Geological Prediction of Subseismic Deformation from Seismic-Reflection Profiles of Contractional Structures*

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Abstract

Subseismic (subresolution) deformation can significantly influence reservoir continuity, porosity, and permeability. The area-depth-strain (ADS) method is a rapid and inexpensive screening technique for recognizing potential locations and magnitudes of subseismic deformation. With this method, a graph of excess area vs. depth yields the boundary displacement. The displacement, together with measured bed lengths and widths of the structure at regional, allow for the calculation of subseismic strain for each marker. An Appalachian outcrop-based example indicates at least two scales of substantial deformation not included on a regional profile: outcrop-scale folds and faults and small map-scale folds. We present ADS results for two seismic profiles from fold-thrust belts: 1) an oil-field-scale fault-bend fold from deep water offshore Nigeria, and 2) the fault-bend fold that produced the Rosario oil field in Venezuela. The results show that the ADS method permits the quantification of subseismic deformation at numerous stratigraphic horizons (including growth horizons) within the structures. The Nigerian example is a single thrust-ramp anticline with growth strata. ADS analysis indicates that layer-parallel strain varies considerably with substantial shortening (13-23%) at some stratigraphic levels and little at other levels. The differences may be related to lithology, with stiffer, brittle units having less subseismic deformation, or to inaccuracy of the seismic profile in a region of steep dip. Horizons with high subseismic strains are likely to be thin-bedded or consist of an inherently more ductile lithology. The predicted subresolution strain is inversely proportional to the separation on the fault, suggesting a partitioning of displacement between layer-parallel shortening/thickening and fault slip. For the fault-bend fold forming the Rosario oil field, the ADS analysis indicates that layer-parallel shortening strains are small at all stratigraphic levels. Thus, the ADS analysis predicts that the Rosario structure has little subseismic deformation when compared to the Nigerian example.

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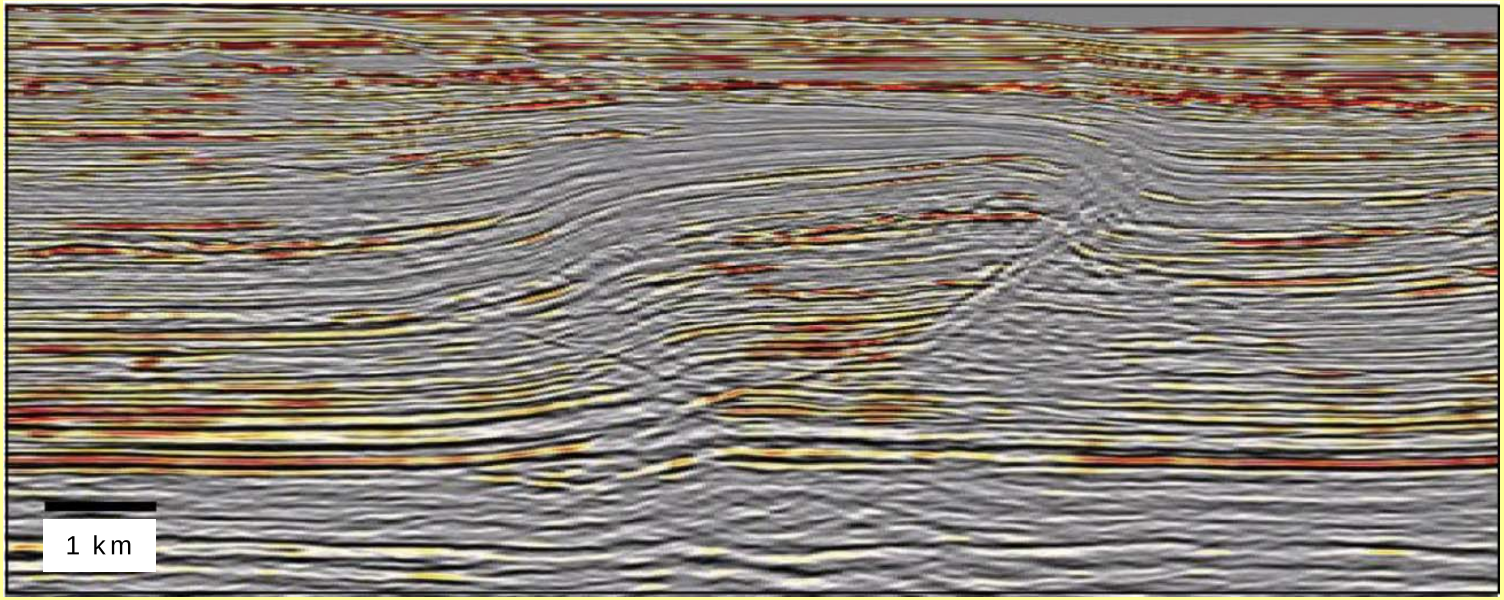
QUESTIONS

- **Is the structure balanced?**
- **What is the total shortening?**
- **What is the growth history?**
- ***Can subseismic strain be inferred?***
  If so, where and how much?



