Sequence of Deformation in Thrust-Fold Belts: Implications for Cross-Section Balancing*

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Abstract

The complex deformational history of thrust-belt structures has implications for the validity of cross-section balancing. 1) The first structures to form are regional fracture sets generated by prevailing plate tectonic stresses. 2) As the thrust wedge grows, the tectonic load flexes the foreland crust leading to extensional fractures sub-parallel to the thrust belt. 3) With continuing thrust advance, the foreland basin rocks experience a third phase of fracturing induced by near-field thrust-tectonic stresses. 4) Perhaps overlapping with stage 3, dominant units, such as carbonate and coarse clastic rocks, undergo layer-parallel shortening (LPS) by pressure-solution cleavage, wedging, and tectonic compaction. Bedding plane detachments accommodate contraction within the LPS zones to produce fold-, cleavage-, and fault-duplexes. 5) The various detachments may link to form through-going thrusts, generating ramp anticlines (fault-bend folds), detachment (lift-off) folds, and fault-cored anticlines (fault-propagation folds). 6) As thrust-related folds evolve, fractures and subsidiary faults initiate in response to constantly changing stress fields in the dominant members. This complex and protracted sequence of deformation raises conflicts with the underlying assumptions of cross-section balancing. Zones of LPS, joined by bedding parallel detachments, produce cryptic global shear strain throughout individual thrust sheets and the thrust wedge as a whole. Cross-section balancing relies on measuring line-lengths and/or areas between established pin-lines, lines perpendicular to bedding in regions presumed to have experienced only plane strain. If rocks have experienced extensive global shear, this assumption is invalid. The validity of balancing is further compromised by an inability to predict the magnitude and distribution of sub-resolution strain produced by LPS in stage 4. Finally, geometric and kinematic relations between thrusts and folds may not be as simple as portrayed in common balancing approaches. Thrust-belt cross sections usually show continuous, through-going master faults (step 5 above), which originate at great depth within the hinterland and step-up section toward the foreland to terminate in triangle zones or emerge at the earth's surface. However, at various stages in their evolution, discontinuous thrust segments may be linked by single folds and fold duplexes, leading to alternative interpretations for many “balanced” sections.

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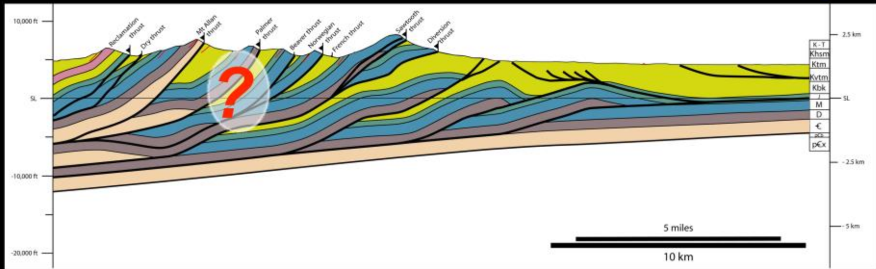
Sequence of Deformation in Thrust-Fold Belts

Implications for Cross-Section Balancing



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Presenter's notes: I have been I have been balancing sections for 40 years with varying degrees of success. Ironically I had the most trouble with the best data sets. The best subsurface data goes with the sections I could not balance.

So for more than a decade I've been trying to reconcile this dilemma. While studying this material, please forget everything you've ever learned about balancing cross-sections and entertain the thought that perhaps the section should not balance.

As petroleum geologists, our goal is to predict accurately the geometry of structures so as to successfully explore for hydrocarbons. To do so, we often employ cross-section balancing in order to obtain the most valid interpretation possible. However, the process of balancing is complicated by the complex deformational history of compressional terranes. In this presentation I wish to discuss outcrop-scale structures and the effect they have on the validity of cross-section balancing techniques.

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Quantifying the geometry, displacements, and subresolution deformation in thrust-ramp anticlines . . . Journal of Structural Geology, v. 69, p. 304-319.

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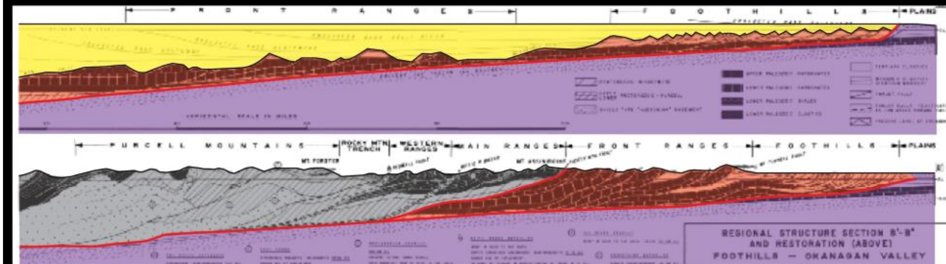
Presenter's notes: This is not news, as Rick Groshong and others (as noted herein) have previously noted the shortcomings of balancing and the difficulties of accounting for sub-resolution strain. I should note that Rick Groshong, Martha Withjack and others have proposed ways to tackle the problem I am about to illustrate. My purpose today is simply to remind you that balancing is far more complicated than it might at first appear.

Balancing & Restoration

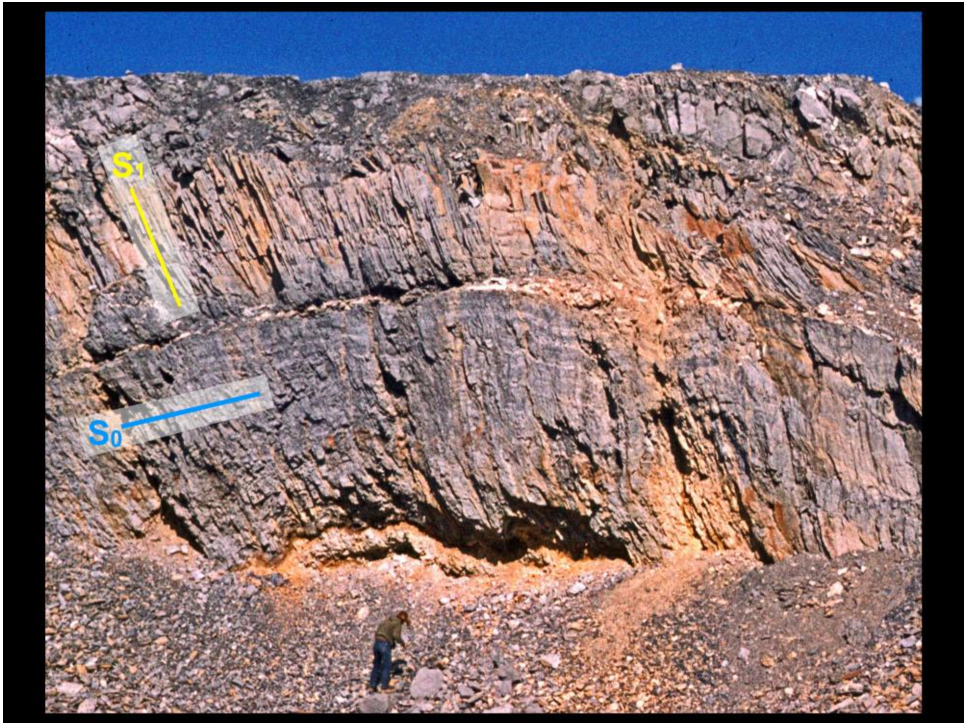


Bally, Gordy & Stewart (1966)
Structure, seismic data, and orogenic evolution of
southern Canadian Rocky Mountains
Bulletin of Canadian Petroleum Geology, v 14, p 337-381

