The Fault Trajectory Method: Estimating the Location and Dip of Controlling Faults Below Forced Folds*

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Search and Discovery Article #41998 (2017)**
Posted February 13, 2017

*Adapted from oral presentation given at AAPG/SEG 2016 International Conference and Exhibition, Cancun, Mexico, September 6-9, 2016

Abstract

Many folded structures form above faults that dip to considerable depth. In petroleum exploration and development, locating the controlling fault is a matter of practical importance. Often, seismic and well data constrain the upper fold geometry but the dip and location of the controlling fault are unknown. Excess-area or area-depth-strain (ADS) analysis can directly determine detachment depth without restrictive kinematic assumptions. However, the standard ADS method is limited to structures with horizontal detachments where regional elevations are the same on both sides of the fault. We present a new ADS method that directly determines fault depth, dip, displacement, and layer-parallel strain for structures characterized by differing regional elevations in the footwall and hangingwall. Referred to as the fault trajectory method, the new technique relates structural relief within a fold to the dip of the controlling fault. By varying the analysis aperture, the method can also locate fault path variations such as ramps and flats.

We validate the method using extensional and contractional models with known fault positions. ADS analysis of area-balanced forward models provides exact matches to the fault trajectory, displacement, and layer-parallel strain distribution. In physical models, the method reliably locates the position and dip of the controlling fault regardless of model rheology. The fault trajectory method also provides results that agree with interpretations constrained by seismic data and well logs. In the Uinta Basin of the western U.S., well and seismic data constrain the shallow geometry of a basement-involved fold. ADS analysis of the well-imaged interval indicates the controlling fault likely steepens to ~50° in the basement. Finally, we apply the fault trajectory method to a series of case studies including a basin-bounding normal fault in the North Sea and fold-thrust belts in the Caribbean Ranges of Venezuela, the Bermejo Basin in Argentina, and the deep-water Mexican Ridges in the western Gulf of Mexico. In these locations, only the shallow fold geometry is seismically imaged while the fault locations and shapes are ambiguous. Area-depth analysis of these structures is only possible using the new fault trajectory method. Each case study shows how area-depth analysis can quickly provide interpreters with the guidance and structural parameters necessary to reduce uncertainty in complex structural settings.

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Selected References

Chester, J.S., J.M. Logan, and J.H. Spang, 1991, Influence of Layering and Boundary Conditions on Fault-Bend and Fault-Propagation Folding: Geological Society of America, Bulletin 103, p. 1059-1072.

Mitra, S., and V.S. Mount, 1998, Foreland Basement-Involved Structures: American Association of Petroleum Geologists Bulletin, v. 82, p. 70-109.

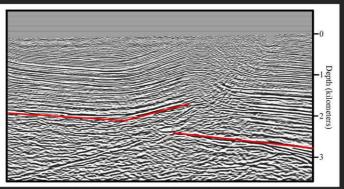
Yarbuh, I., and J. Contreras, 2015, The Interplay Between Deformation, Erosion and Sedimentation in the Deep-Water Mexican Ridges Foldbelt, Western Gulf of Mexico Basin: Basin Research, p. 1-19.

The Fault Trajectory Method:

StructureSolver

Estimating the Location and Dip of Controlling Faults Below Forced Folds

Presented at 2016 AAPG/SEG International Convention and Exhibition; Cancun, Mexico