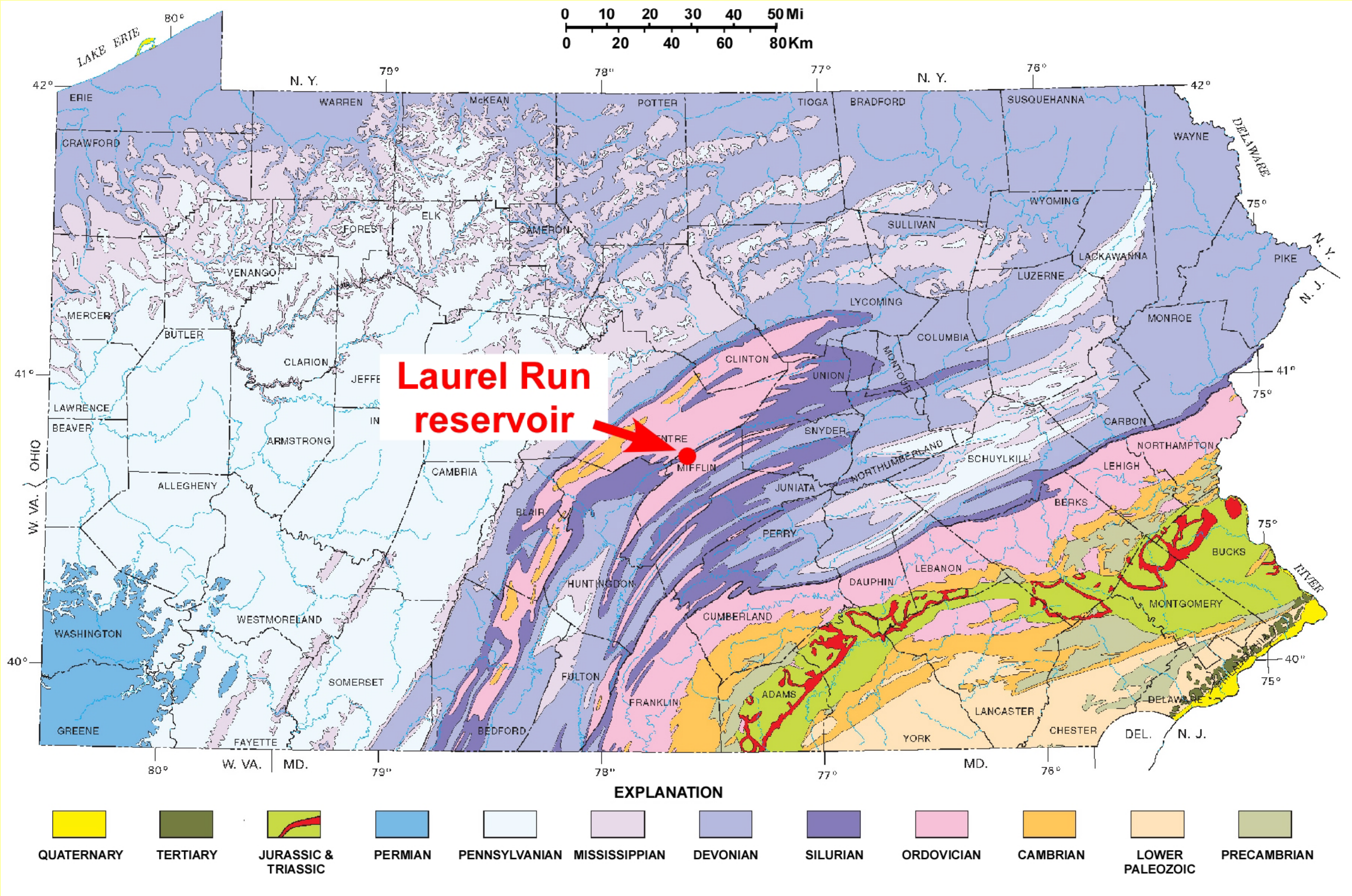
profile from deep water Niger delta

Butler, R., 2008, Virtual Seismic Atlas http://see-atlas.leeds.ac.uk:8080/homePages/regionalProject.jsp?resourceId=090000648000f208

OUTLINE

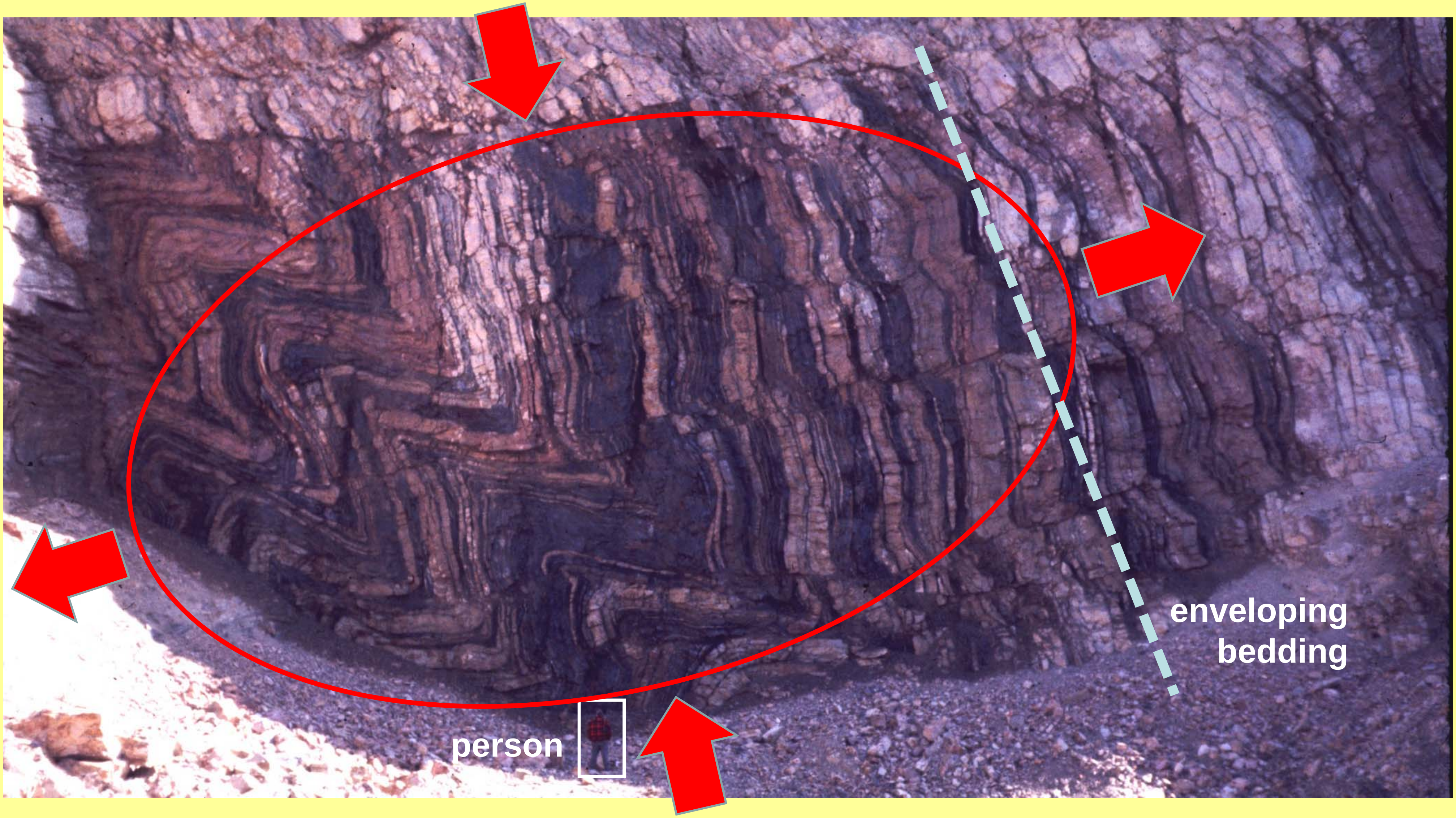
- What does subseismic strain look like?
- Inferences from flexural-slip restoration
- Inferences from mass balance relationship
- Conclusions