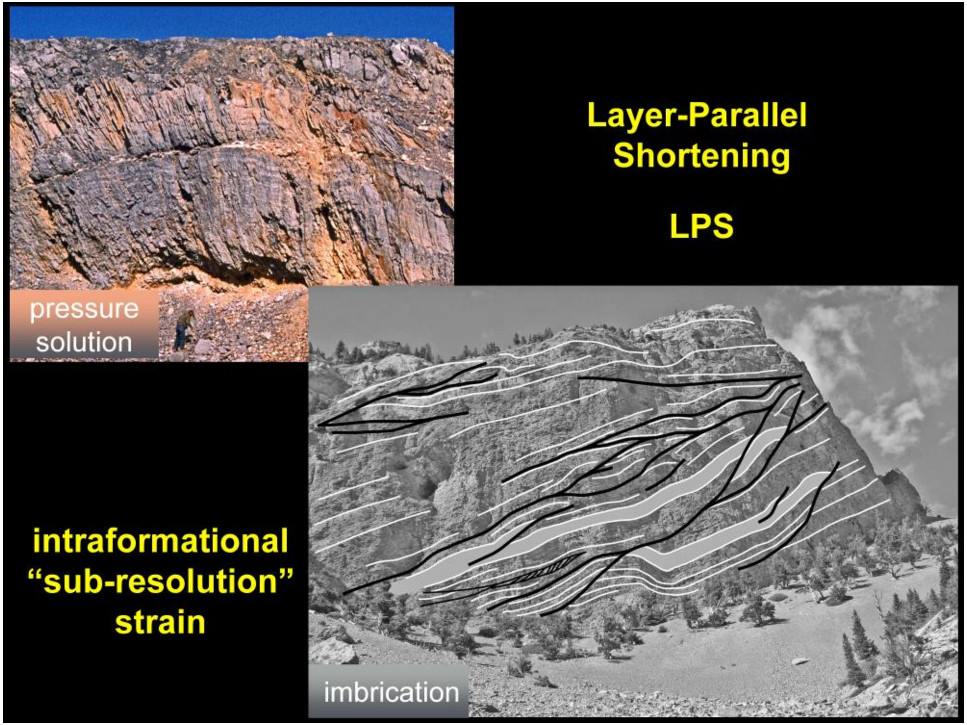
Dahlstrom (1969)
Balanced cross sections
Canadian Journal of Earth Sciences, v 6, p 743-757

Presenter’s notes: As an exploration tool, cross-section balancing and restoration has been employed for about 50 years, having been created in its current form by petroleum geologists working in the Alberta Foothills of Canada. Bally, Gordy, and Stewart, working for Shell, are frequently cited as having published the first examples of regionally balanced and restored sections, and & Dahlstrom of Chevron wrote a classic paper on the balancing method. Bert Bally and Clint Dahlstrom have never taken credit for the concept, however, noting that balancing was widely employed by Alberta geologists by the late sixties. Yet, it was through their publications that US geologists working the Rockies and Appalachians became familiar with the method.

Balancing is based on the simple concept that matter is neither created nor destroyed, the Law of Conservation of Matter. The mass of the restored section should equal the mass of the deformed section. When reduced to a cross section, this means that conservation is conserved. As noted by Dahlstrom in his classic balancing paper, if folds are concentric, as often seems to be the case, then the constant-area test can be simplified to a comparison of line lengths between units and between the deformed and restored sections. The method seems to work well on a regional scale. Howeever, even here I would like you to take note of a problem. What is all that yellow "stuff" that makes up approximately 2/3 to 3/4 of the restored section. That is missing section removed by erosion. How does one balance "stuff" that is not there. Answer: we can’t. Problem one. Now it gets more interesting.



Presenter’s notes: If you read much of the petroleum literature you would never know that pressure-solution cleavage exists. It is rarely mentioned, but yet it can account for strains in excessive of 50%, and if the system is open to fluid flow, as is often the case, then this 50% strain equates to 50% volume loss. Since some of you may not be familiar with pressure-solution cleavage, I provide a brief explanation. In this photo you can see folded Upper Silurian, possibly Lower Devonian, Tonoloway Limestone. Bedding indicated by So. Calcite veining indicates the presence of a bedding plane detachment. The yellow line, perpendicular to bedding, is cleavage, indicated by S1. Cleavage is produced when calcite is removed by pressure solution, passes out of the system by migrating formation and meteoric waters and leaves a residue of insoluble minerals. The rock is weakened & splits along the planes of selvage material to produce the cleavage pattern of this photo.



Presenter's notes: This internal imbrication makes up what has become known as layer-parallel shortening. The term was coined to describe tectonic compaction and pressure-solution cleavage depicted in the photo at upper left. This sub-resolution strain may make up 10-50% of the overall tectonic shortening. Regionally, it may average out at 35%. In distal portions, far onto the foreland, the LPS may be 10%. Locally it approaches 50%.

In addition to LPS by internal imbrication, the other form of LPS shortening is by pressure solution. Tectonic compaction is yet another. By discounting tectonic compaction here, please realize that when I discuss PS cleavage and imbrication, I am only covering 2/3s of possible LPS strain. The missing 10-50% occurs as LPS. Pressure-solution cleavage and internal imbrication constitute what is known as layer-parallel shortening, abbreviated as LPS. I believe Pete Geiser or Terry Engelder coined the term LPS. Rick Groshong calls such strain "sub-resolution", indicating that these features cannot be imaged and accounted for with seismic reflection methods. Because they rarely can be adequately accounted for when constructing cross sections, the sections should rarely balance. In fact, I now think that a perfectly balanced section is most certainly wrong, invalid.

