upwarp in underlying reflectors (visible in Figure 4) that are related to through-going faults that offset basement. Flattening on the Elk Upper Devonian reflector indicates that these through-going faults (and associated upwarp) were reactivated in Late Devonian. These reactivated "basement" faults are similar to those that were hypothesized to have initially opened in Iapetan-opening times (e.g., Scanlin and Engelder, 2003; Jacobi et al., 2003, 2004a,b, Jacobi, 2010).

The anticline with the thrust fault (Figure 2) apparently was developing from Onondaga time through Bradford time, based on thinning and thickening reflector intervals. Flattening on successive reflectors above the Onondaga shows that the Marcellus and Geneseo black shales thin over the developing anticline, and that the Rhinestreet thickens appreciably on the limb of the anticline. Significant differential deposition over the anticline in the Rhinestreet-to-Elk interval and the Elk-to-Bradford sand interval totally remove effects of the anticline farther upsection. Similarly, the thrust fault also climbs only to the Elk or Bradford (depending on the location). Thus, we suggest that the anticline and its associated thrust are also Acadian in age. In contrast, the broad anticline indicated by the bracket in Figure 2 clearly affected the highest reflectors we recorded, and thus, it is primarily an Alleghanian feature.

That reflectors representative of the Upper Devonian Bradford and Elk onlap the collapse syncline over the zone of removal indicates that the syncline and syn-slumping phase faults developed initially during the (neo) Acadian, not Alleghanian. All these faults were thus already present when the sediments subsided into the oil and gas windows during the Alleghanian. We propose that these fault systems were conduits for oil and gas migration, which resulted in charging the Upper Devonian sands (and also probably resulted in seeps at the seafloor). Subsidence curves suggest that oil was generated in the Carboniferous and gas from Permian onward (Chris Willan and Scott McCallum, personal communication, 2012). Independent evidence, from which we might infer that the faults were indeed present and open when the sediment entered the oil and gas windows, comes from two sources. In a core of Devonian fine-grained sandstone, associated pyrobitumen was observed; it might indicate a liquids charge to the system from underlying black shales and subsequent conversion to gas. For gas migration times, limited image log data suggest that the orientation of J1 fractures deviates close to the fault. If that observation is correct, then the fault was open at the time of J1 generation. Thus, the gas-driven J1 fractures delivered gas in the fractures directly to the faults, which were open.

A summary cartoon of some of the critical elements in the slump model is shown in Figure 5. Note that in this model the effects of the Alleghanian orogeny are not shown.

References Cited

Beardsley, R.W., R.C. Campbell, and M.A. Shaw, 1999, Appalachian Plateaus, *in* C. Schultz, (ed.), The Geology of Pennsylvania: Pennsylvania Geological Survey (Harrisburg), Special Publication, v. 1, p. 286-297.

Gwinn, V.E., 1964, Thin-skinned tectonics in the Plateau and northwestern Valley and Ridge provinces of central Appalachians: GSA Bulletin, v. 75, p. 863-900.

Loseth, H., L. Wensaas, and M. Gading, 2011, Deformation structures in organic rich shales: AAPG Bulletin., v. 95/5, p. 729-747.

Jacobi, R.D., J. Fountain, C. Lugert, T. Nelson, G. Smith, and Industrial Associates, 2003, Characteristics of Trenton/Black River structures in the Finger Lakes: Progress Report: Silver Jubilee Anniversary Symposium, Gerald Friedman, organizer: Northeastern Science Foundation, Troy, NY, p. 23-24.

Jacobi, R.D., S. Loewenstein, G. Smith, J. Fountain, and T. Nelson, 2004a, Faults and hydrocarbon resources in the Appalachian Basin of New York State: GSA Abstracts with Programs, v. 36/2, p.146.

Jacobi, R.D., S. Loewenstein, G. Smith, J. Fountain, C. Lugert, and J. Martin, 2004b, Iapetan opening/Rome trough-related faults and their reactivation history in New York State: AAPG Search and Discovery Article #90031. Website accessed 21 May 2013. http://www.searchanddiscovery.com/abstracts/html/2004/eastern/jacobi02.htm

Jacobi, R., 2010, Geophysical and geological evidence for arcuate Iapetan opening rift faults in the Pennsylvania Salient and New York recess: implications for the ragged Laurentian margin: NYSERDA, Albany NY, Final Draft Report, 42 p.

