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Incorporating Simple Erosion into Structural Forward Models: Reconstructing Burial Histories from Angular Unconformities in Growth Strata*

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Search and Discovery Article #42365 (2019)**
Posted April 1, 2019

*Adapted from oral presentation given at AAPG 2018 Annual Convention & Exhibition, Salt Lake City, Utah, United States, May 20-23, 2018
 DOI:10.1306/42365Eichelberger2019

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Abstract

Fault-related structures in onshore and nearshore basins often show signs of regional subaerial erosion. In seismically imaged growth strata, syn-deformational erosion is evidenced by angular unconformities within hangingwall strata and missing section within footwall strata. Erosion complicates correlation across faults and has significant implications for burial history. This study presents a new approach to structural forward modeling that parameterizes model surfaces by age as well as depth. By including surface age, we can define complex footwall and hangingwall burial histories that include periods of erosion. The modeled fold geometry depends on fault shape, shear angles, and horizon slip, according to established kinematic theories (specifically inclined shear fault bend folding and tri-shear fault propagation folding). Where younger model surfaces intersect older fold surfaces, the younger surfaces erode and truncate the older surfaces. The models are fully interactive, allowing us to continually modify footwall to hangingwall correlations and fault shape until the computed horizon shape and unconformity geometry match the observational data.

In this presentation we apply the new modeling technique to seismic examples of extensional and contractional structures with complex burial histories indicated by hangingwall unconformities. The first example is a basin-bounding growth fault within the Bohai Bay, South China Sea where over 5 km of syn-extensional erosion has removed the entire footwall section. By interactively modeling the observed hangingwall angular unconformities, we quantitatively reconstruct both the eroded footwall and burial history for the growth fault. The second two examples are inversion structures from the Subandes in Peru and the Junggar Basin in China. Both inversion structures feature multiple types of angular unconformities that independently reflect periods of extension and contraction. Forward modeling these structures refines the timing and magnitude of each deformational phase as well as providing the burial history. A final example from the Outeniqua Basin in South Africa

shows how complex hangingwall unconformities can arise solely from movement along simple faults. For each example, quantitative animations show the sequential development of the structures including periods of burial, erosion, and changes in deformation style.

Selected References

Eichelberger, N.A., A. Nunns, N.D. Perez, S. Ball, D.J. Claron, and D. He, 2018, Incorporating simple erosion into structural forward models: The effects of regional erosion on growth strata geometry: Journal of Structural Geology, v. 116, p. 146-158, Web Accessed February 17, 2019, https://www.sciencedirect.com/science/article/pii/S0191814118303183?via%3Dihub

Shaw, J.H., S.C. Hook, and E.P. Sitohang, 1997, Extensional Fault-Bend Folding and Synrift Deposition: An Example from the Central Sumatra Basin, Indonesia: AAPG Bulletin, v. 81/3, p. 367-379.

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Incorporating Simple Erosion into Structural Forward Models:

Reconstructing Burial Histories from Angular Unconformities in Growth Strata

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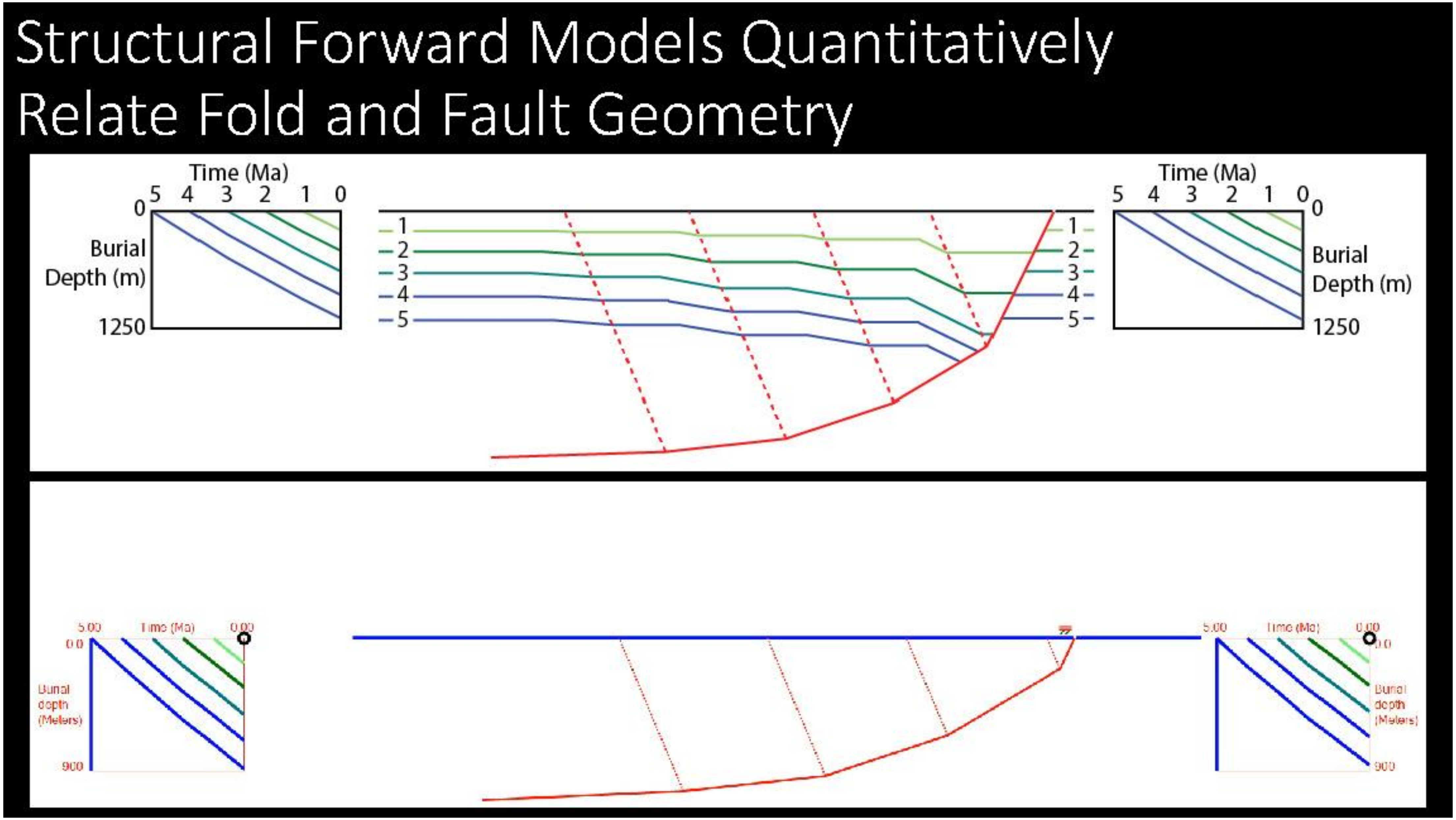
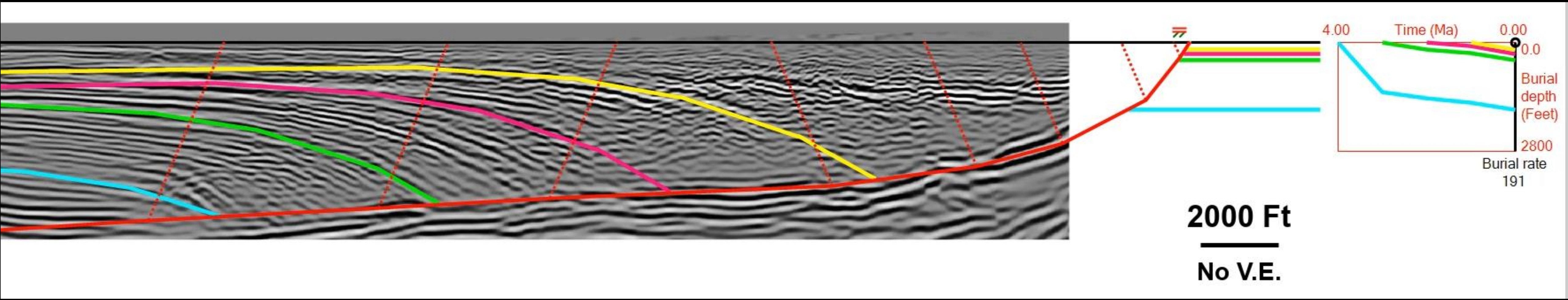


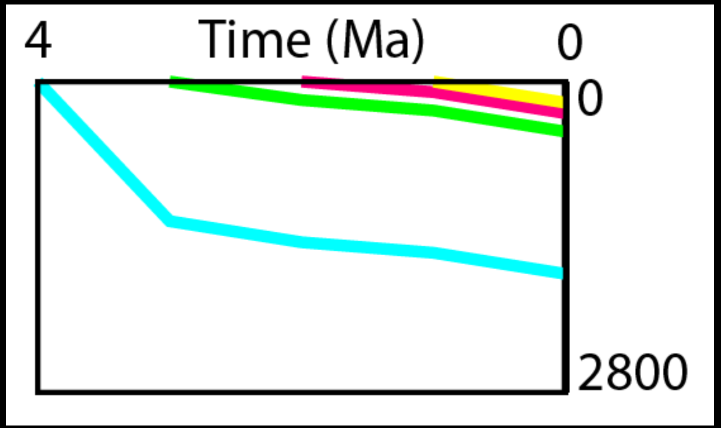
Presenter’s notes: By way of background, structural models quantitatively relate fold shape to fault shape based on kinematic assumptions such as area conservation during deformation. The forward model shown at the top uses inclined shear to model the growth fold geometry that would be produced above a listric normal fault. An important aspect of forward models is that they show the interplay between regional sedimentation, indicated by footwall stratigraphy, and fault slip. This model is defined by a constant rate of burial and fault slip, giving a classic growth fold geometry with fanning dips and thicknesses that increase toward the fault.