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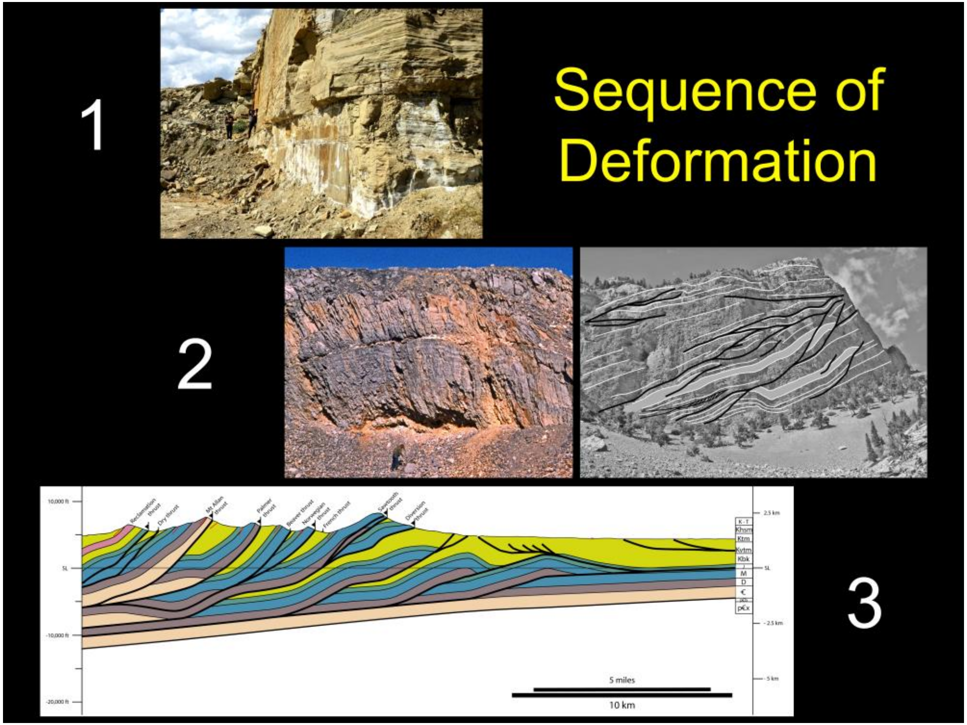
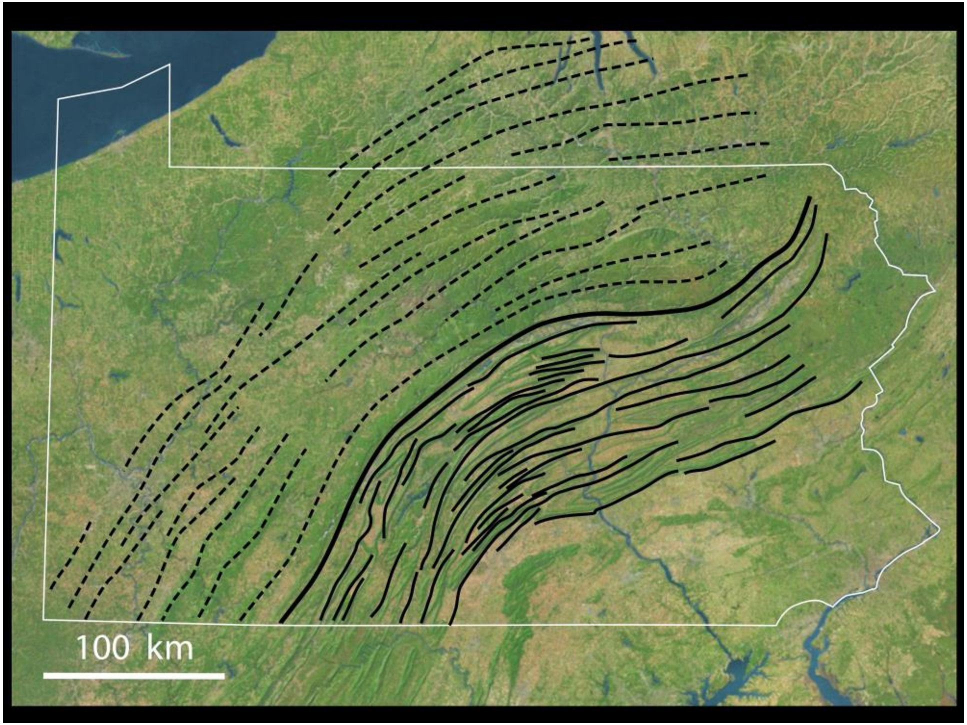
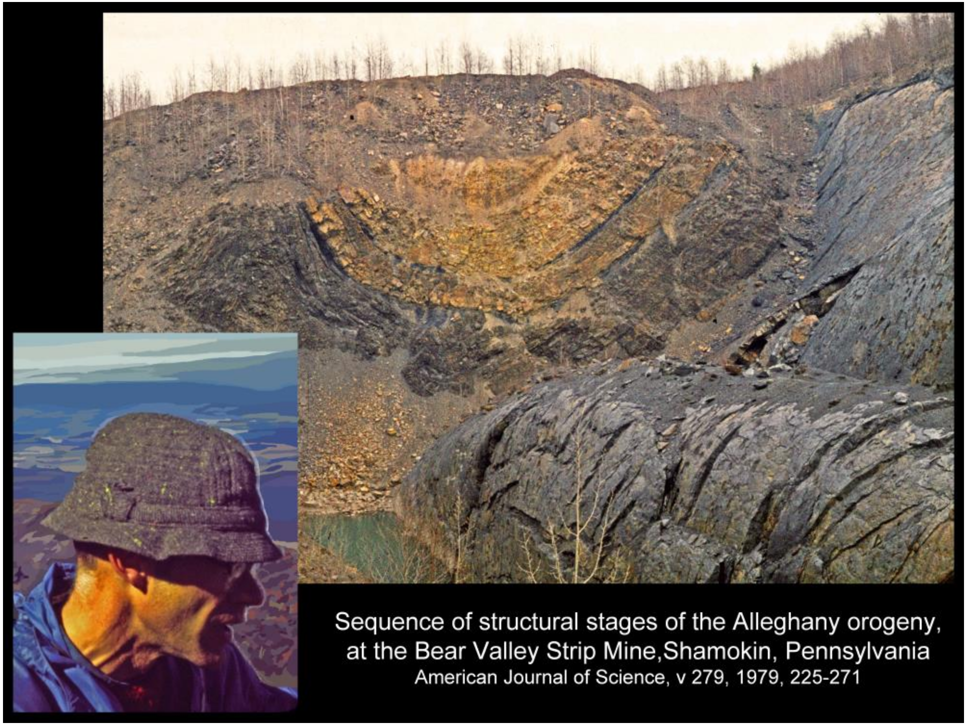


Presenter’s notes: This layer-parallel shortening by PS cleavage and imbrication is the 2nd phase of deformation. As noted above, time constraints do not allow for discussion here of tectonic compaction, also a very important part of LPS. The sequence of deformation: 1) brittle fractures, 2) ductile pressure-solution cleavage and brittle intraformational faulting, and 3) the major thrust-fold structures that become the exploration targets. Fracturing may occur at all stages, especially during fold development.

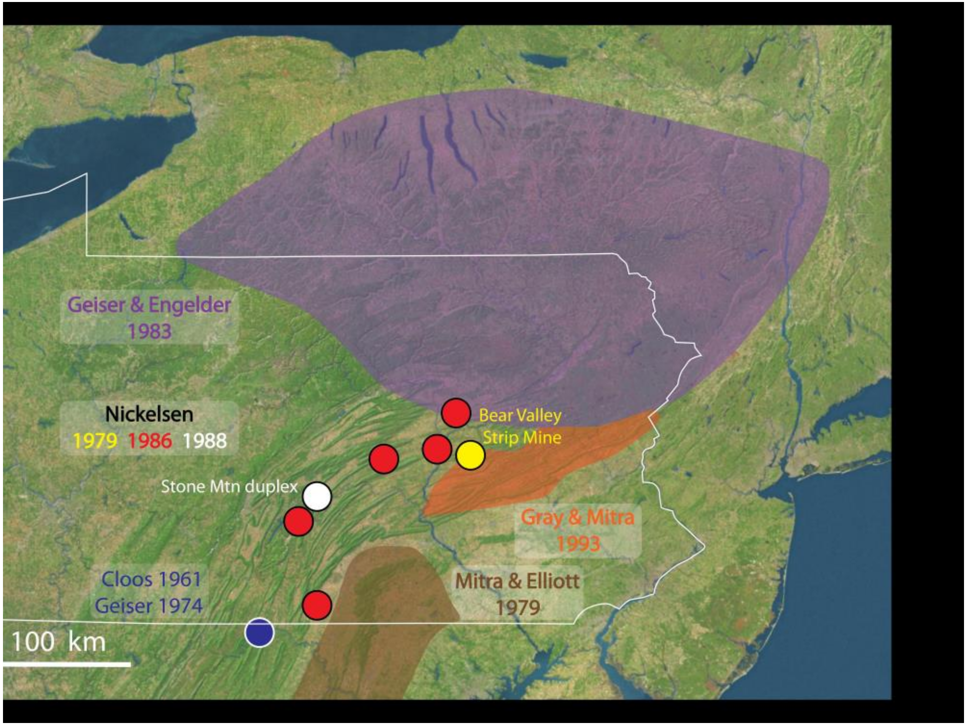
As petroleum geologists and geophysicists, we commonly focus on two scales of deformation and three types of structures – fractures, major thrust faults & folds. These are the scales that normally attract the petroleum geologist. The production geologist and the petrophysicist are interested in fractures. The exploration geologists and geophysicists are interested in defining traps by interpreting reflection seismic and constructing cross sections. Herein I am interested in the intervening stage of penetrative deformation at the outcrop scale, pressure-solution cleavage and internal imbrication.



Presenter's notes: The 2012 paper by Sak and others, published in Geosphere, provides a very good summary of the problem with suggested solutions.