What does subseismic strain look like?



location of outcrop example in Appalachian fold-thrust belt, Pennsylvania

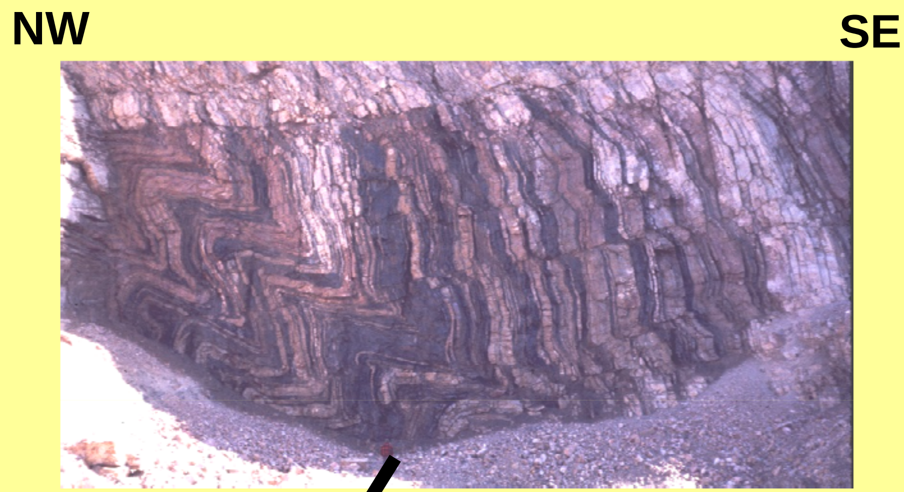
Layer-parallel shortening and thickening



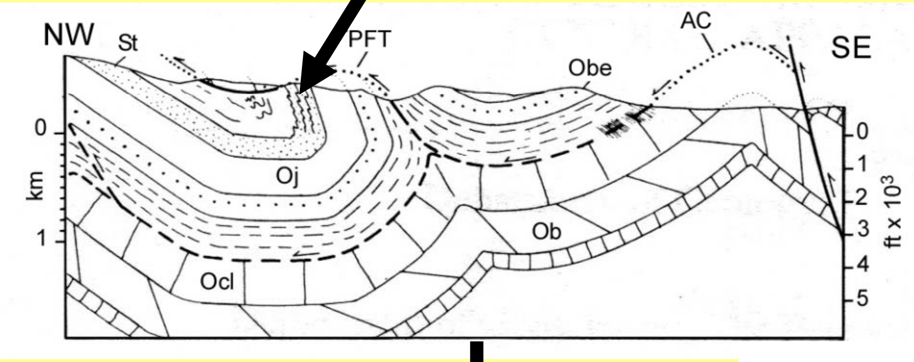
at the outcrop scale, basal Silurian Tuscarora sandstone, central Pennsylvania

How does the outcrop fit into the oil-field scale structure?