Variation in Growth Fold Geometry Reflects Changes in Sedimentation and Fault Displacement

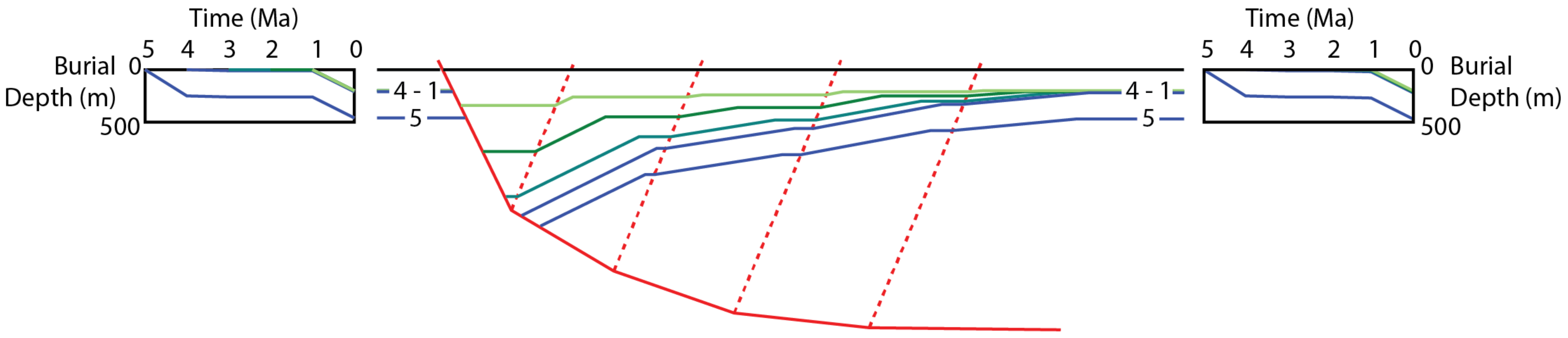


- Forward models establish horizon correlations across faults
- Models are constrained by seismically-imaged hangingwall fold and/or fault geometry
- Resulting modeled footwall depths and thicknesses are assumed to be representative of regional sedimentation (undeformed)
  - Horizon burial history can then be plotted as a function of age, either relative or absolute

Burial History Plot

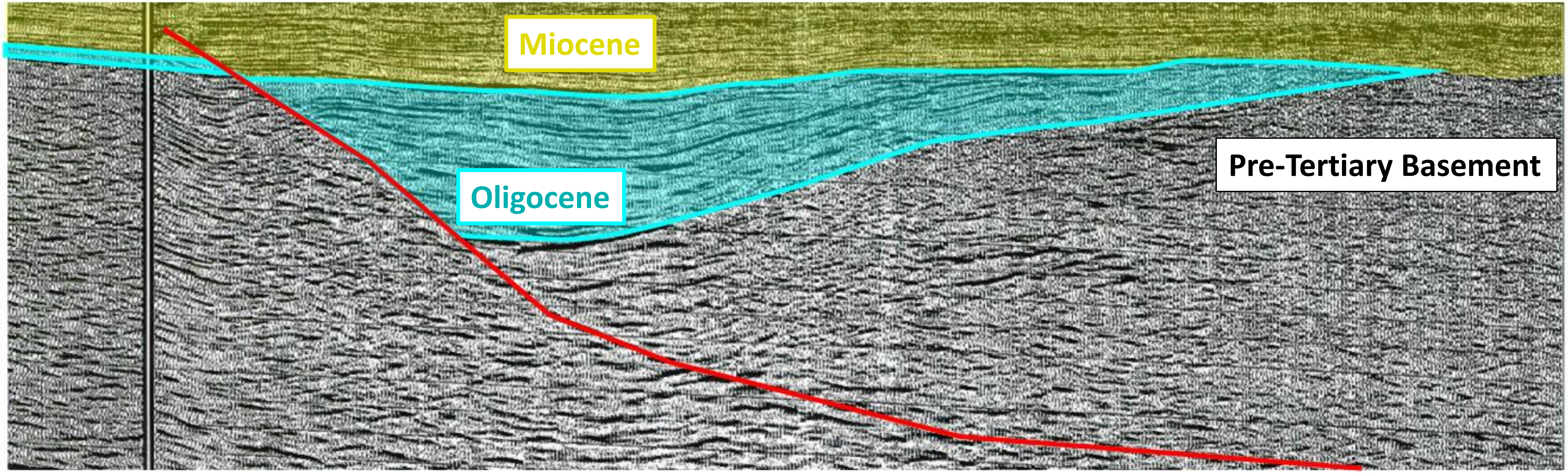


Variation in Growth Fold Geometry Reflects Changes in Sedimentation and Fault Displacement



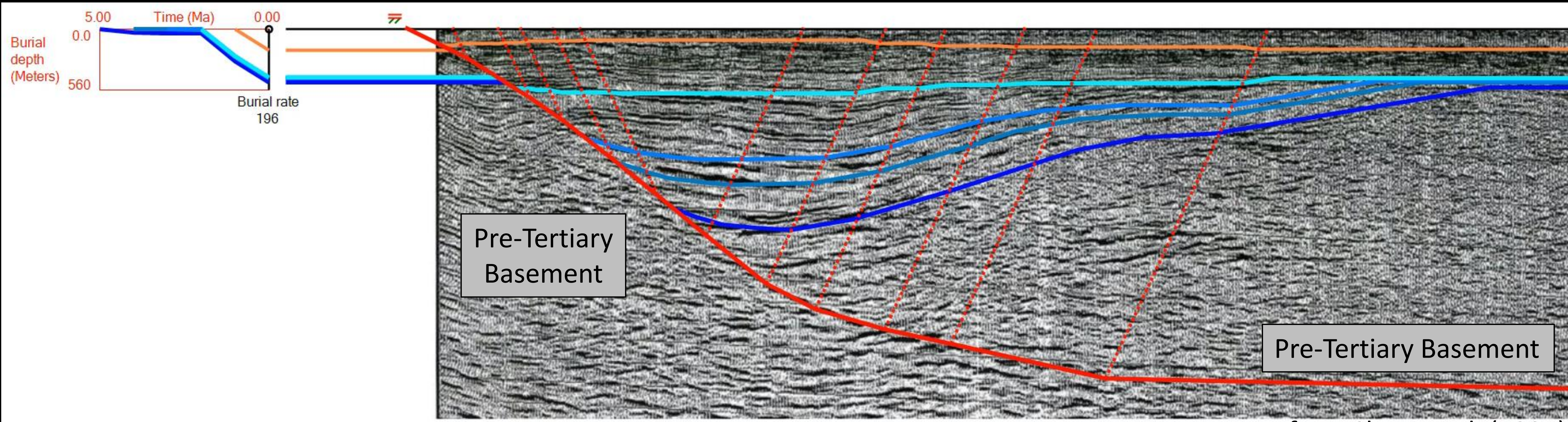
- Established models can reproduce burial histories that range from continual sedimentation to non-deposition
- Models can reproduce growth strata with angular unconformities associated with underfilled basins
- Footwall characterized by condensed section but not true erosion

Central Sumatra Basin: Underfilled but not regionally eroding



Data from Shaw et al. (1997)