Scanlin, M.A., and T. Engelder, 2003, The basement versus the no-basement hypothesis for folding within the Appalachian Plateau detachment sheet: American. Journal Science, v. 303, p. 519-563.

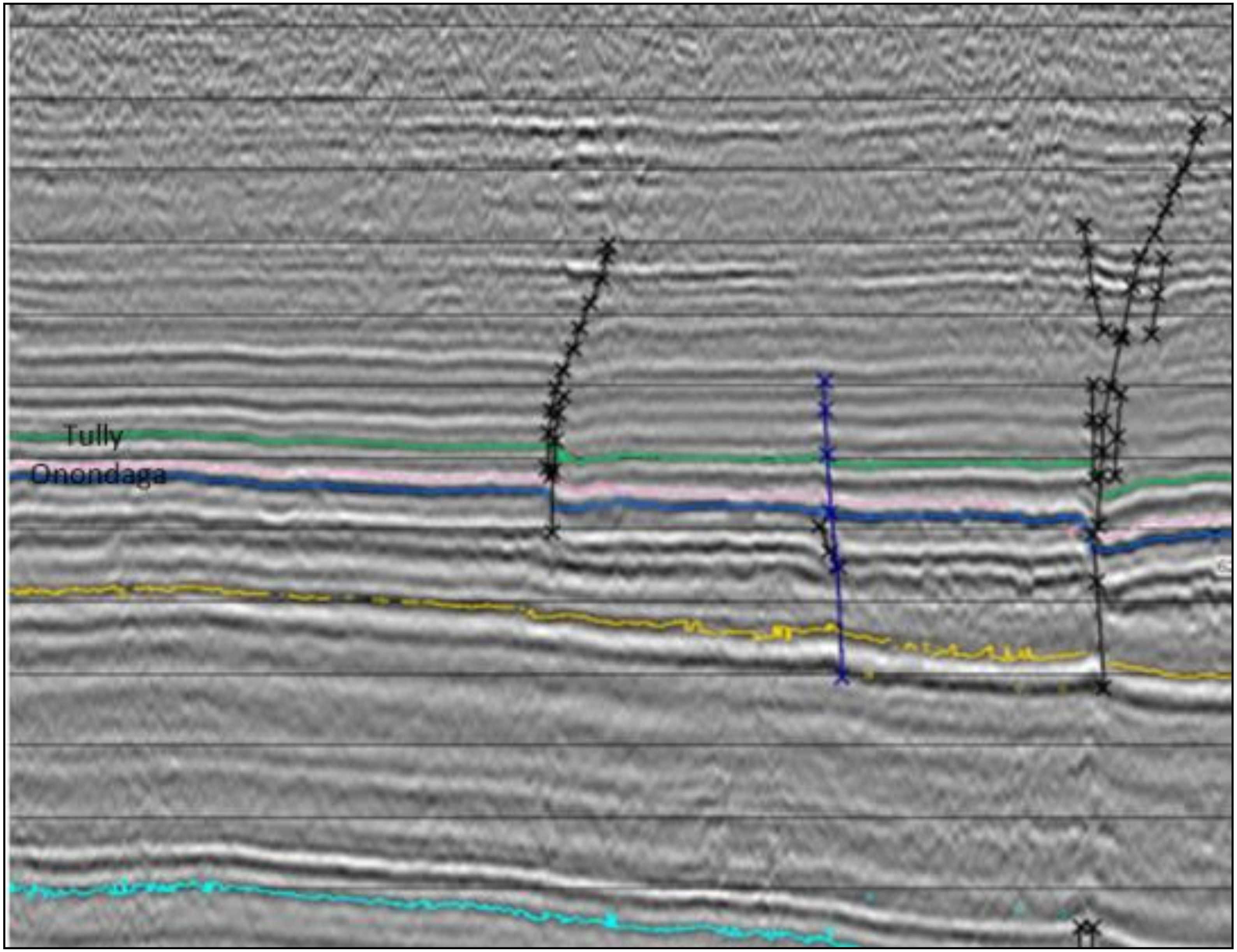

Figure 1. Rotated fault blocks gliding on Vernon and lower Salina.