Resolvable fold shortening strain at the outcrop scale

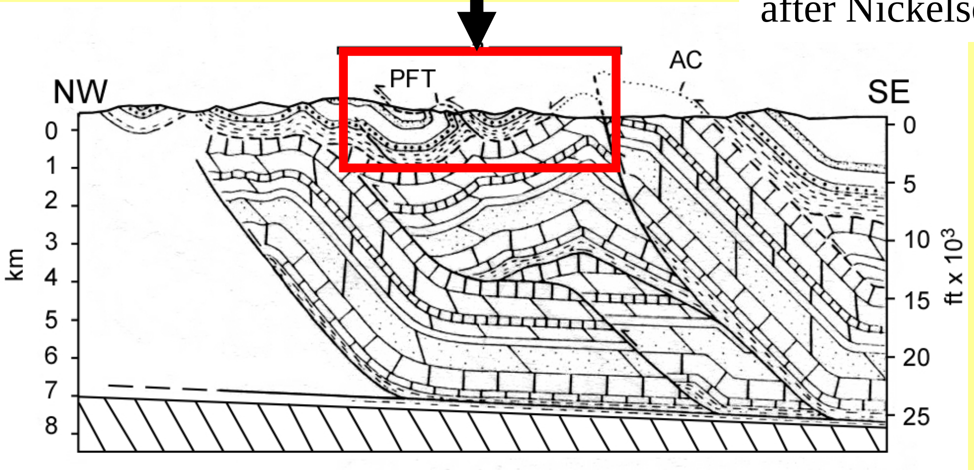


Subresolution fold shortening, mappable fault shortening at the map scale



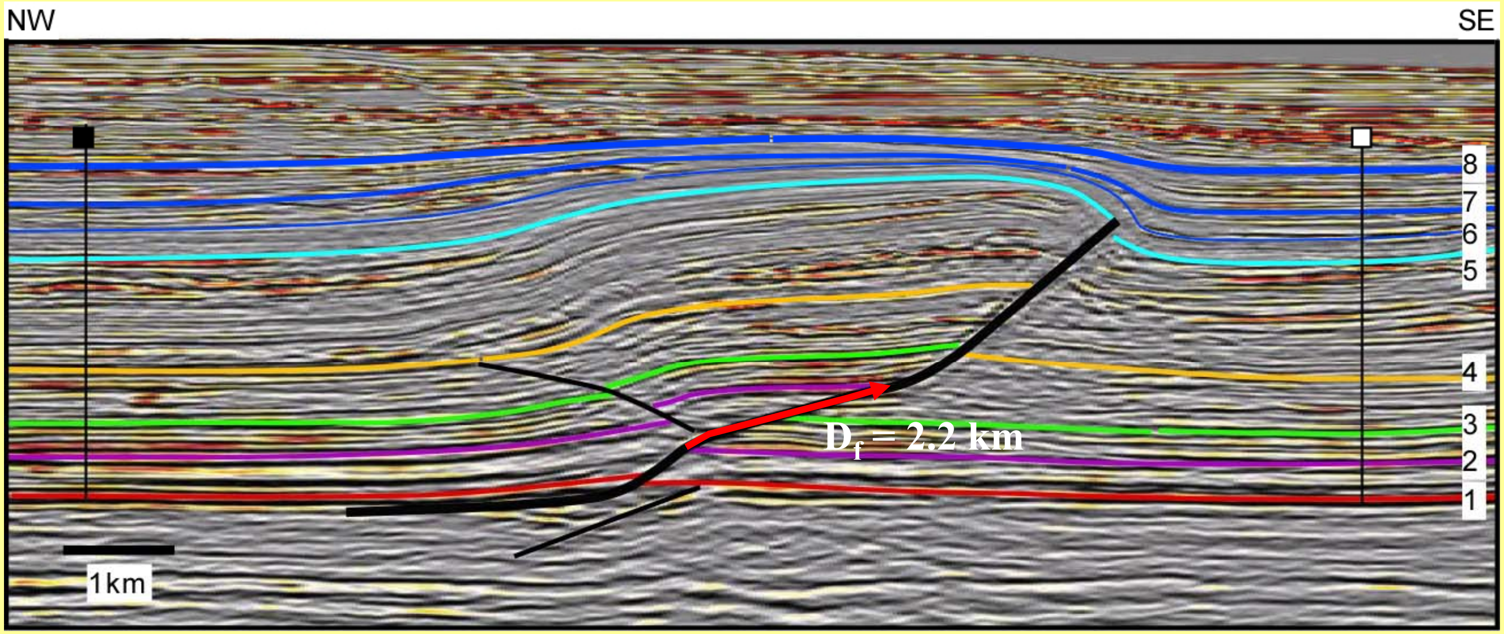
after Nickelsen & Engelder (1989)

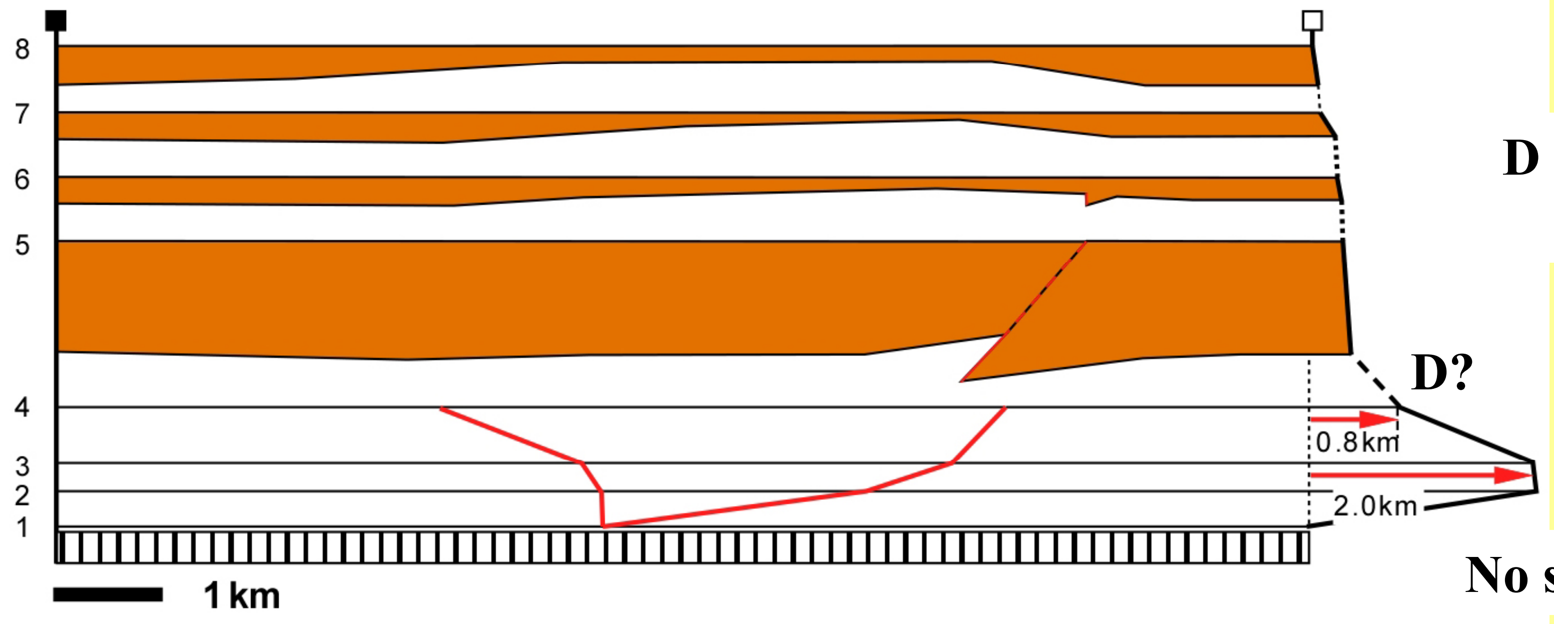
Subseismic fold and fault shortening at the oil-field scale



Flexural-slip restoration

constant bed lengths & thicknesses are assumed





D = less than slip on ramp?