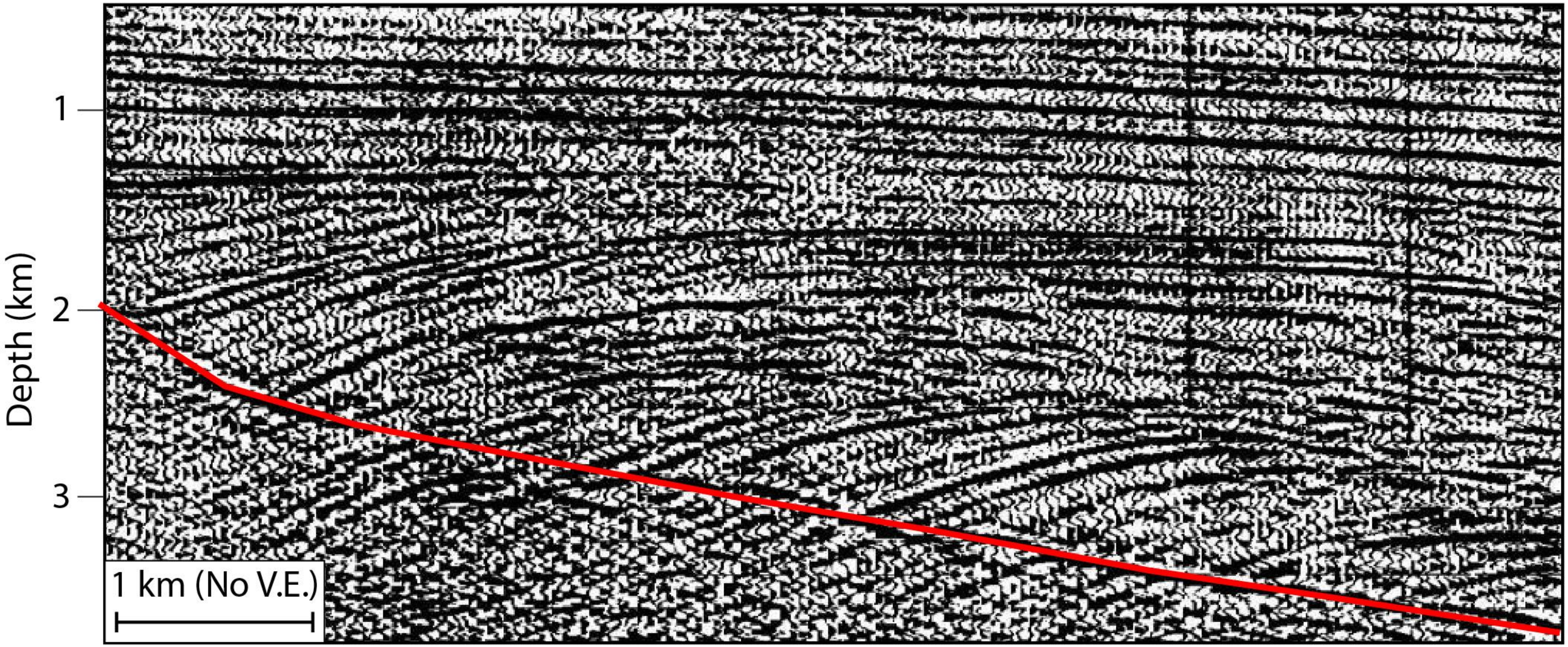
Central Sumatra Basin: Underfilled but not regionally eroding



Data from Shaw et al. (1997)

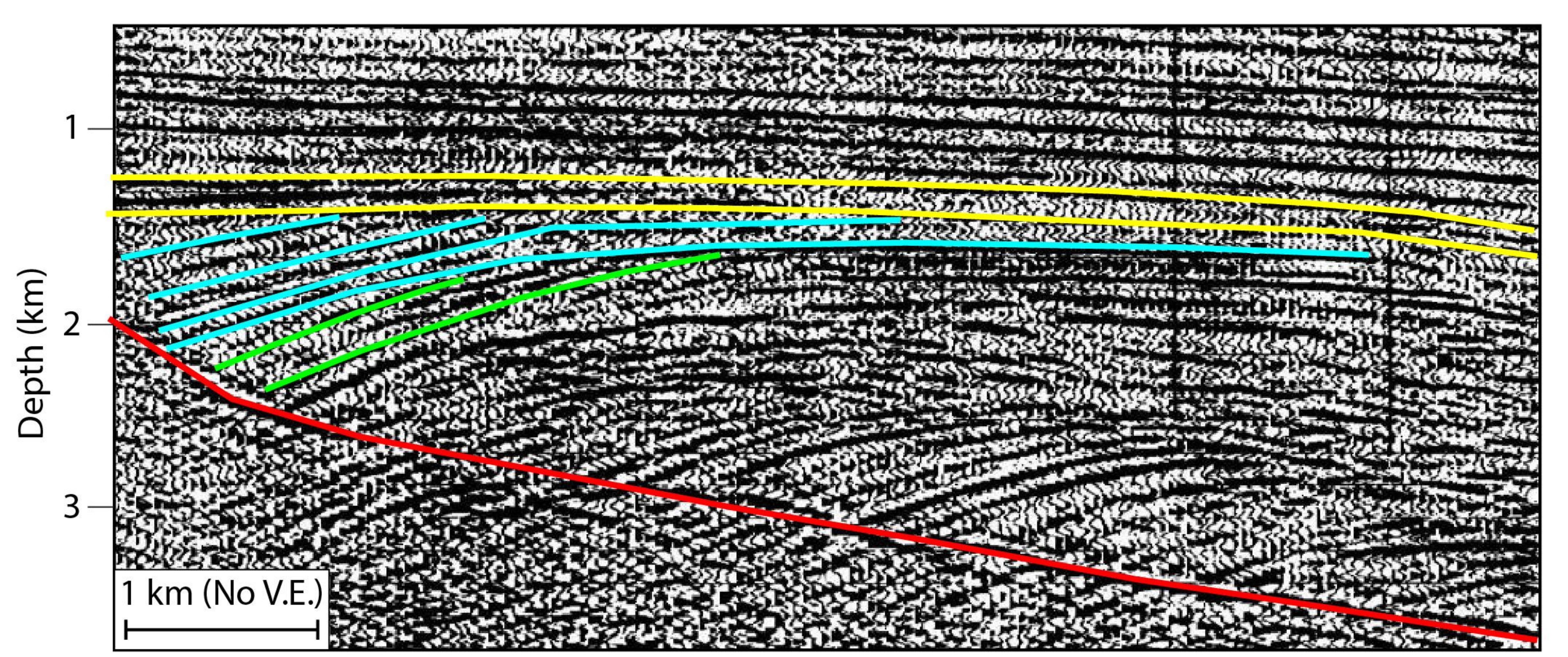
- Apparent angular unconformity develops due to non-deposition or underfilling
- Growth strata intersect at low angle and merge into condensed section
    - Not a classic angular contact (erosion of tilted strata)
- <u>Model unconformity develops over flat detachment</u> where horizons return to regional/footwall depths

Slick Ranch Rollover, Vicksburg Glide Plane, Texas: Angular Unconformities Above a Dipping Fault



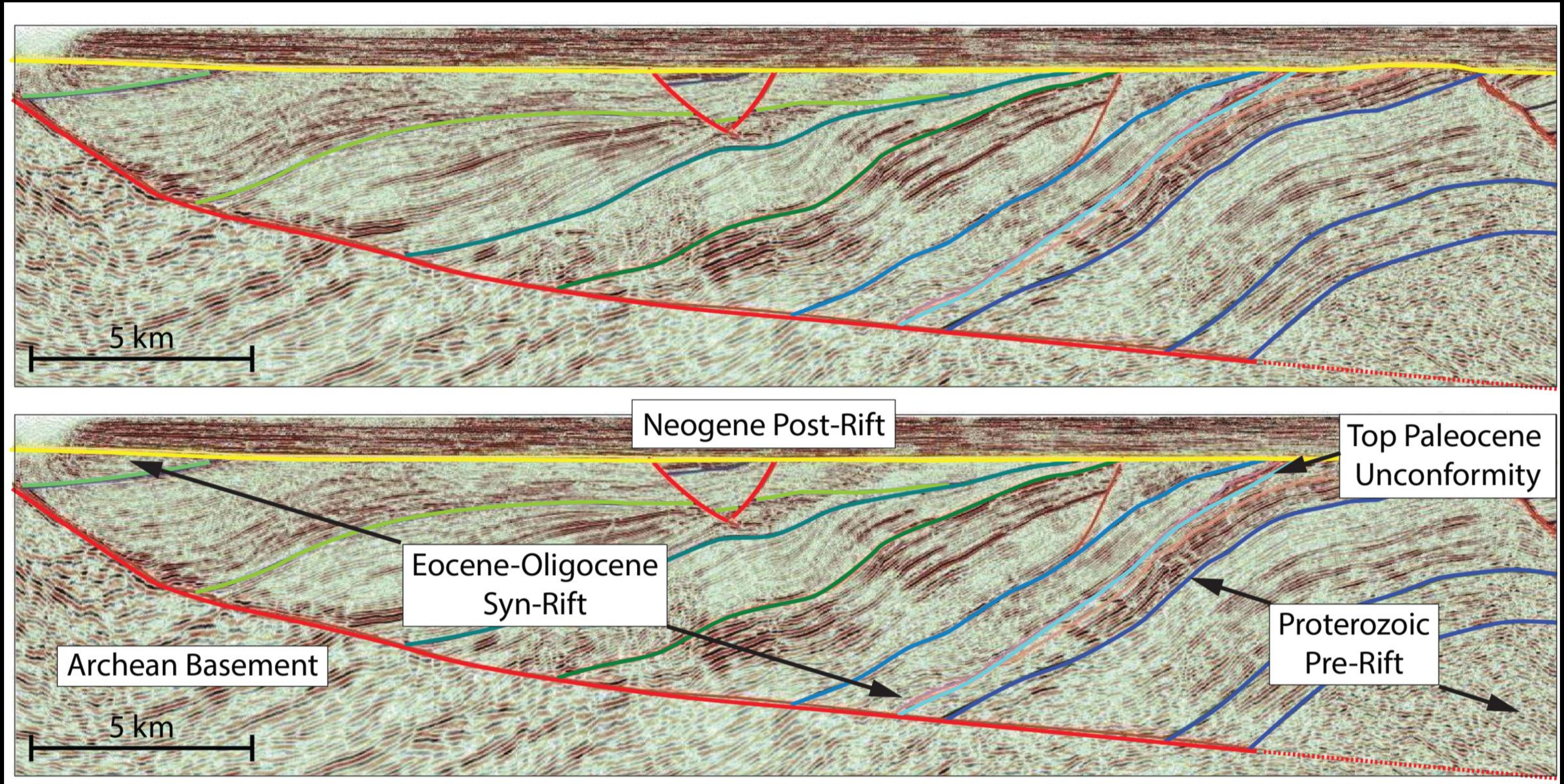
Data from Xiao and Suppe (1992)