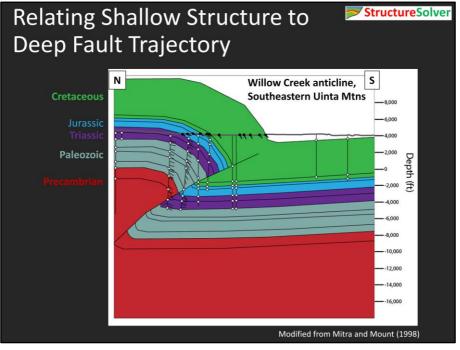


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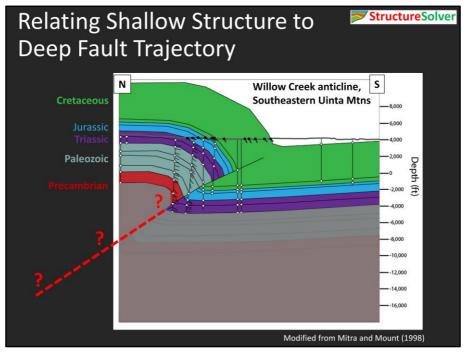
Ismael Yarbuh, Centro de Investigación Científica y de Educación Superior de Ensenada



Presenter's notes: Even with modern seismic data, the problem persists. This is a significantly more advanced cross section from the Willow Creek anticline on the southern flank of the Unita Uplift that incorporates well, seismic, and surface data.

The shallow fault trajectory is known from wells but the deep fault geometry isn't directly known.

As is standard practice in this situation, a geometric model was applied. The model predicts a fault bend at depth in order to explain the anticlinal geometry of the hangingwall.



Presenter's notes: But if we restrict the section to the well constrained parts of the structure, we see that the available data could allow for different fault trajectories, depending on the structural model used during interpretation.

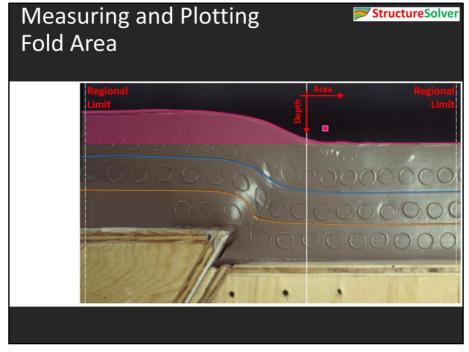
Area-depth analysis is an alternative to forward models can independently estimate the deep fault trajectory from the near-surface structural geometry with fewer kinematic assumptions.

Previously however, area-depth analysis was only applicable to structures where regional elevations are the same on both sides of the fault, implying a flat detachment.



Presenter's notes: Today, I'm going to show you a generalized area-depth method that works in areas where hangingwall and footwall elevations differ, significantly expanding the applicability of the method.

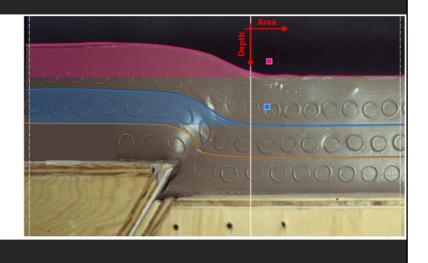
We'll go into the specifics shortly, but first we'll start with a basic clay model that is stylistically similar to many Laramide uplift structures. So to start, we are going to do an area-depth analysis of the colored horizons. You'll notice that they are exclusively folded with the fault tipping out below them.



Presenter's notes: Area-depth analysis is performed by measuring the area in a horizon from a horizontal datum set at a specified regional limit. For structures with differing footwall and hangingwall elevations, fold area is measured between the footwall regional and the horizon. That area is then plotted at the average depth for the horizon. In this presentation, we'll directly overlay the area-depth plot on the image.

Measuring and Plotting Fold Area

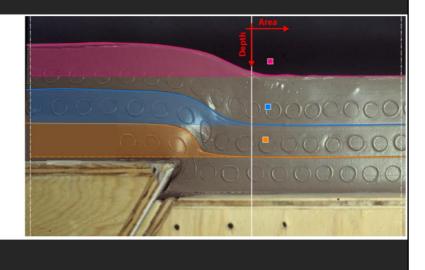




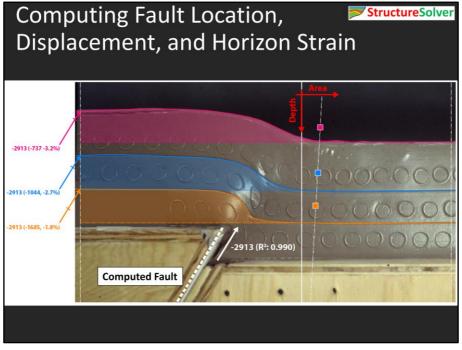
Presenter's notes: We repeat this process for each horizon.