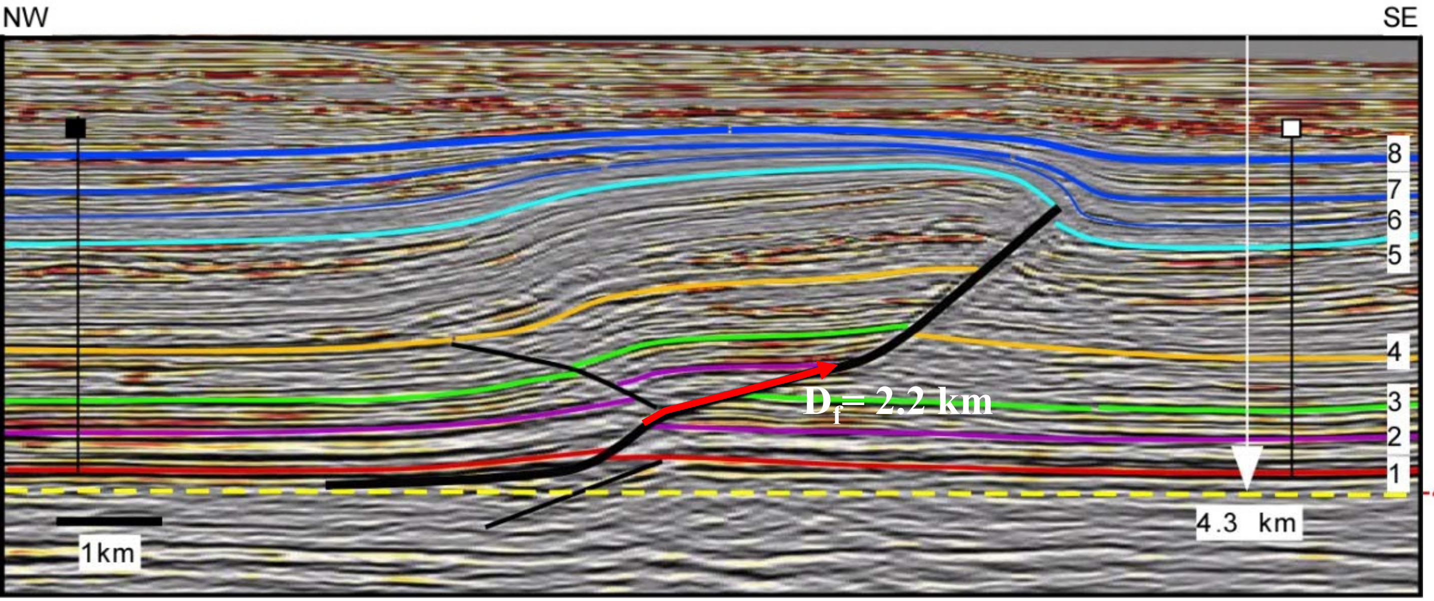
Unbalanced?