Slick Ranch Rollover, Vicksburg Glide Plane, Texas: Multiple Sets of Angular Unconformities



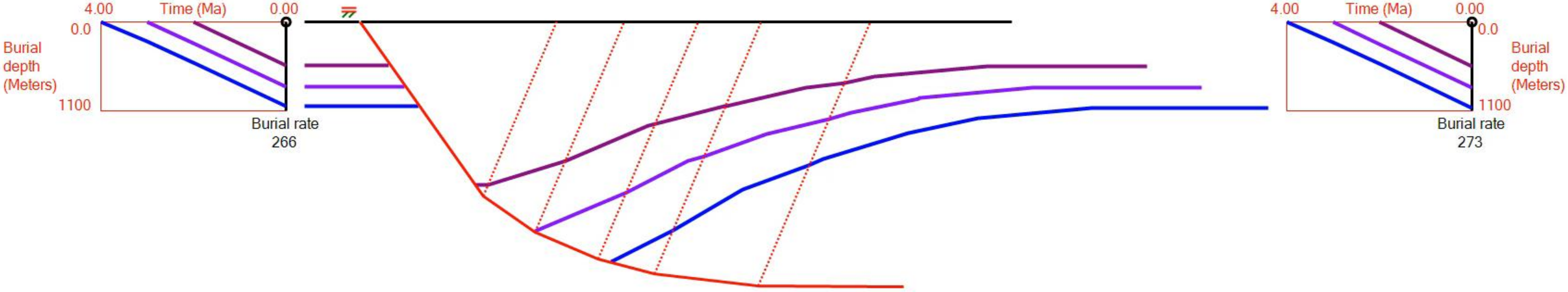
Data from Xiao and Suppe (1992)

Bohai Rift Basin:
Complete Erosion of Footwall



Constructing Kinematic Forward Models with Periods of Erosion

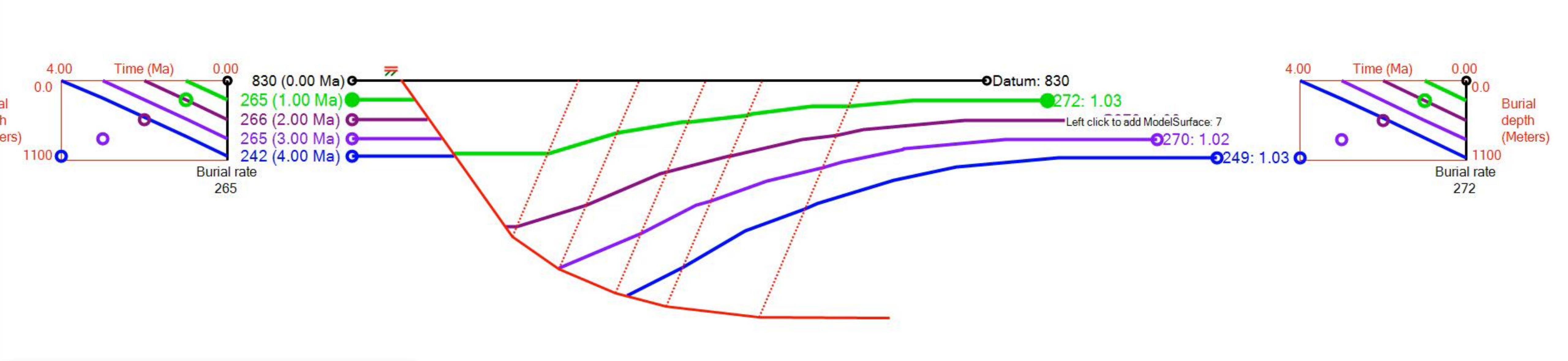
Model surfaces are parameterized by age



- Initial model characterized by regional deposition at a constant rate
  - Conformable stratigraphy: ages increase with depth
- All three surfaces are growth folds, geometry computed by inclined shear
  - Expansion ratio = 1.03

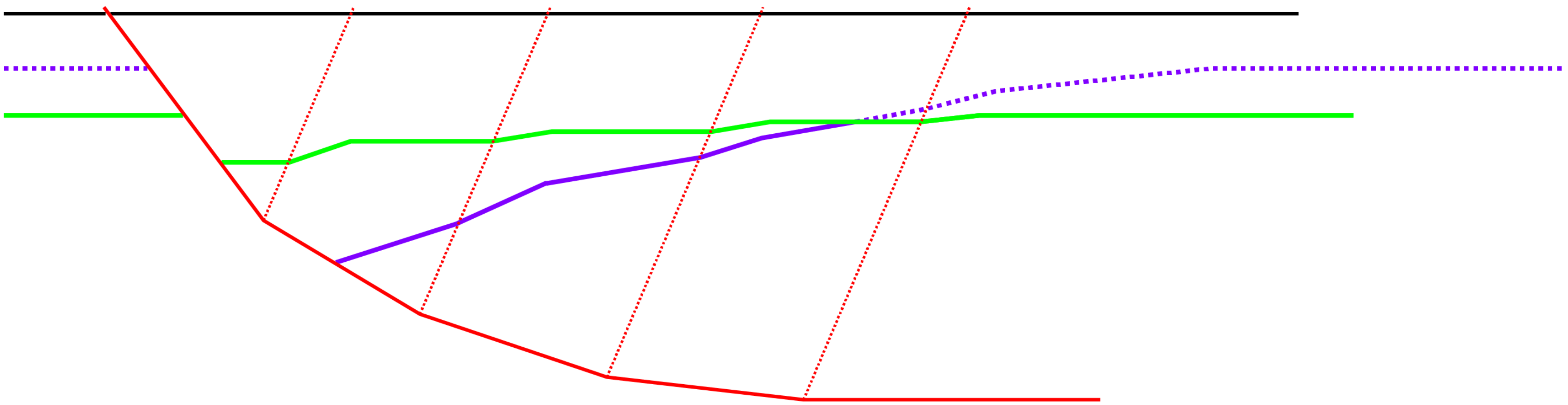
Constructing Kinematic Forward Models with Periods of Erosion

Model surfaces are parameterized by age



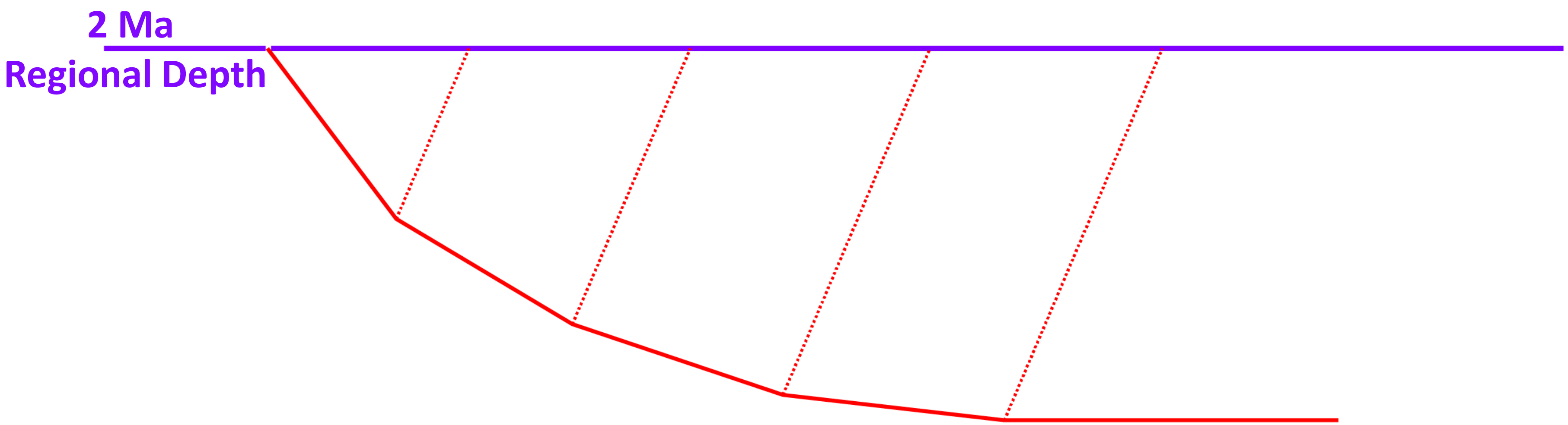
- Younger (1 Ma) growth surface added with same expansion index
- Imposed erosion: 1 Ma footwall depth is below older horizons (2 – 4 Ma)
    - Older model surfaces eroded at regional depth, truncated by younger surface