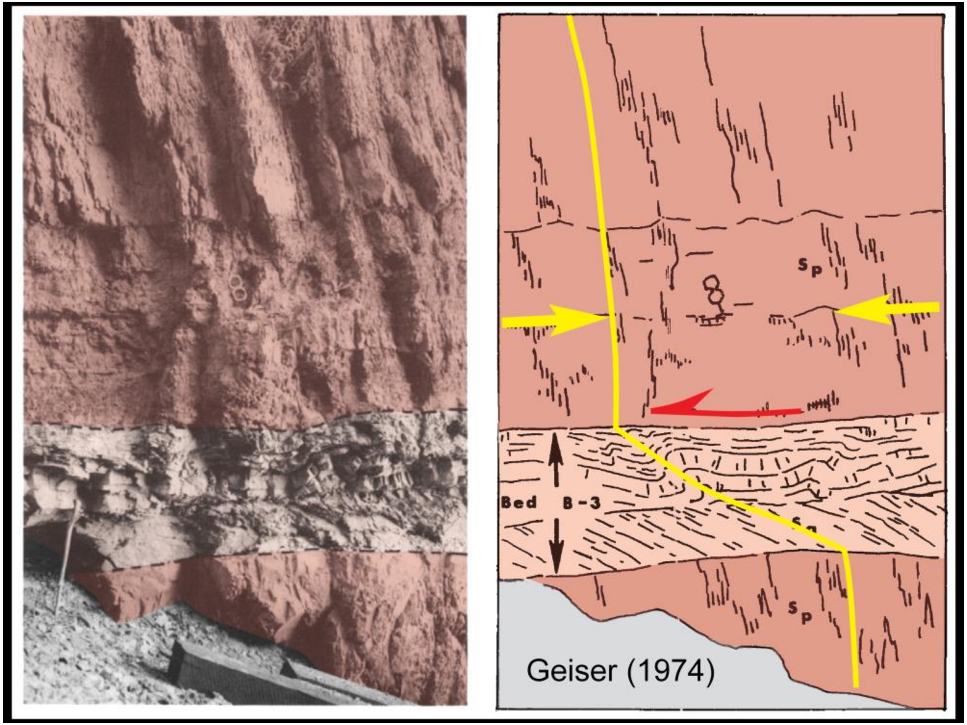
Presenter’s notes: I dedicate this presentation to two of my mentors, Richard Nickelsen, Nick to his friends & colleagues, and Dave Elliott. Nick was the consummate field geologist who never left a stone unturned, and Dave Elliott, who loved being in the field, is best known for his work on thrust mechanics and cross-section balancing. From Dave’s interaction with Shell geologists in Calgary, he came back to John Hopkins enthused about the potential of balancing to aid in better structural interpretation. The computerization of cross-section construction and balancing remained one of Dave’s interests at the time of his death.



Presenter's notes: Now, I'd like to take you on a virtual field trip. Most of us get structural geology training as undergraduates. We may go to a field camp and actually look at rocks, but in later years, we go to work in industry, put on coat and tie and retreat to air-conditioned offices to look at well logs and seismic-reflection data. We may never again set foot in the field, except for the occasional field school.

But real geology is in the field. What we work on in the office is not geology, it is a map of the geology. None of us would confuse the map for the road when we drive a car. When we go on a hike, we realize that the map is not the terrain. Maps are representations of the terrain, the road. It id one thing to look at a map; it is quite another to get in your car and drive the route. The same is true with seismic data. It is a map of the terrane, it is not the terrane. So now let's go to the field and see what rocks really do.

The focus is on Pennsylvania. Why? Balancing problems noted by Gwinn in the 1960s have troubled geologists ever since. over 50 years of good field work has gone into understanding the evolution of this terrane on the outcrop scale. Real geology: I only have a time to touch on a very few of the important contributions.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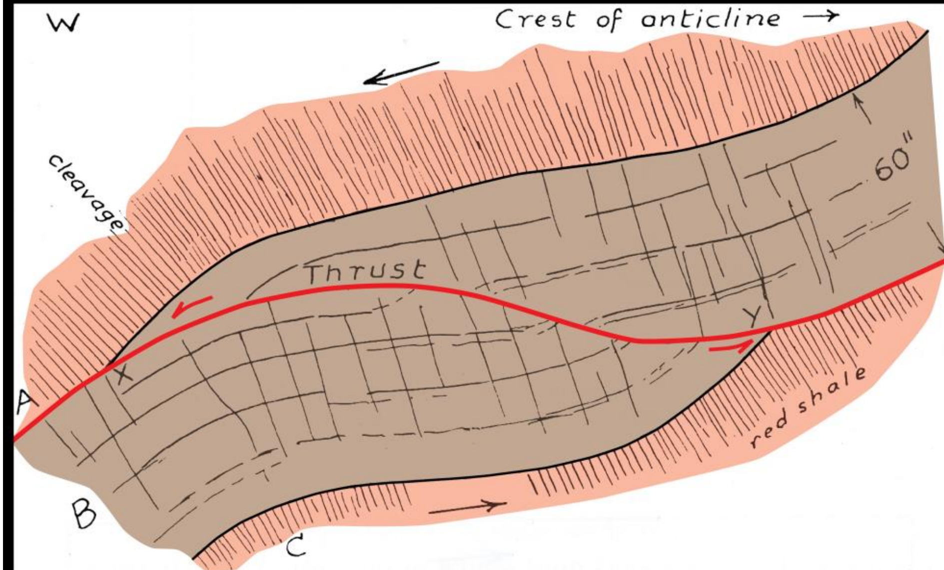
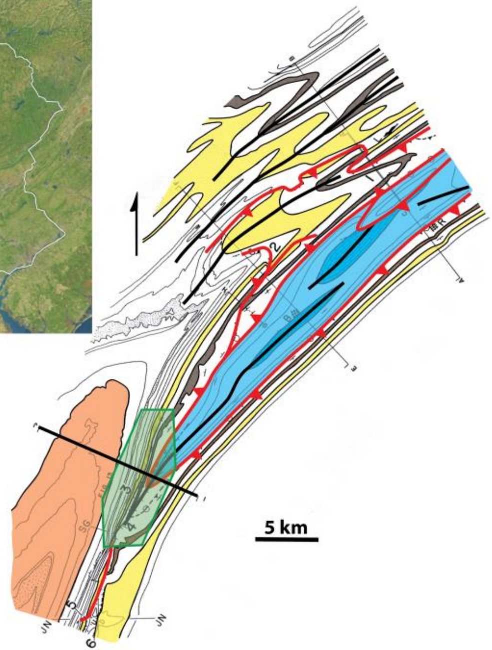
Geiser (1974)

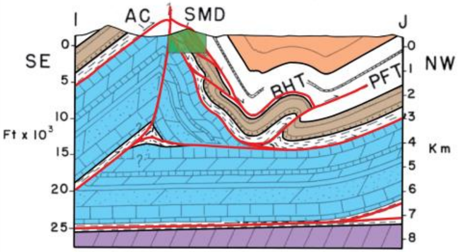


Cloos (1961) – Bedding slips, wedges, and folding . . .