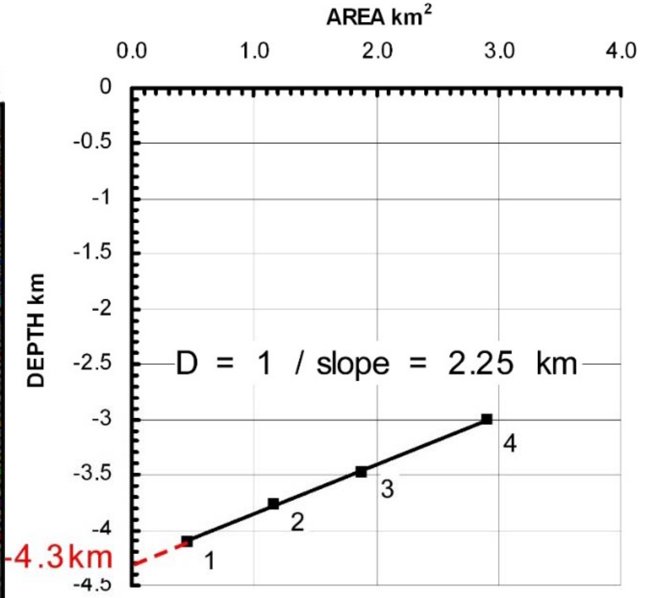
No subseismic strain

Inferences from mass balance

Pregrowth units

Excess area vs. depth graph

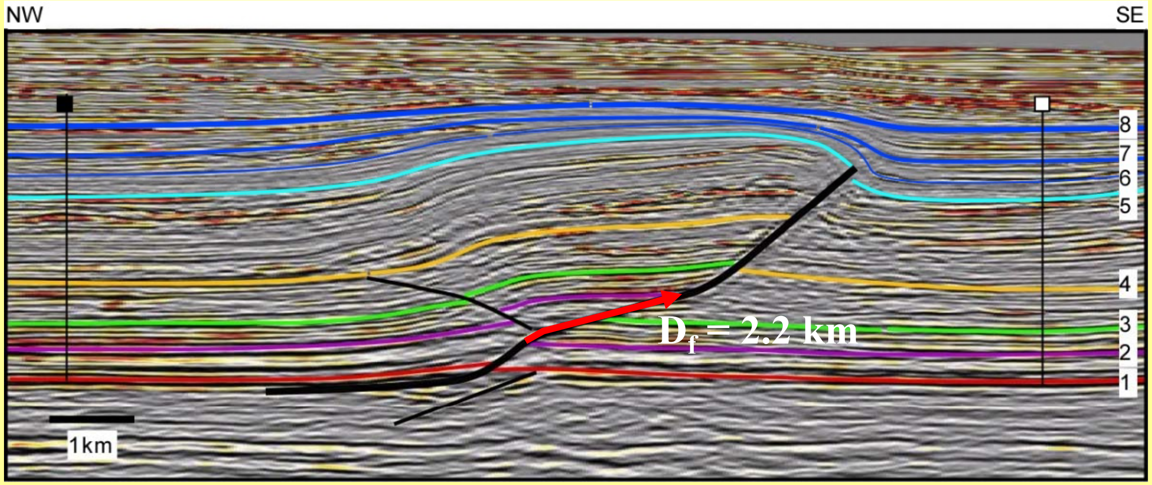




Results

1. Pregrowth strata 1-4 are balanced with reasonable lower detachment
2. D = 2.25 km ≈ maximum fault offset on seismic profile
3. All pregrowth markers have same total D = 2.25 km, despite their different lengths

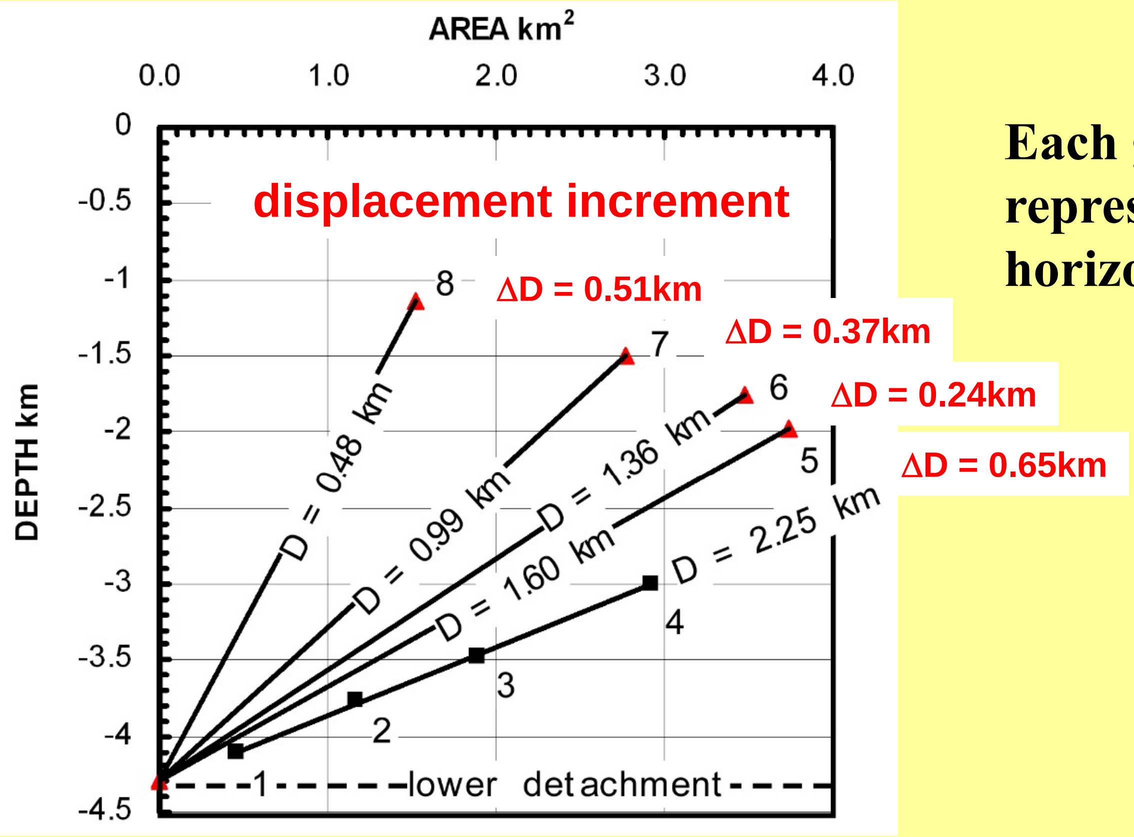
Inferences from mass balance



Growth units

Markers 5-8 are growth units

Displacements are found separately from each marker



Results

Each growth increment represents substantial horizontal displacement

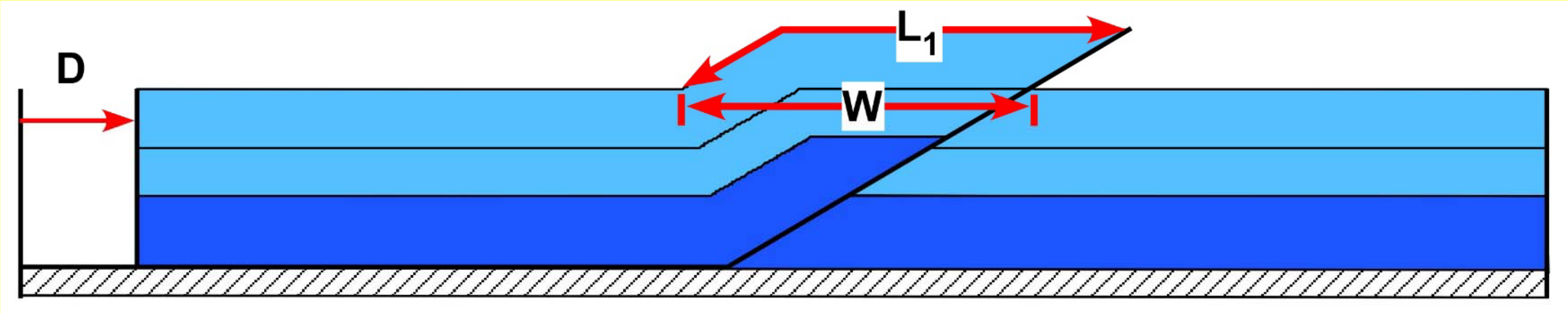
Strain calculation from area-depth relationship