Angular Unconformity Geometry: Interplay between fault throw and erosion magnitude

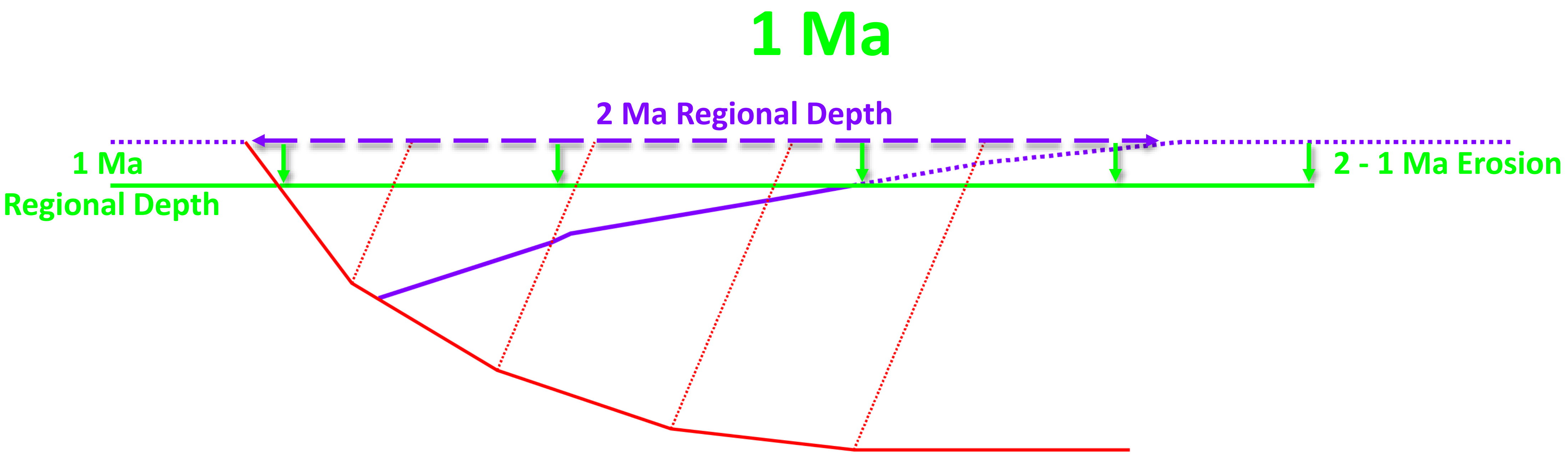


Angular Unconformity Geometry:
Interplay between fault throw and erosion magnitude

2 Ma

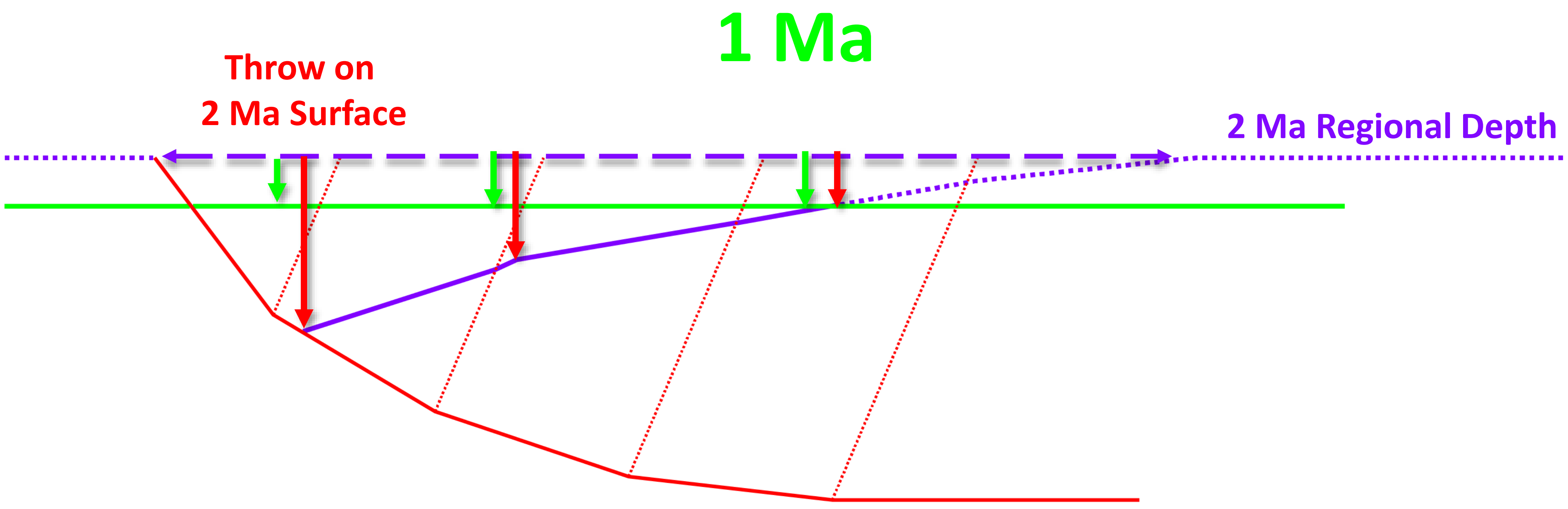


Angular Unconformity Geometry:
Interplay between fault throw and erosion magnitude



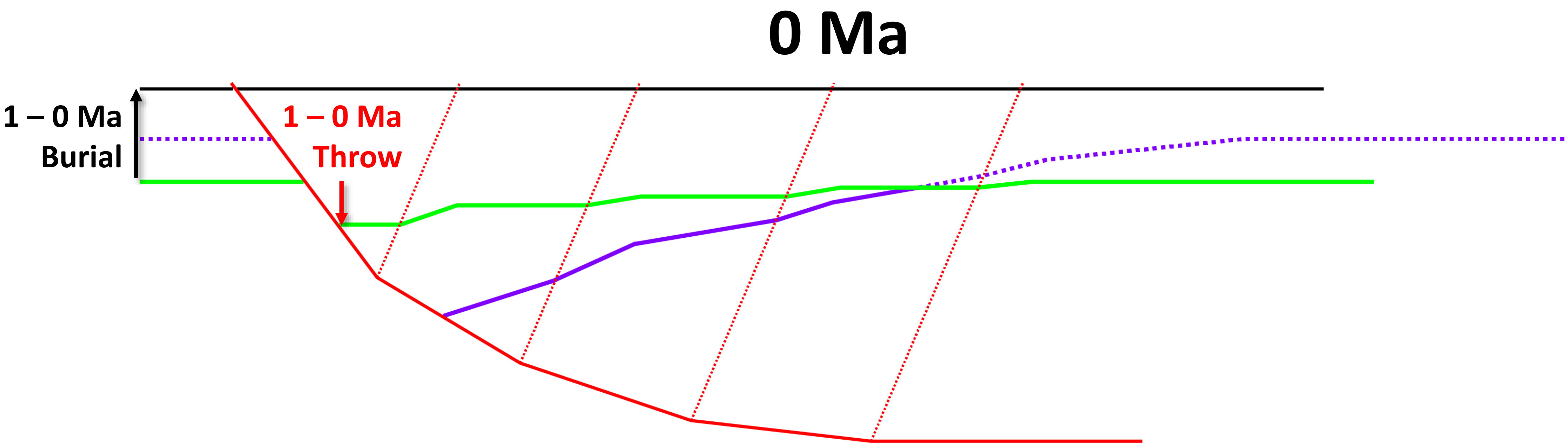
- 1 Ma footwall surface has greater regional depth than 2 Ma footwall surface
- 2 Ma growth fold eroded between its regional depth and depth of erosion (1 Ma surface)

Angular Unconformity Geometry:
Interplay between fault throw and erosion magnitude



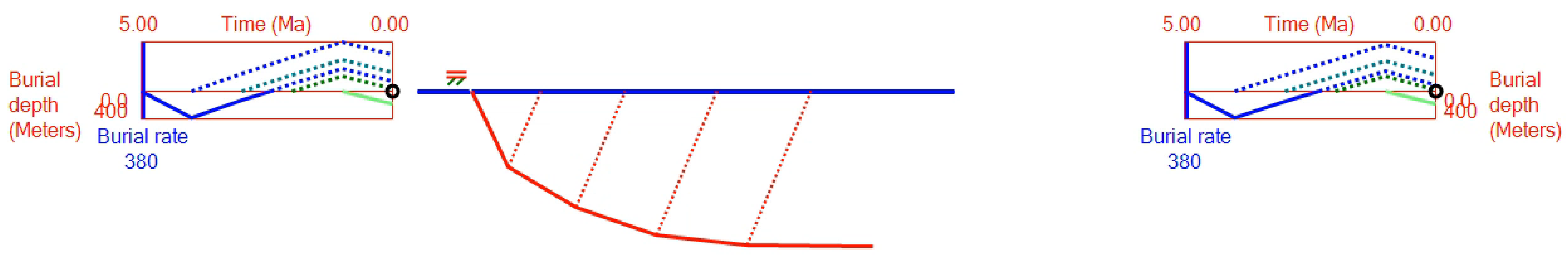
- 2 Ma surface is preserved in hangingwall where **fault throw** was greater than **erosion**
- Pinch-out located where **fault throw** was equal to **erosion**