Measuring and Plotting Fold Area





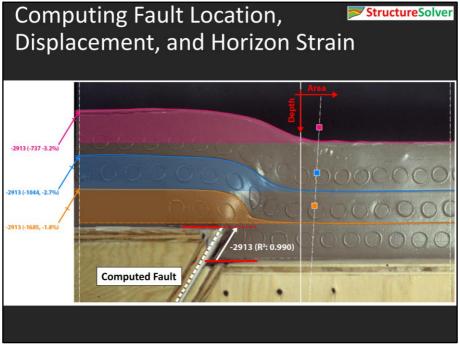
Presenter's notes: Note that the fold area progressively decrease with depth.



Presenter's notes: The systematic relationship between fold area with depth can then be used to directly calculate the fault location, dip, and displacement as well as estimate horizon strains.

In this case, the computed detachment from area-depth is almost exactly at the modeled fault.

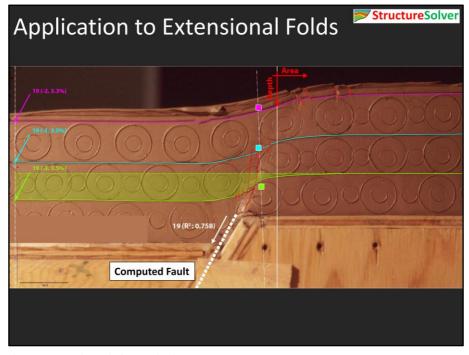
The area-depth displacement and fault displacement are nearly identical as well.



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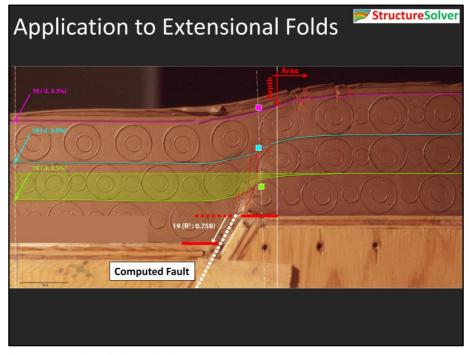
The area-depth displacement and fault displacement are nearly identical as well.



Presenter's notes: The same process also works for extensional structures.

This is a similar model, but with a normal fault.

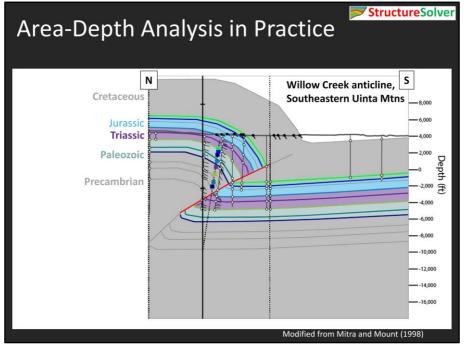
Again the fault location and displacement from area-depth are a good fit to the model.



Presenter's notes: The same process also works for extensional structures.

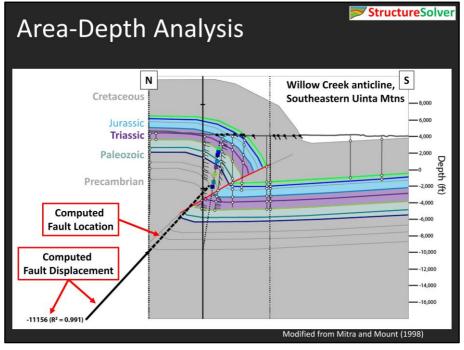
This is a similar model, but with a normal fault.