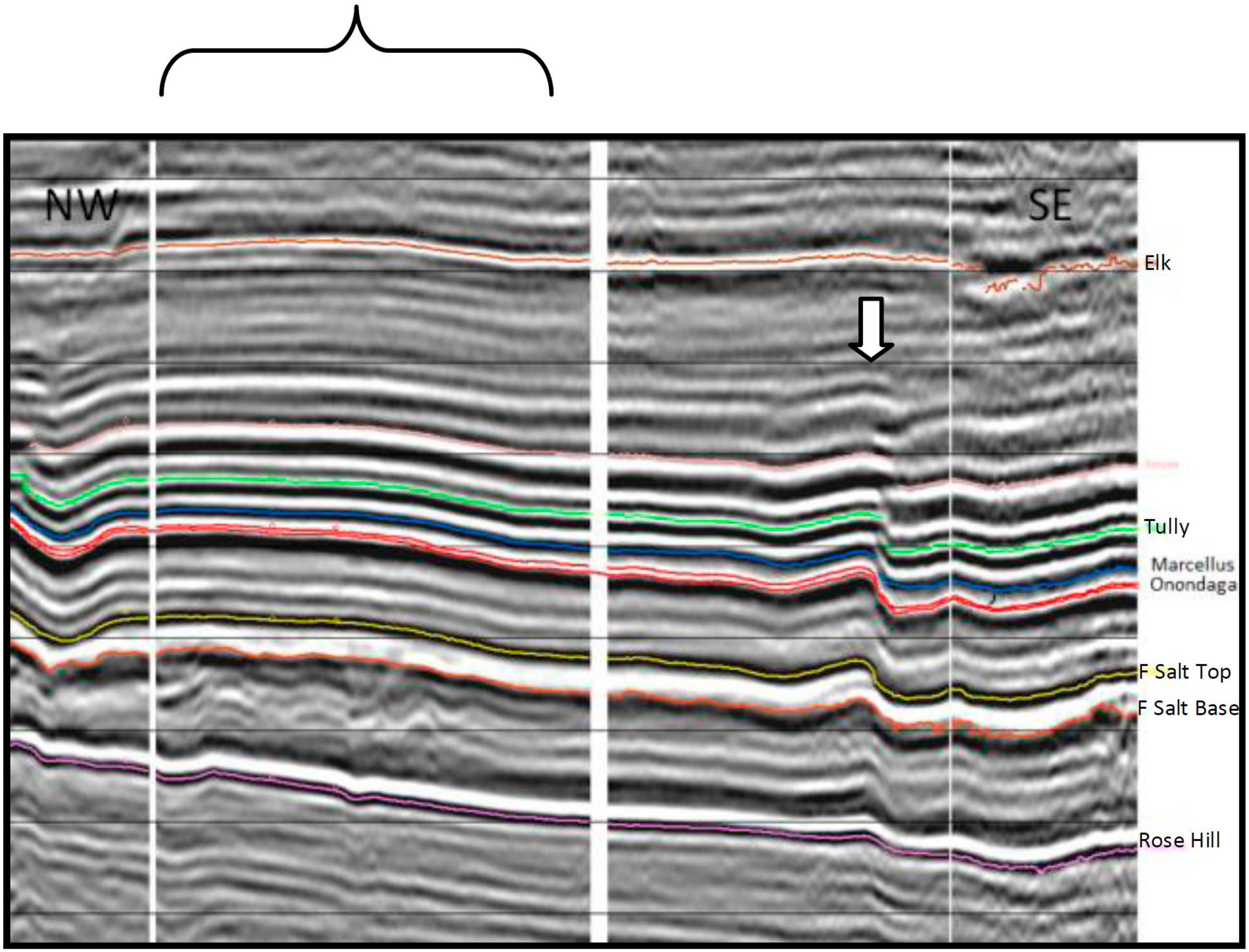

Figure 2. Seismic reflection section from a 3D seismic survey in PA. Broad, low-amplitude anticline discussed in text is indicated by bracket. Arrow indicates the thrust-fault-associated anticline.