Angular Unconformity Geometry:
Interplay between fault throw and erosion magnitude



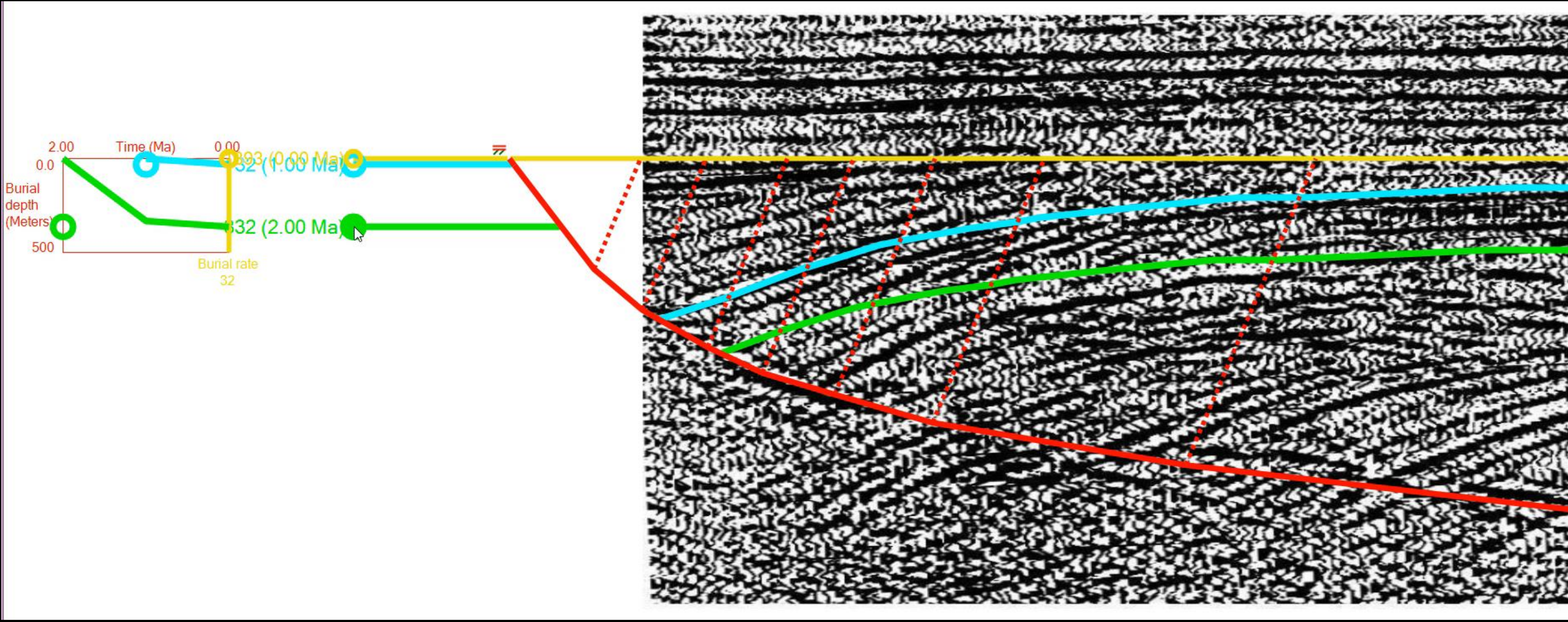
- 1 – 0 Ma: Burial resumes and extension continues
    - 1 Ma erosional surface buried and angular unconformity is preserved

Angular Unconformity Geometry: Interplay between fault throw and erosion magnitude

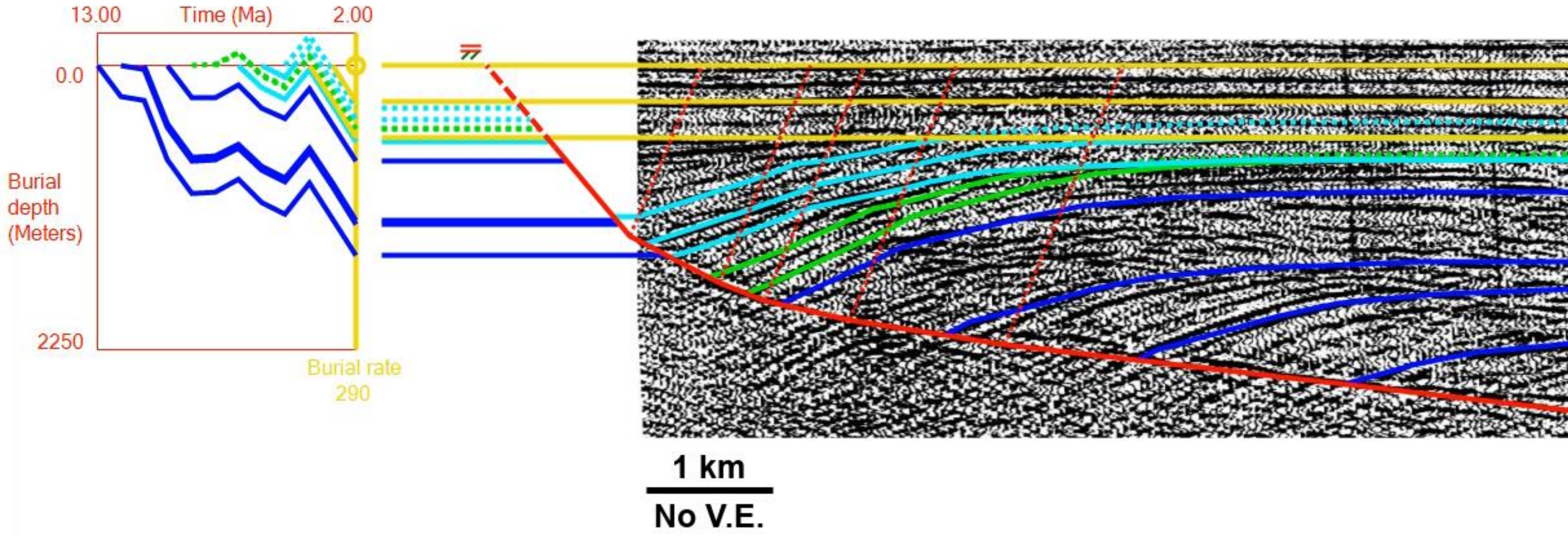


- With constant erosion and sufficient fault throw, multiple unconformable surfaces can be preserved and subsequently folded
- Regional erosion results in characteristic angular unconformities in growth sections that pinch-out away from the controlling fault

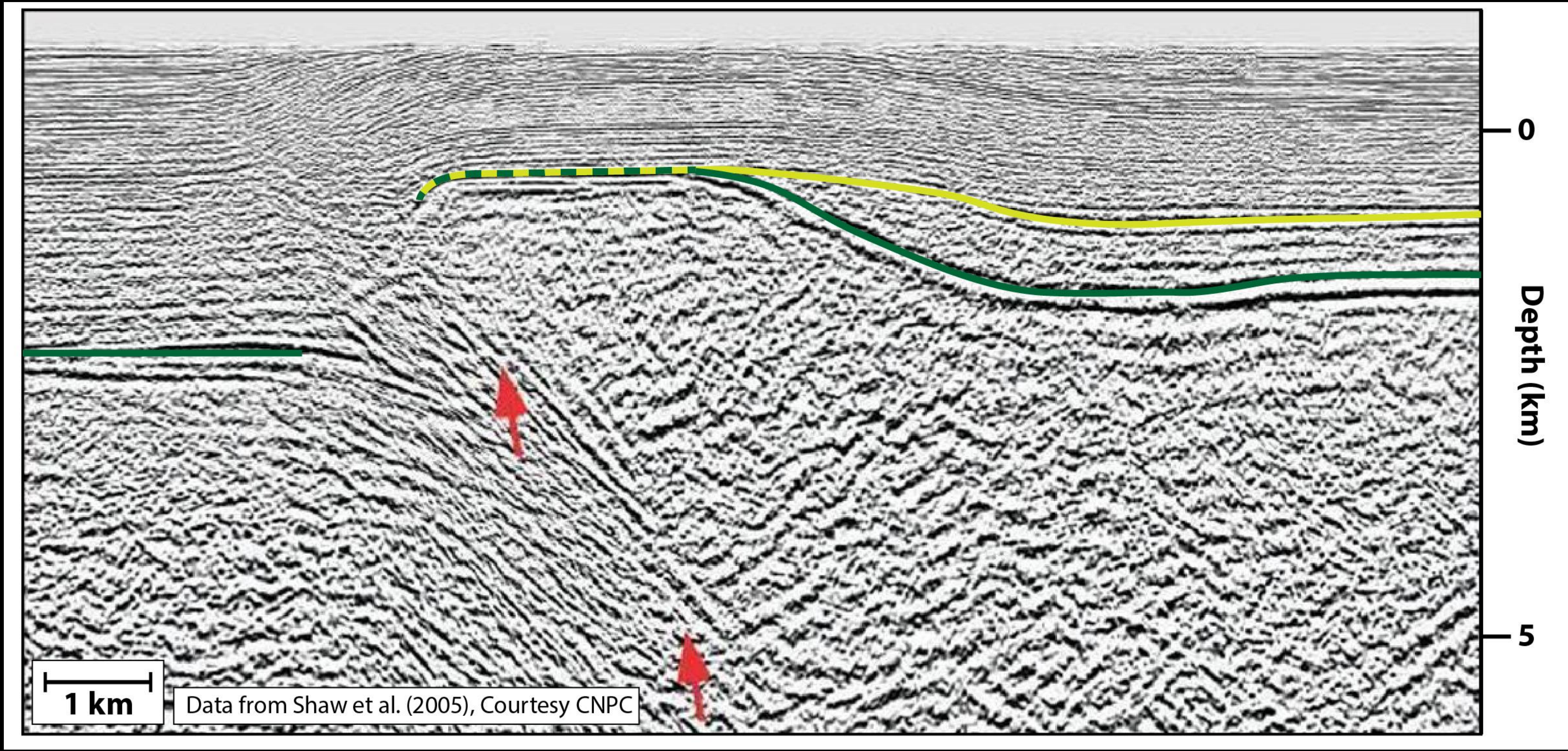
Slick Ranch: Fitting Models to Seismically-Imaged Unconformities