Again the fault location and displacement from area-depth are a good fit to the model.



Presenter's notes: The significant advantage of area-depth analysis is that we can lavage the structural information we have to determine the likely fault position at depth.

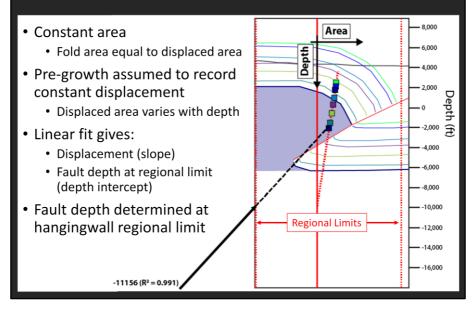
For example in the Willow Creek structure, we use only the horizons and fault segments with the best structural constraints from wells.

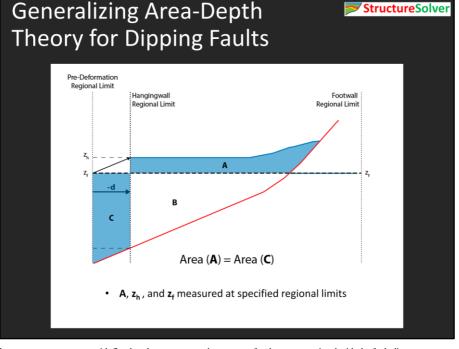


Presenter's notes: The linear relationship between fold area and depth gives a computed detachment that is slightly steeper than the fault dip predicted by the kinematic model, but it confirms that the fault dip increases with depth.



Area-Depth Theory



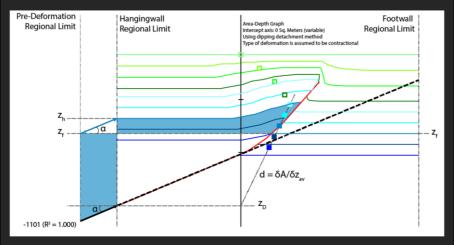


Presenter's notes: In constrast to structures with flat detachments, we need to account for the area associated with the fault dip.

To account for the difference, fold area A is measured using the footwall and hangingwall depths at the regional limit and equated to the displaced area, C. This estimates the area associated with the fault dip from the footwall-hangingwall depth difference.



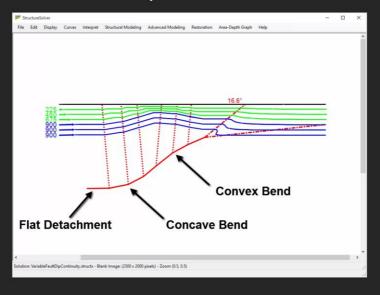
Defining Fault Location



Displacement (d), fault depth (z₀), and dip (d) define the best-fit detachment location



Fault Flat to Ramp Transitions



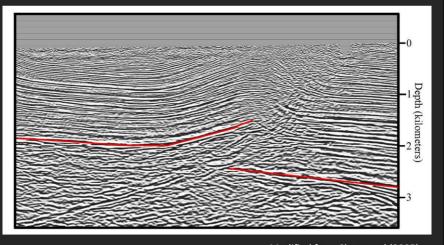


Locating Faults at Depth

Case Studies

Locating Faults at Depth: Argentina

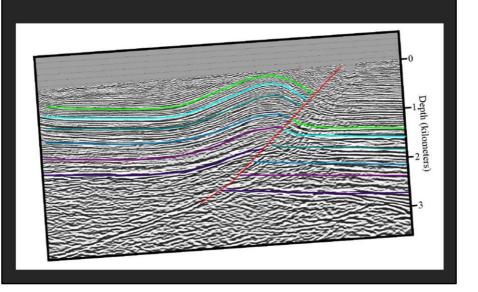




Modified from Shaw et al (2005)