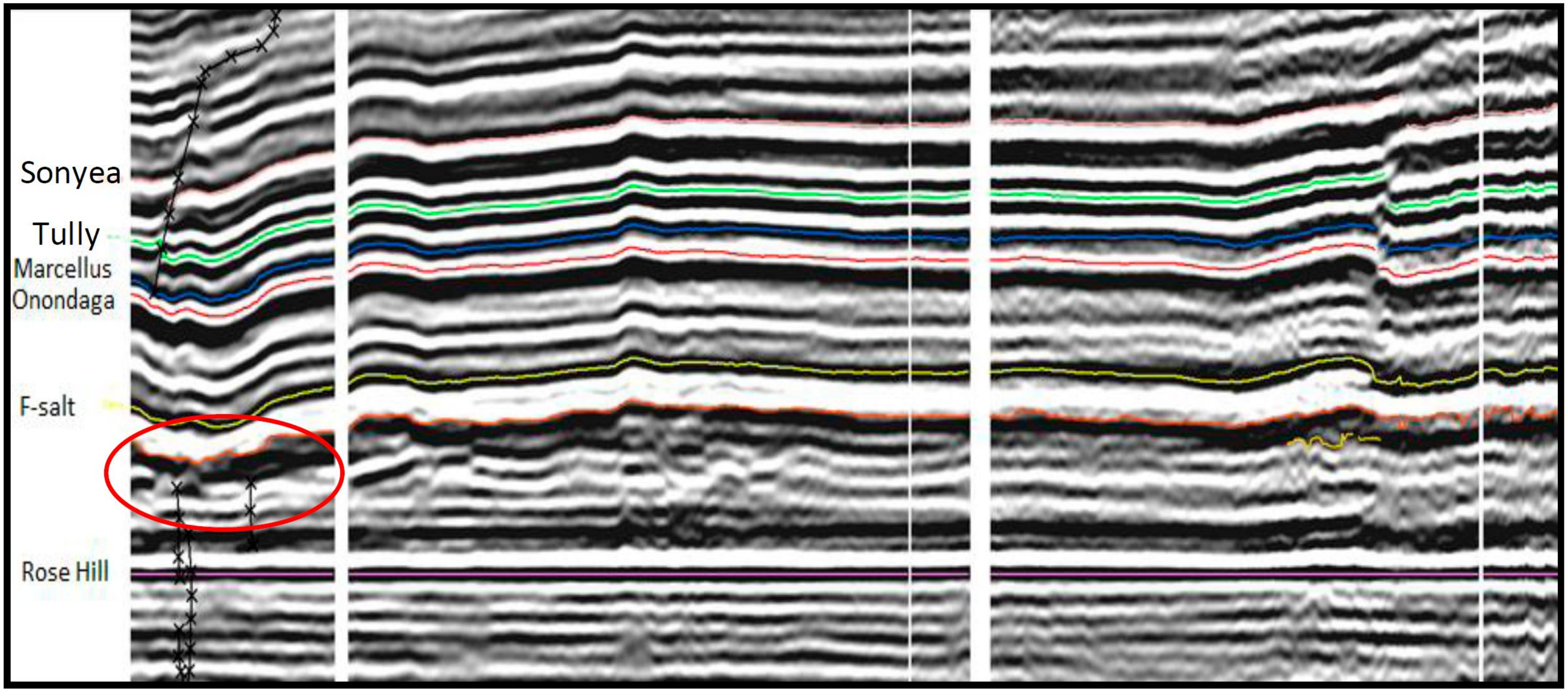

Figure 3. Seismic reflection section from a 3D seismic survey in PA, flattened on Silurian Rose Hill reflector. General location of the zone of removal discussed in text is indicated by the ellipse. Seismic section is in the same location as Figure 2.