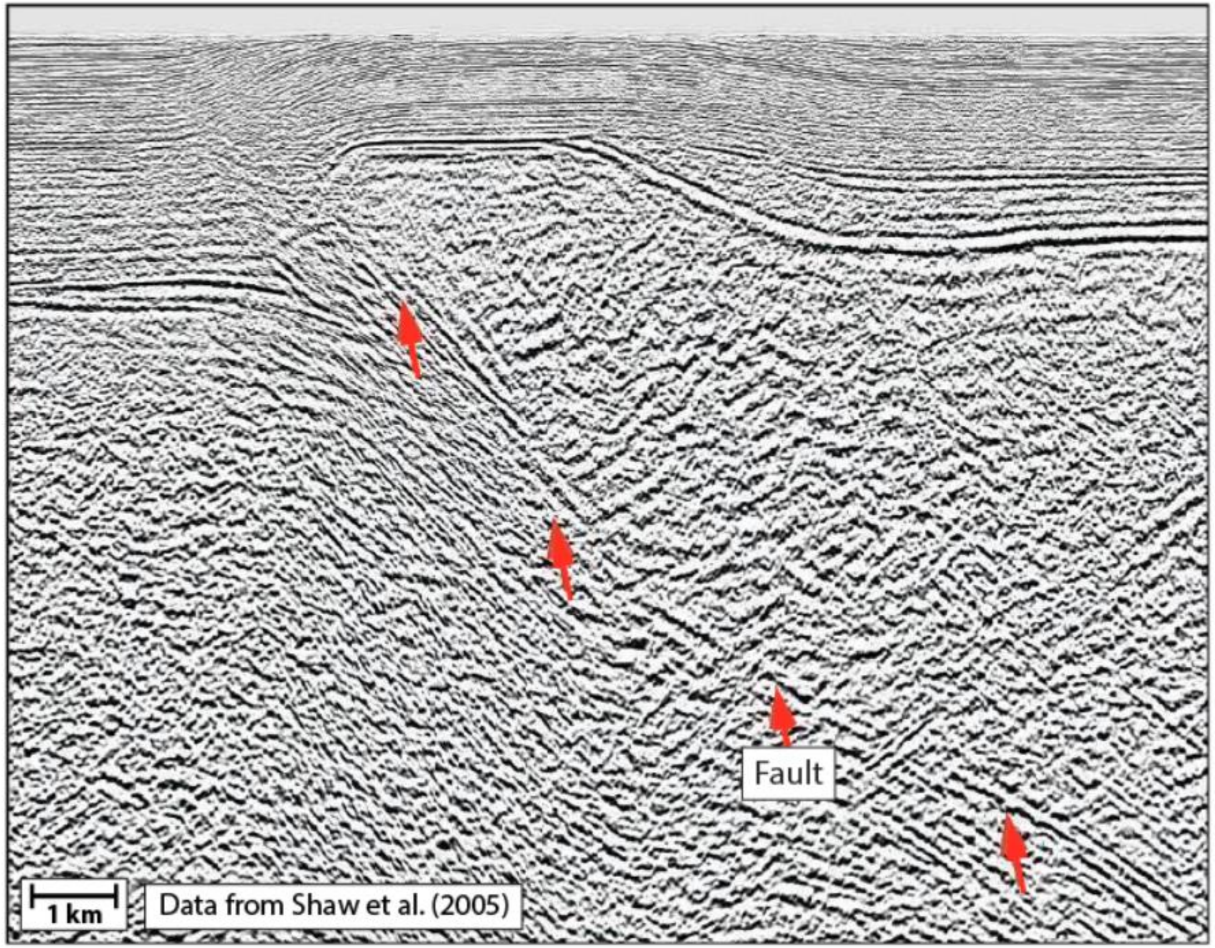
Slick Ranch Rollover Unconformity: Two Phases of Regional Erosion During Extension



Tanan Uplift, China:
Differentiating Regional Erosion from Structurally-Driven Erosion

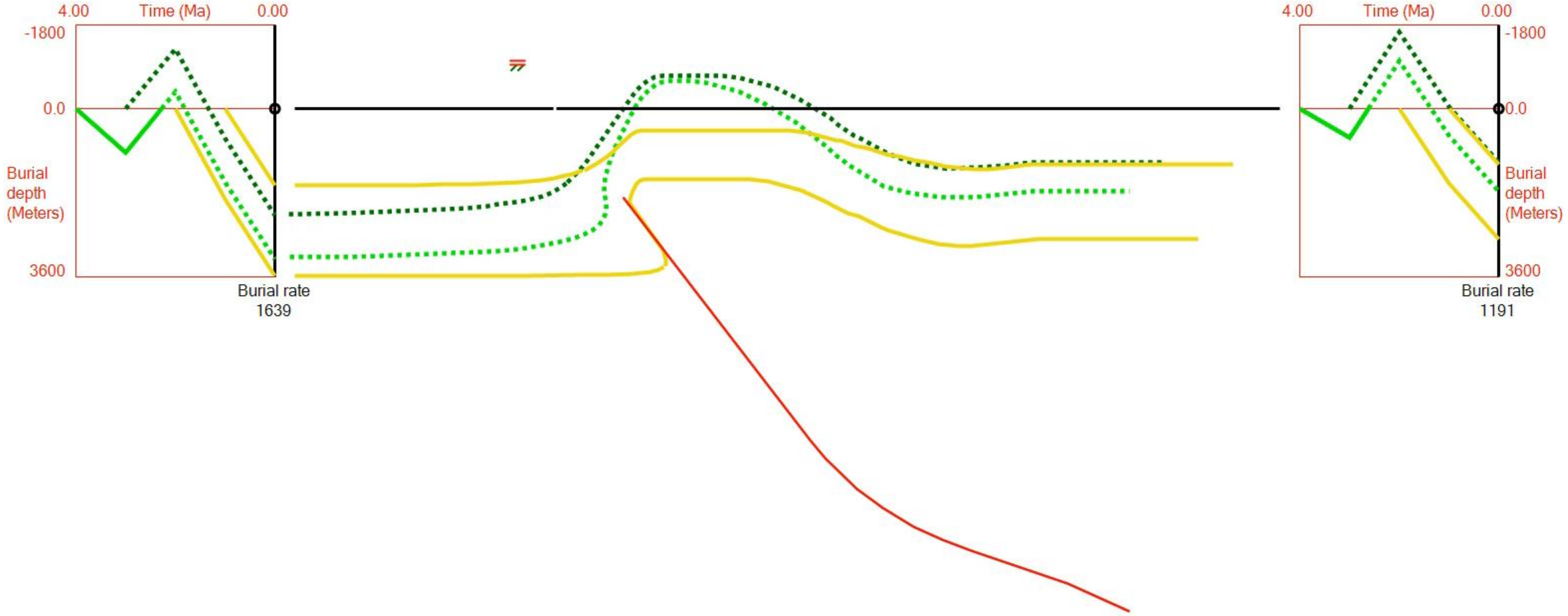


Tanan Uplift Unconformity:
Local Erosion Due to Fault Kinematics, Burial Rate



Unconformity develops where vertical fault displacement locally exceeds burial rate (Suppe et al. 1992)