Extrait des Comptes Rendus d la Société géologigue de Finlande



Nickelsen 1988
Structural evolution of
folded thrusts & duplexes . . .
GSA SP 222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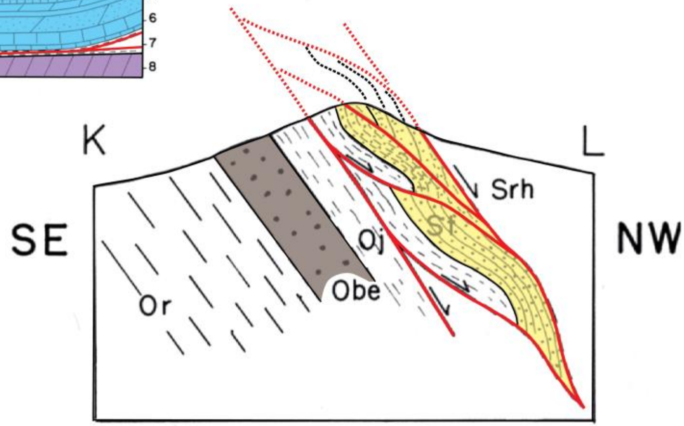
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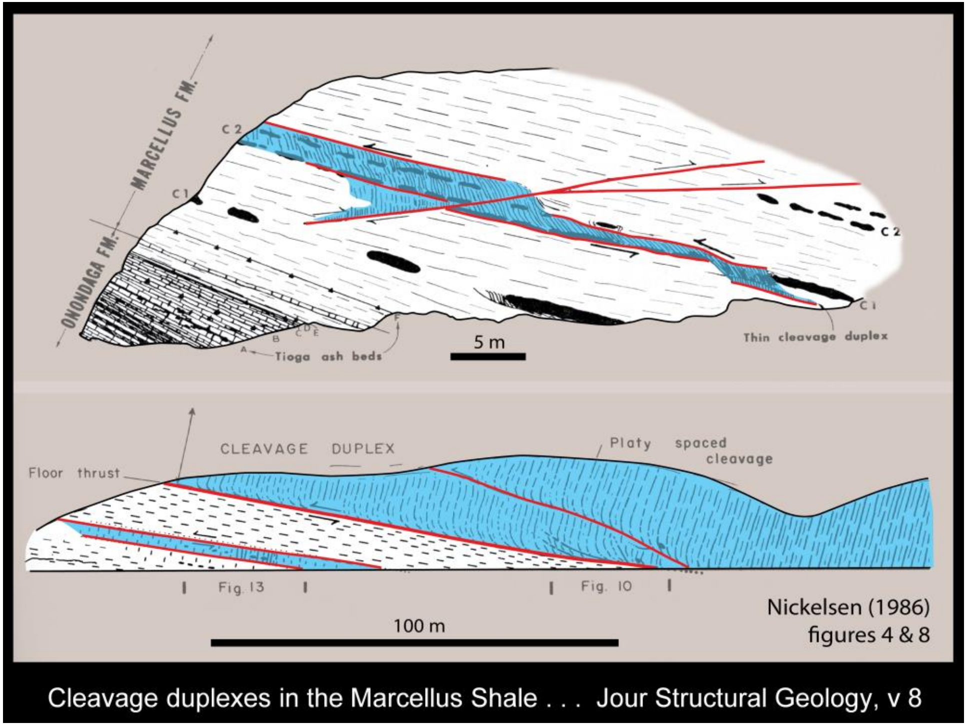
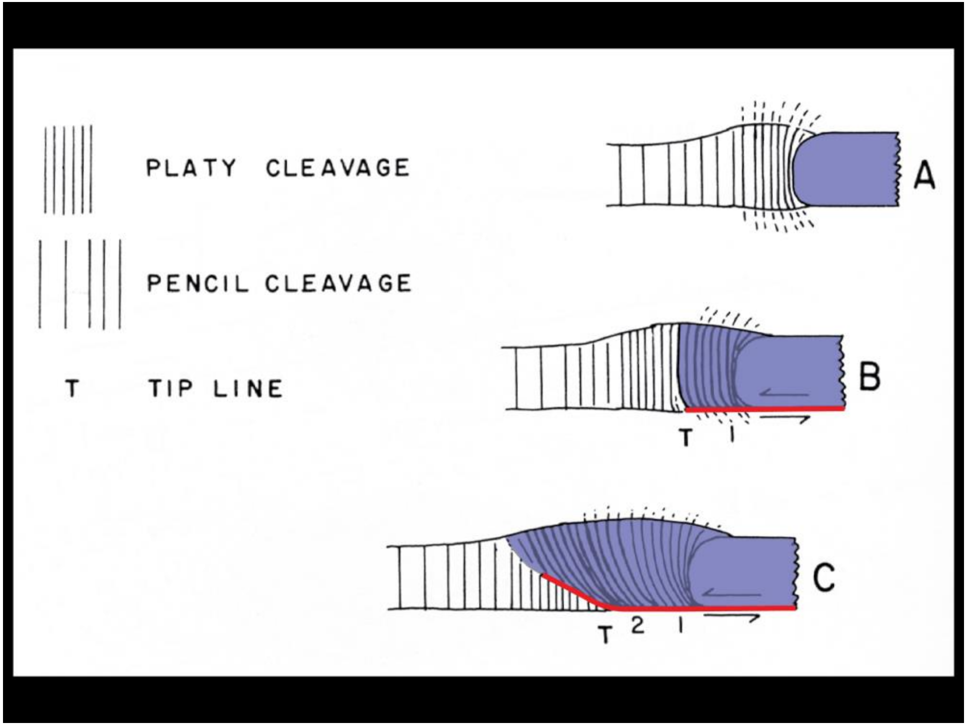


Presenter's notes: Top of Onandaga, a bentonite, is radiometrically dated at 390 Ma.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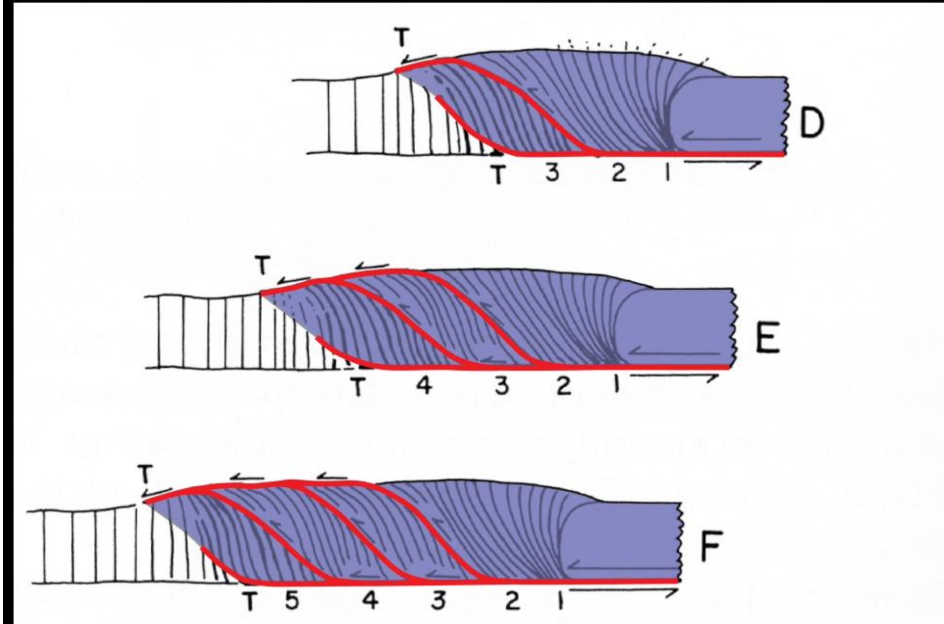