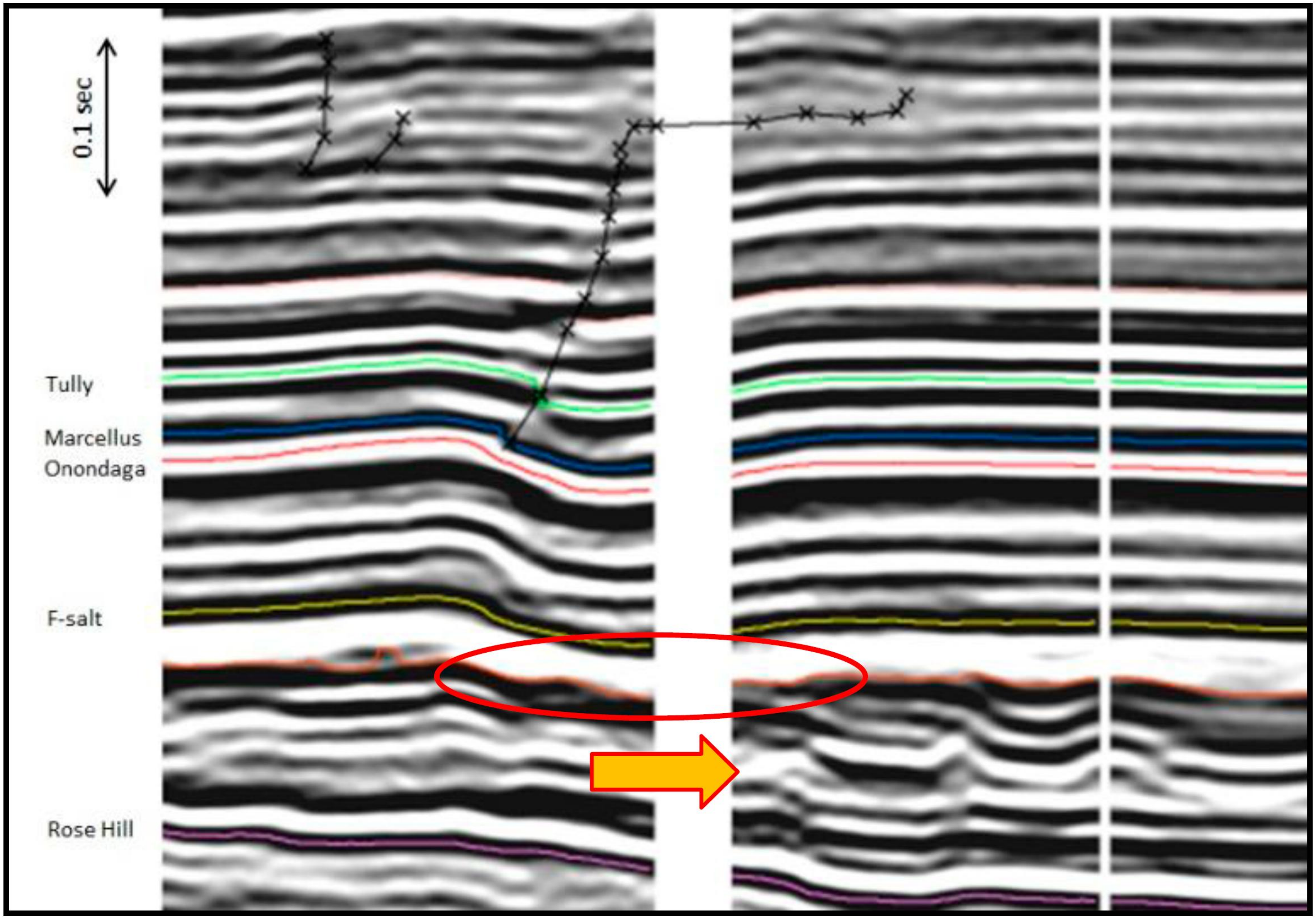

Figure 4. Seismic reflection section from a 3D seismic survey in PA. Selected faults indicated. Major decollement obvious at horizon indicated by arrow. The zone of removal that results in the drape syncline can be seen just above the arrow where the F salt cuts down-section in the syncline (indicated by the ellipse).