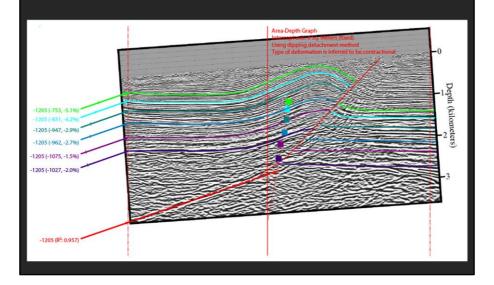
Locating Faults at Depth: Argentina





Locating Faults at Depth: Argentina

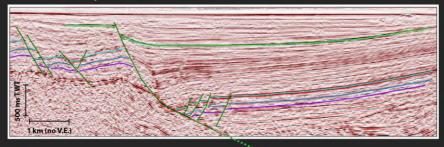






Delineating Fault Curvature

Inner Moray Firth, North Sea

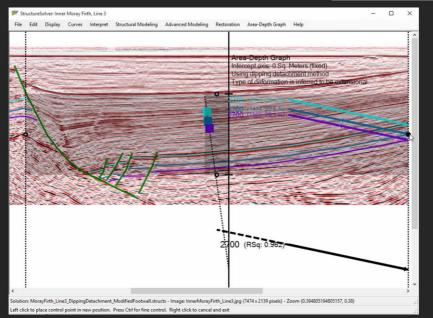


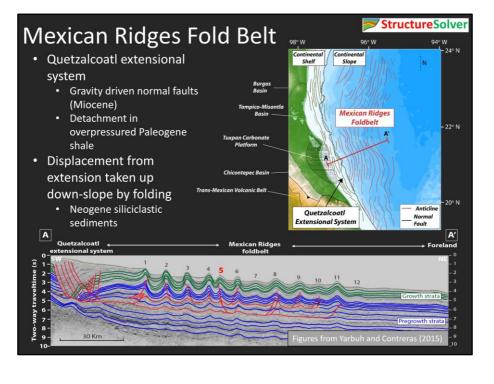




Virtual Seismic Atlas
Sharing the geological interpretation of seismic data



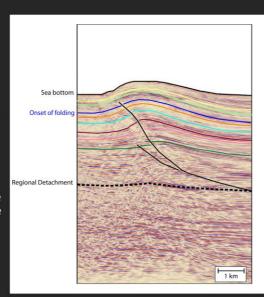






Fold Interpretation

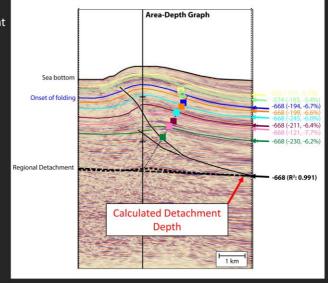
- Upper fold is well-imaged
 - Growth
 - · Pregrowth
 - Fault splays
- Regional detachment visible
 - Parallel to stratigraphy
 - Negligible folding at depth
- Seismic reflectors are discontinuous at core of fold





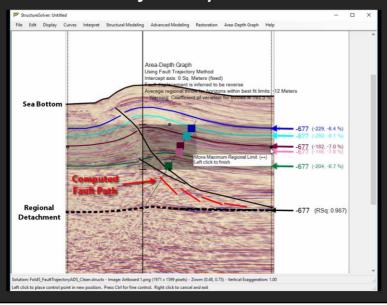
ADS: Depth-to-Detachment

- Standard
 Depth-to-Detachment
 method locates
 regional detachment
- Regional dip of ~3°