$e = (L_1 / L_0) - 1$

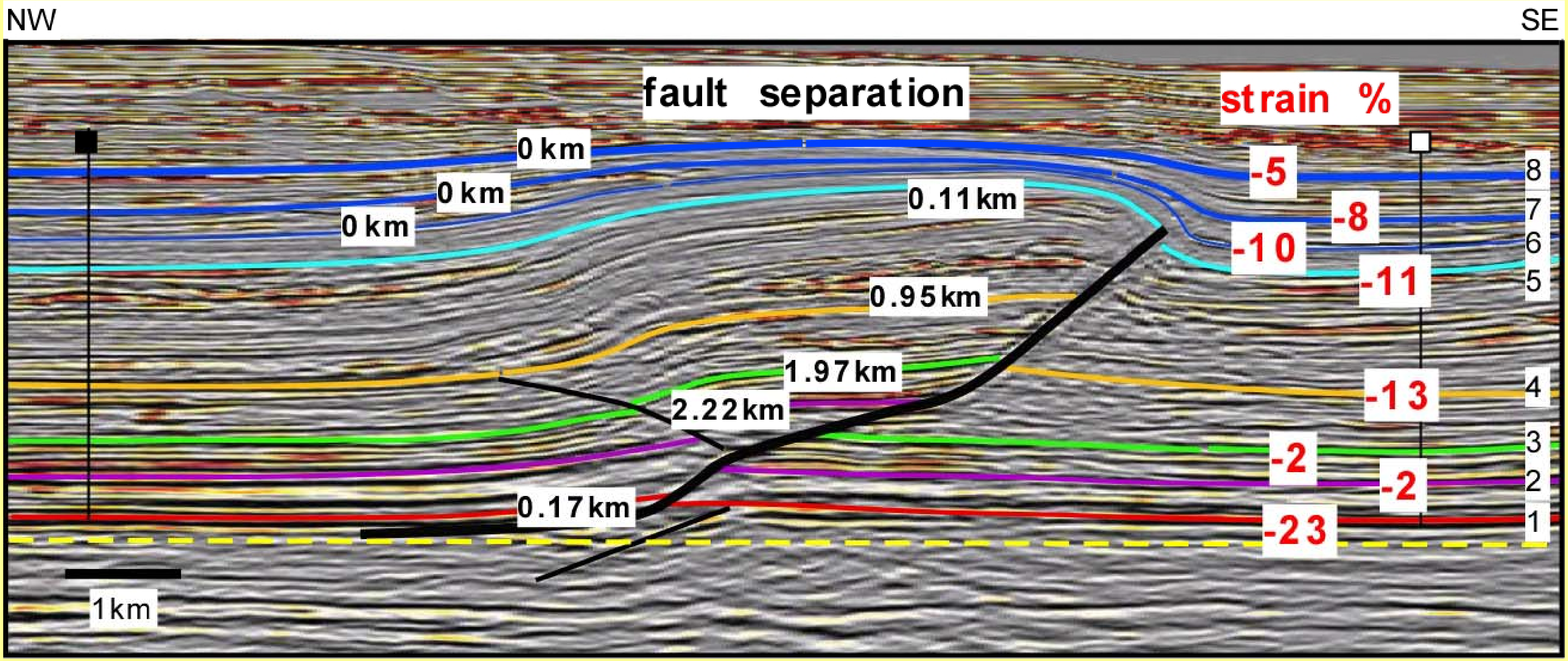
the key, D is from A-D graph

$e = (L_1 / (W + D)) - 1$

$\underbrace{W + D}_{L_0}$



Subseismic Strain

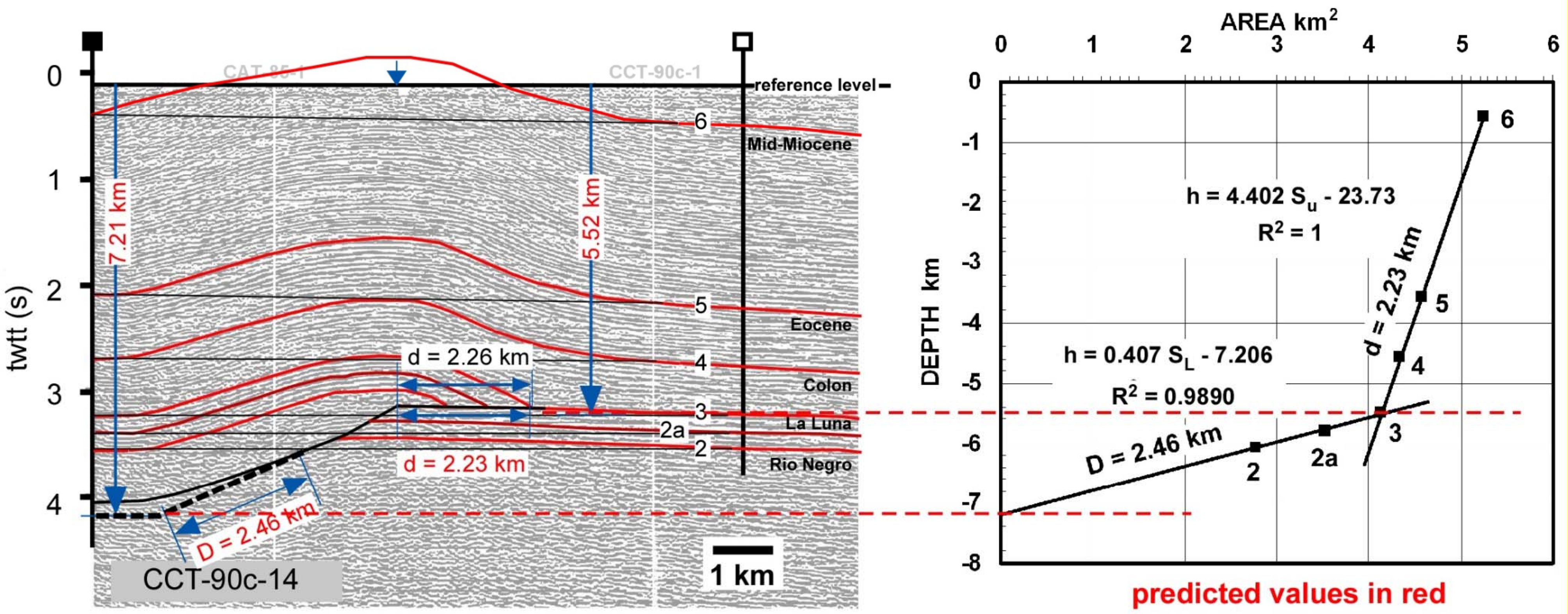


Results

1. All growth markers (5-8) have significant subseismic strain
2. Markers 2 & 3 carry most of the boundary displacement & little subseismic strain: they can be expected to be structurally simple reservoirs
3. Markers 1 & 4 have substantial subseismic strain: they can be expected to be very complex reservoirs

Rosario oil field, Maracaibo basin, Venezuela

50 million barrels oil, 107 bcf gas estimated ultimate recovery

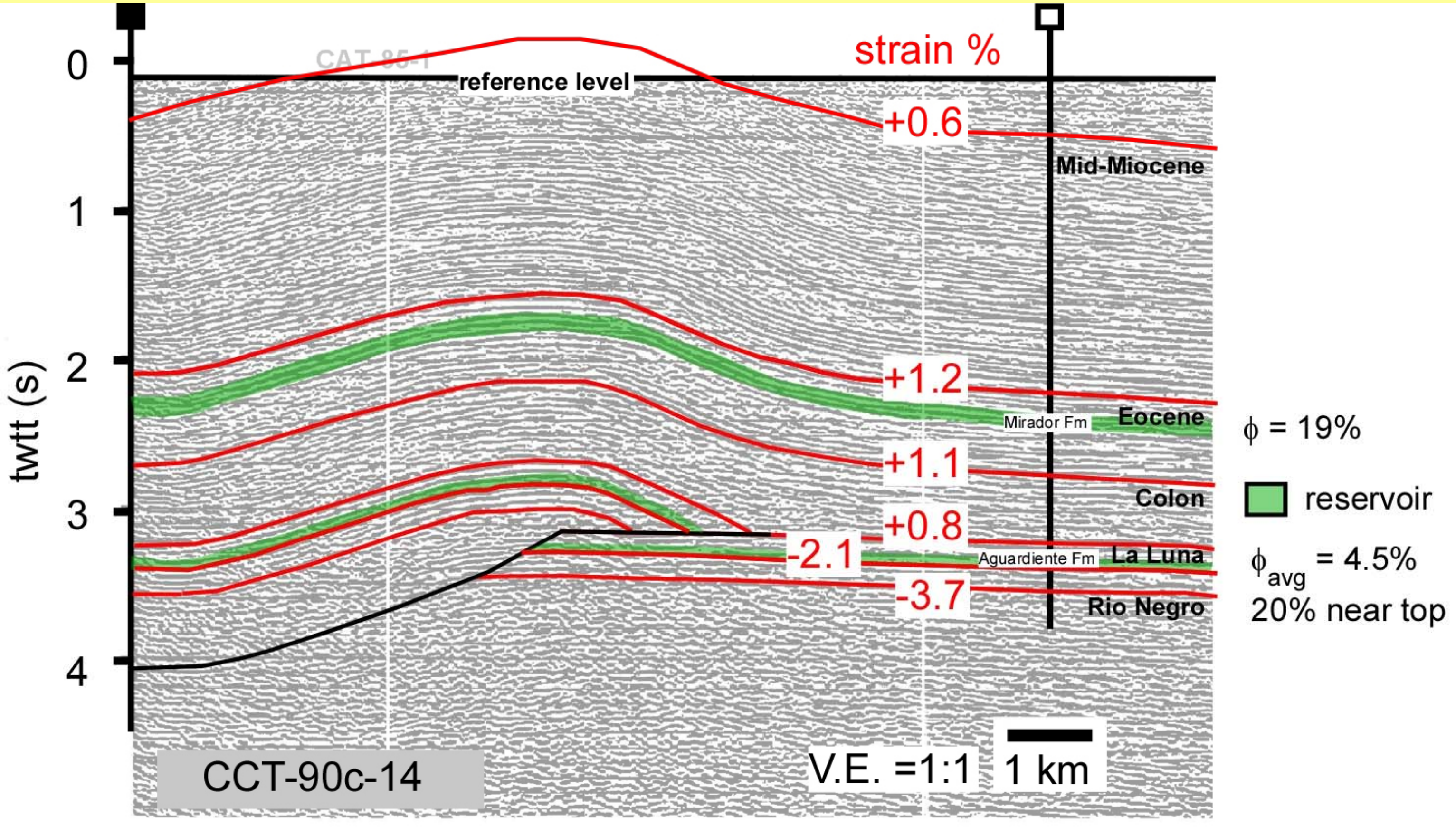


(after Groshong et al., 2012, profile from Apotria and Wilkerson, 2005)

Result

Excellent match between area-depth graph and observed upper detachment location and offset

Rosario oil field, Maracaibo basin, Venezuela



(after Groshong et al., 2012; reservoirs from Molina, 1992)

Results

1. Very small subseismic strains are predicted
2. All units should be structurally simple reservoirs
3. Extension fracturing might be enhanced in upper reservoir

CONCLUSIONS

• Most markers on Nigerian seismic line indicate substantial subseismic shortening and can be expected to have significant subseismic reservoir-scale deformation

• The two -2% strain markers on the Nigerian line indicate little subseismic deformation will be encountered

• Very low predicted strain values in Rosario field indicate little subseismic deformation

• For sections with dense data, the Area-Depth-Strain method provides a direct measure of balance, displacement, and subseismic strain