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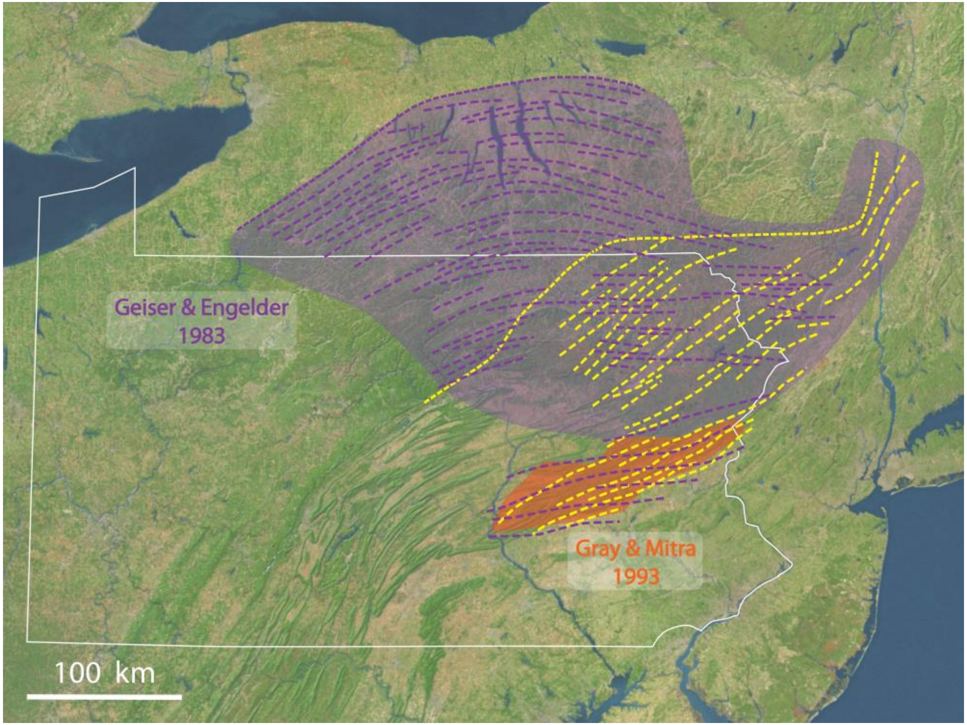