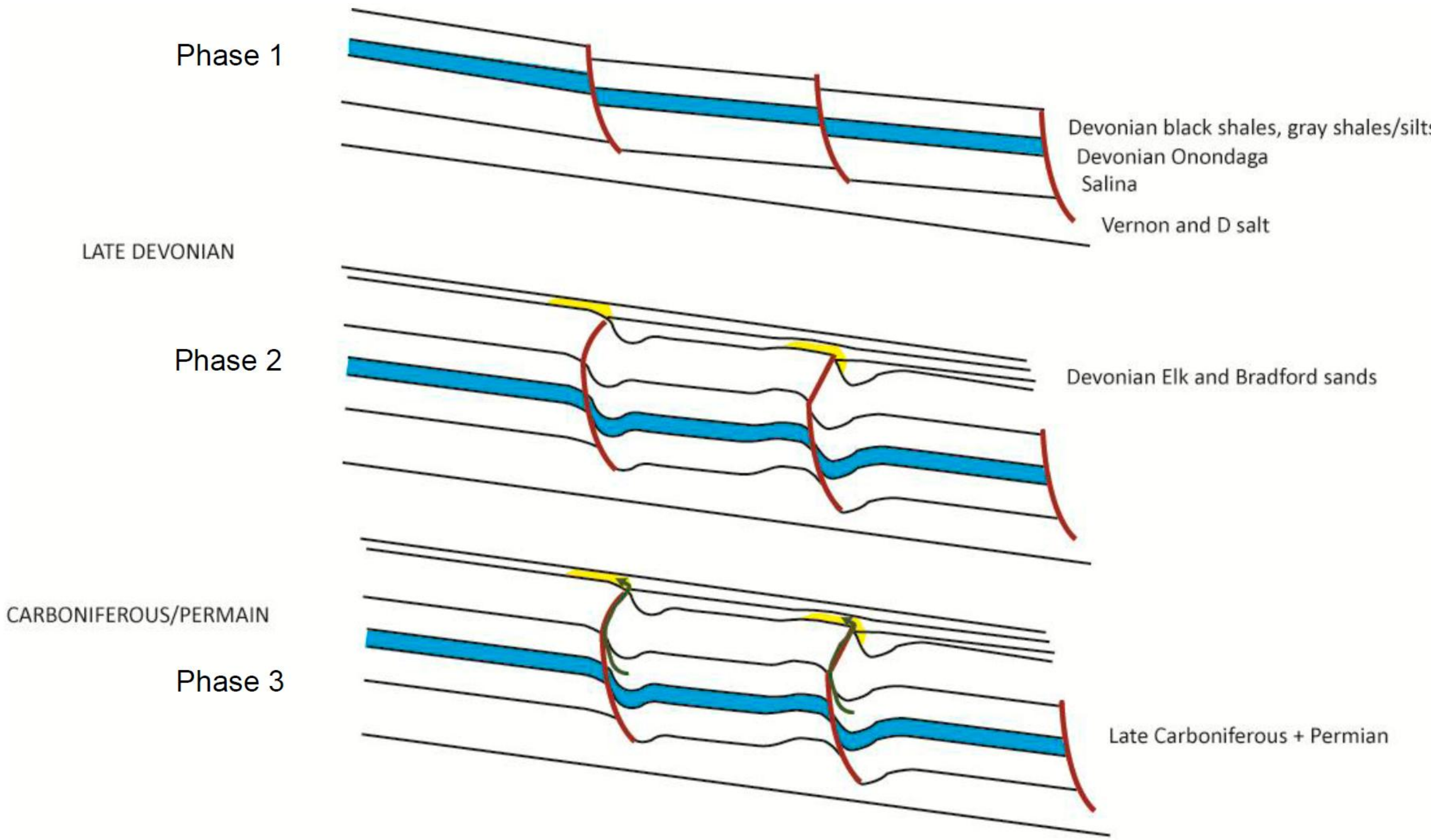

Figure 5. A summary cartoon of some of the critical elements in the Acadian slump model. Green lines with arrows indicate hydrocarbon migration. Yellow blobs indicate Bradford and Elk sands. Phase 1 and 2 are Late Devonian in age. Note that the Alleghanian structural effects are not displayed in this model.