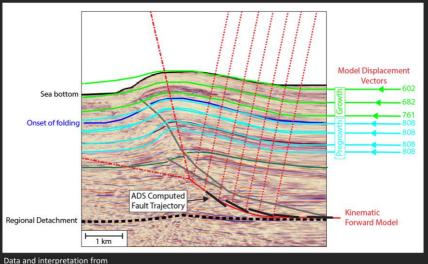


ADS: Fault Trajectory



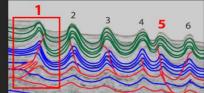


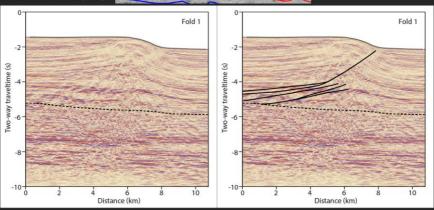
Forward Model: Fold 5





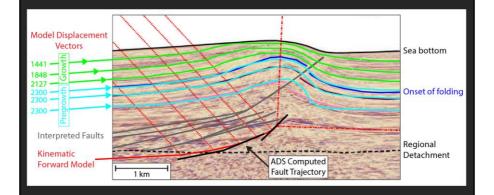
Imbrication at Fold Cores





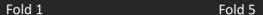


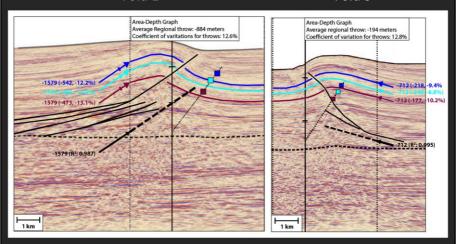
Forward Model: Fold 1





Imbrication at Fold Cores



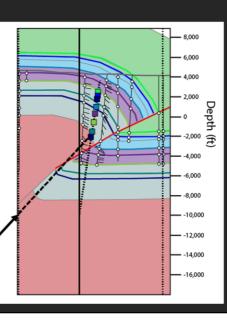




Summary

- Expands applicability of areadepth analysis to dipping faults
- Deep fault trajectory estimated directly from shallow fold geometry
 - Displacement
 - Strain
- Generalized method can estimate variations in fault shape
- Paper in press at AAPG Bulletin

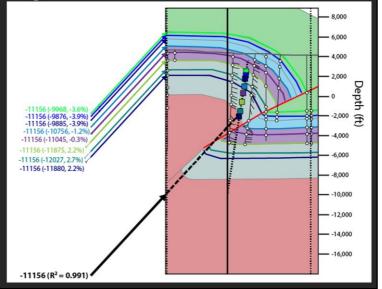




A Parting Thought:

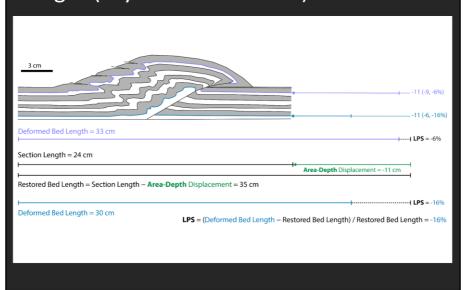


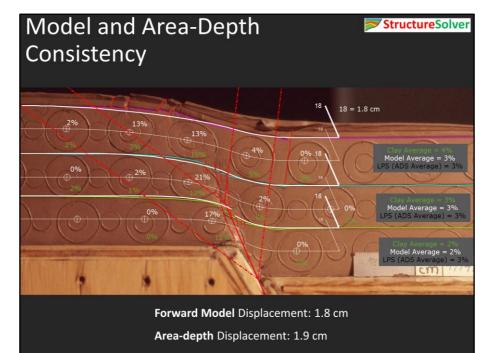




Estimating Change in Bed Length (Layer Parallel Strain)

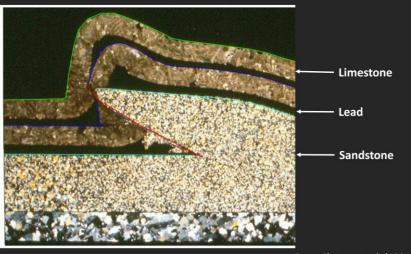








Mechanical Heterogeneities



From Chester et al. (1991)

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LPS Reflects Mechanical Strength Contrasts