Geiser & Engelder
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Gray & Mitra
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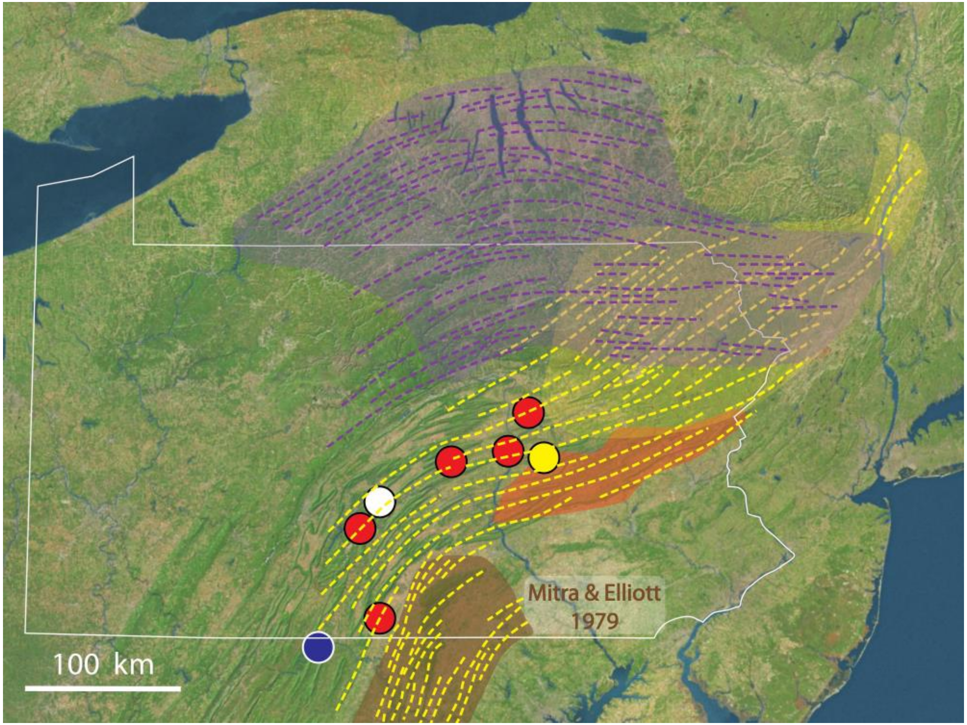
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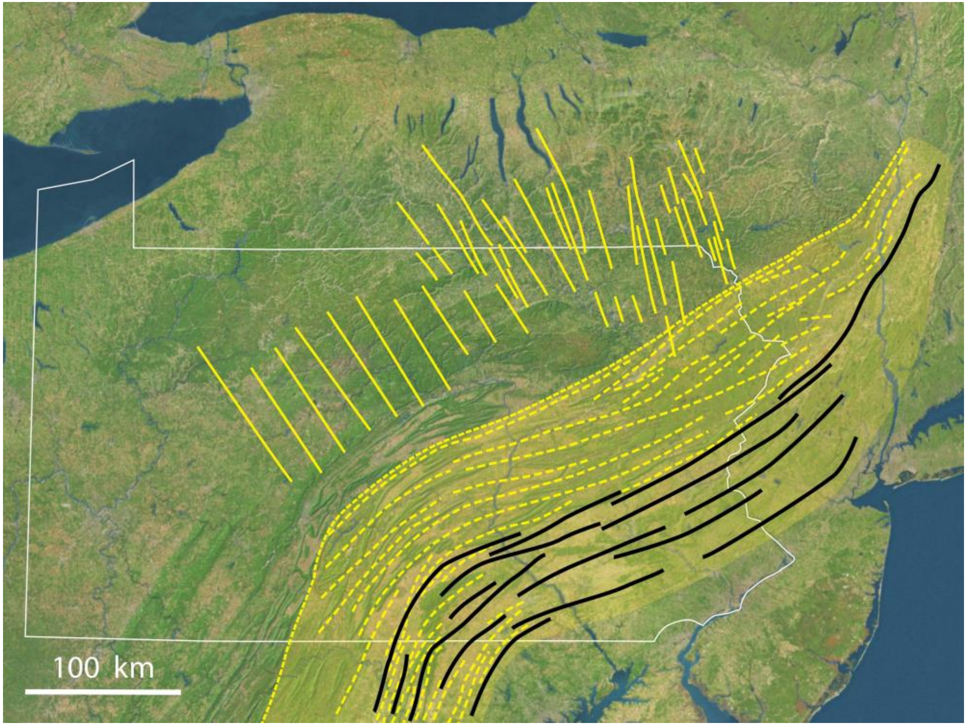
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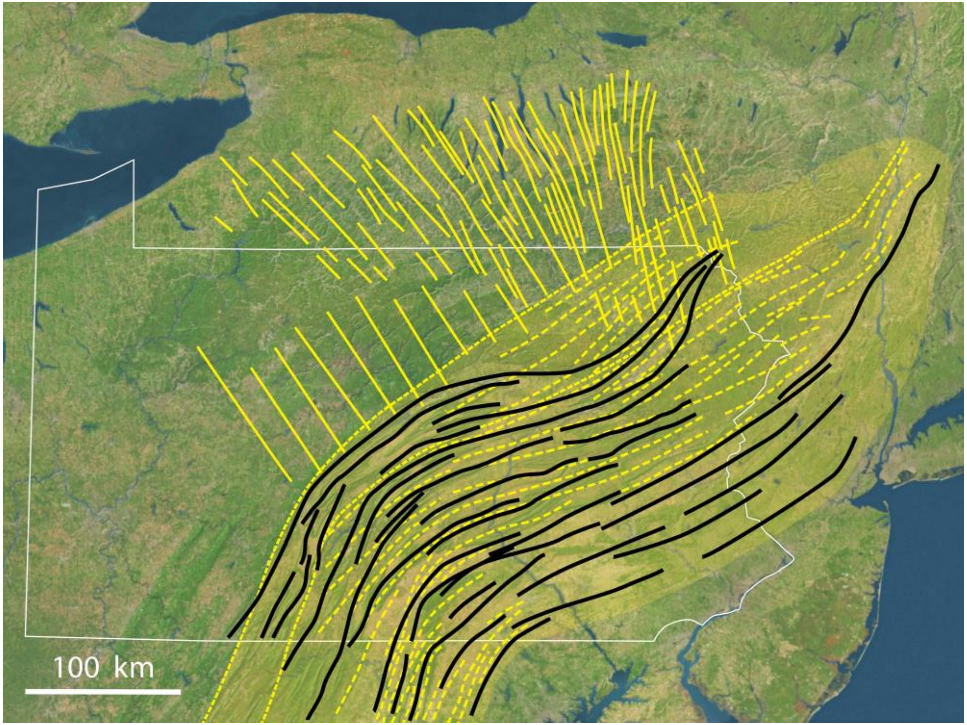
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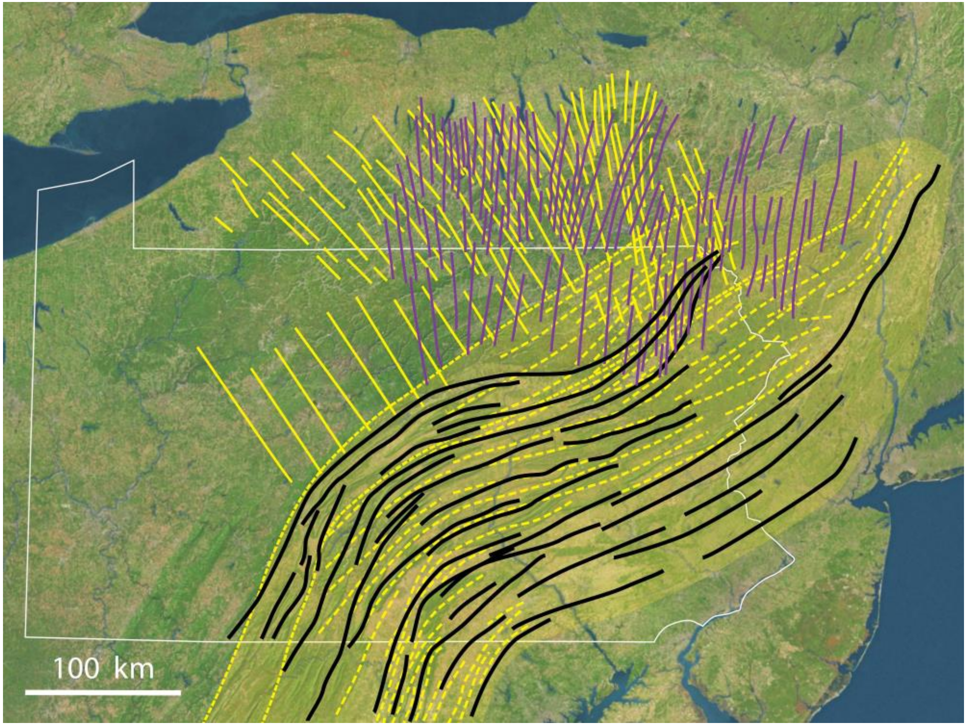
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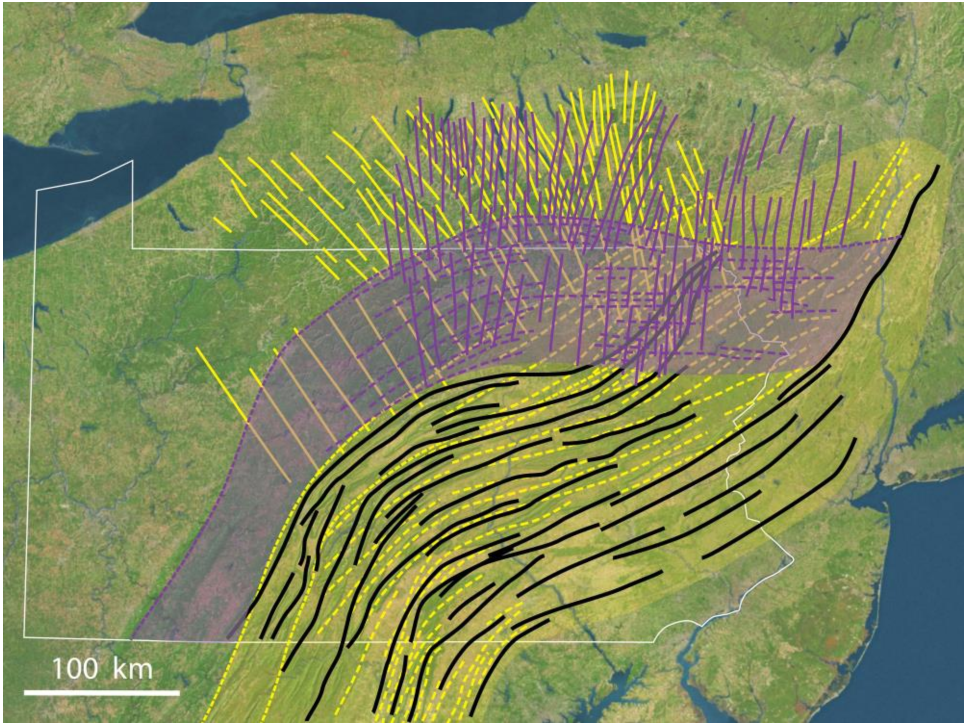
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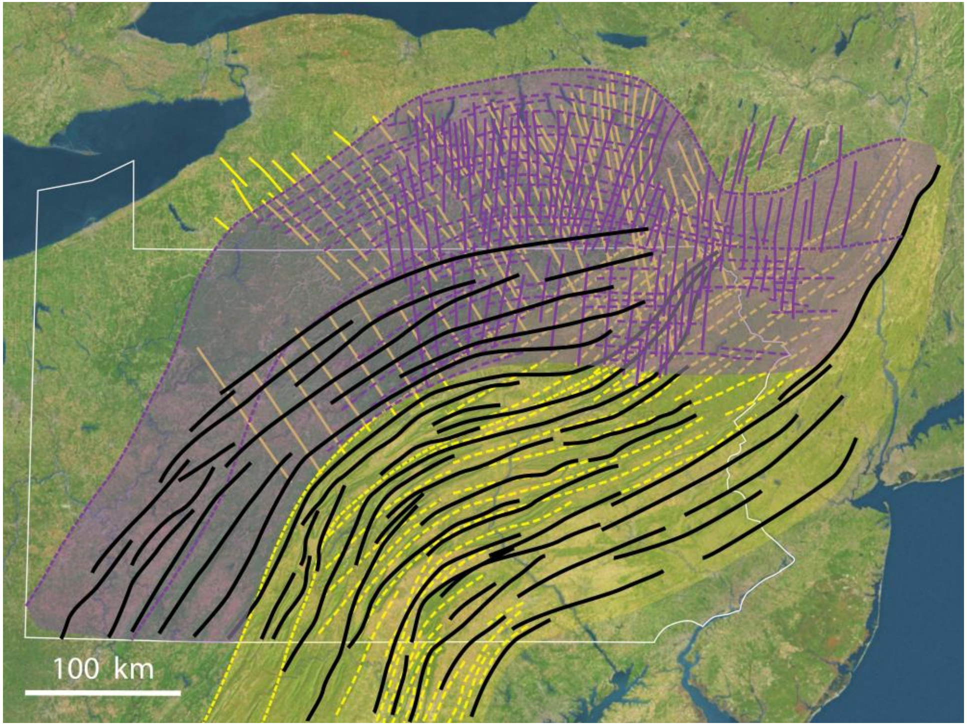
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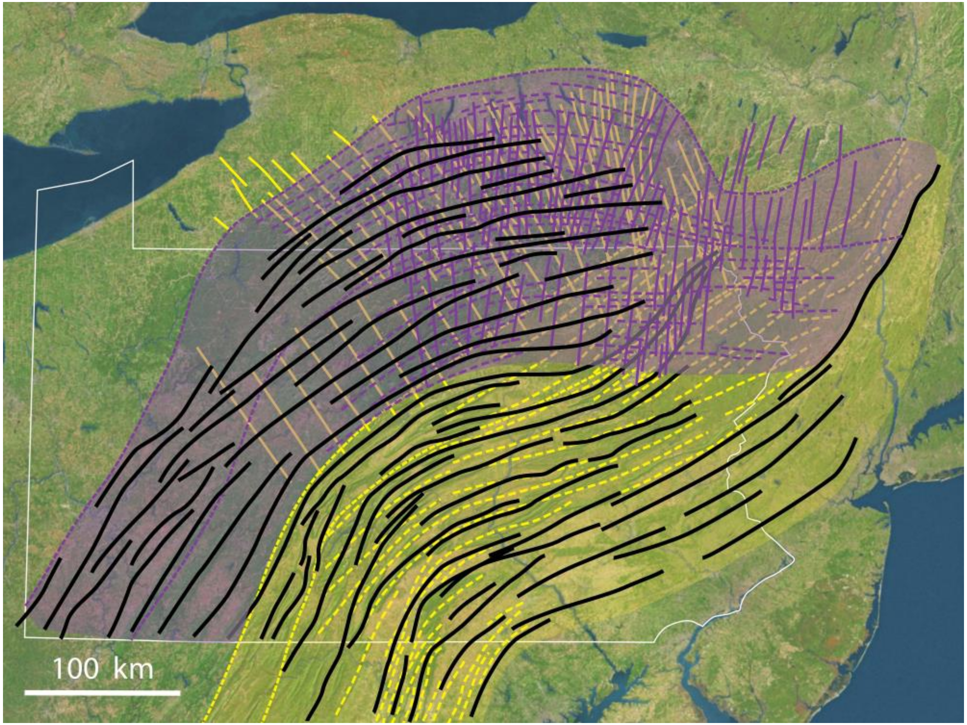
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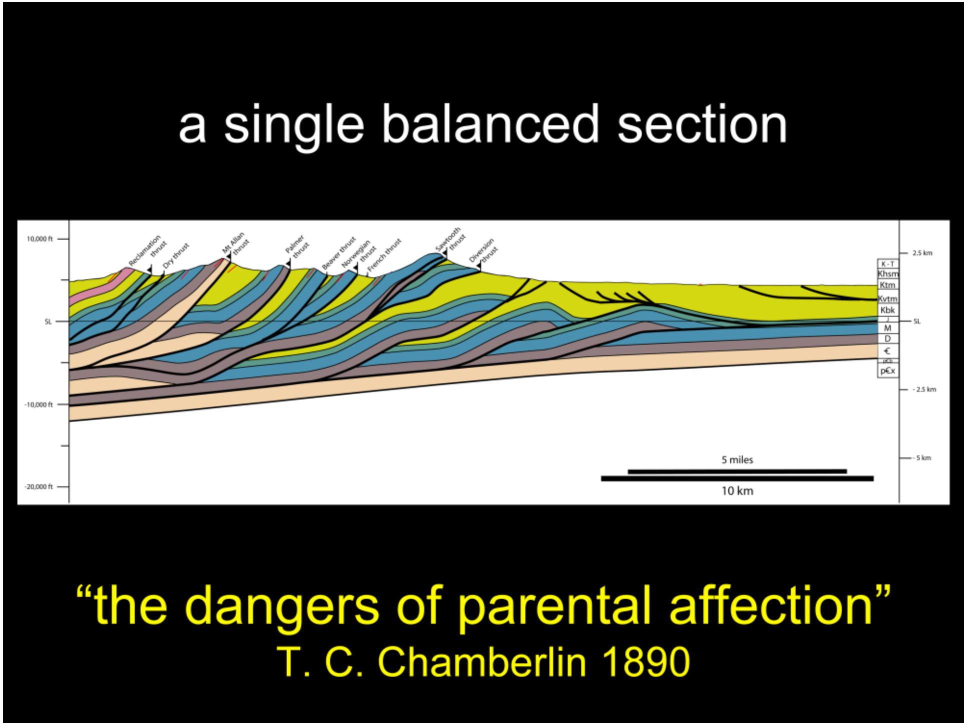
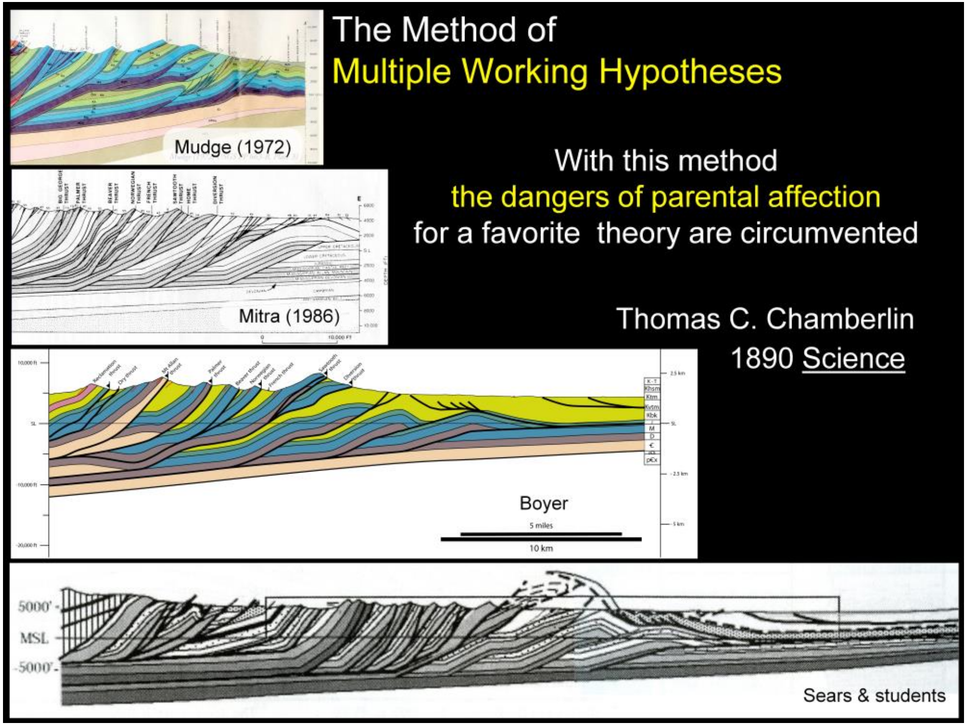
Cross Sections Should Rarely Balance: Volume Loss & Sub-resolution Strain



Presenter’s notes: The problem with a “balanced cross section” is that since it meets the “criteria” for a valid section as interpreted in the past, it is easy to accept this as the most likely interpretation and cease inquiry.

When we have just one interpretation, it becomes our only child. We invest a lot in this only child. Chamberlin called this the DANGER OF PARENTAL AFFECTION. The danger of balancing is that it usually produces a single working hypothesis. Once we have constructed a balanced section we are likely to congratulate ourselves, publish it and move on. Rather than devoting so much time to one balanced and restored section, one might be better served to use that time to construct multiple interpretations.



Presenter's notes: By entertaining multiple interpretations, rather than a single balanced section, we avoid Chamberlin's problem of parental effection. My cross section, second from the bottom, is but one possible interpretation through the Sawtooth Ranges thrust belt of western Montana. These lines of section are at the same scale and are a transect that closely follows Sun River Canyon. Of course, I favor my own creation, but that's pure prejudice. I have used the triangle zone from Jim Sears and his students, and my section shows perhaps some influence from Mel Mudge. Mudge's section is generally balanced and for the most part a valid representation. Shanka Mitra has yet another interpretation. I don't know that one is to be favored over the other.