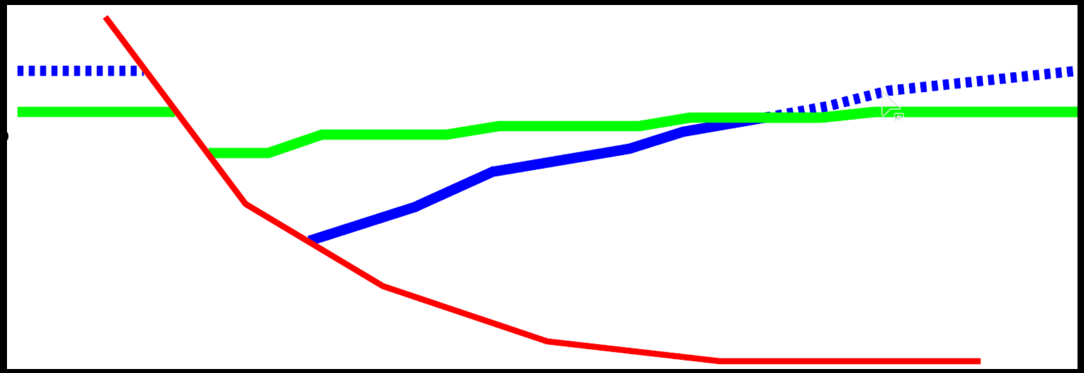
Regional Erosion in a Contractional Model: Complete Surface Erosion Due to Kinematics



Angular Unconformity Geometry in Growth Strata is Characteristic of Structural Style

Regional Unconformity:

Pinch-out away from controlling fault

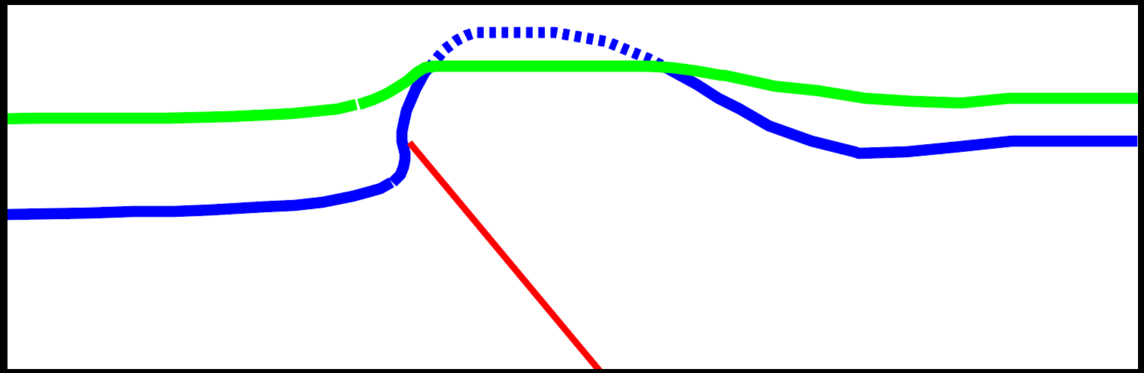


- Horizons eroded at regional depth
- Unconformity occurs below regional depths
- Only develop during extensional fault slip
- Development and preservation requires:

normal throw > erosion

Local Unconformity:

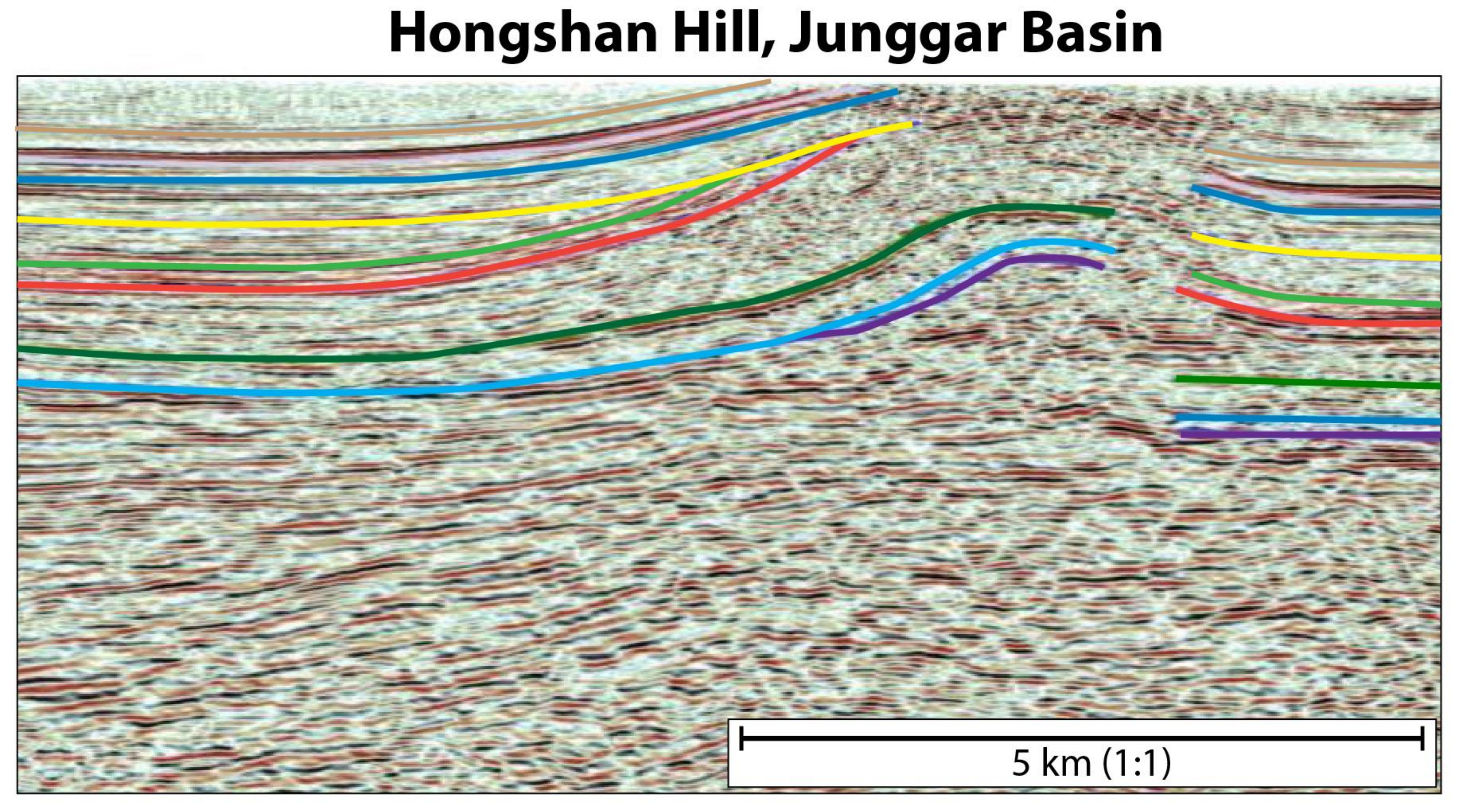
Pinch-out towards controlling fault



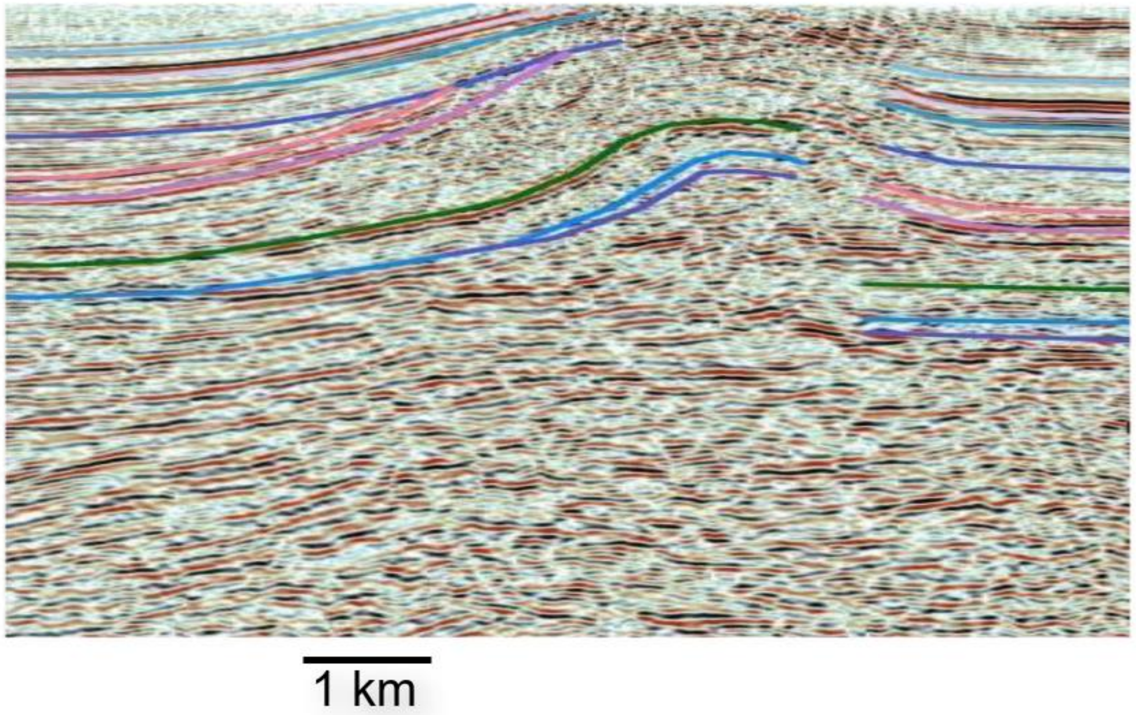
- Horizons preserved at regional depth
- Unconformity occurs above regional depths
- Only develop during contractional fault slip
- Development and preservation requires:

reverse throw > burial

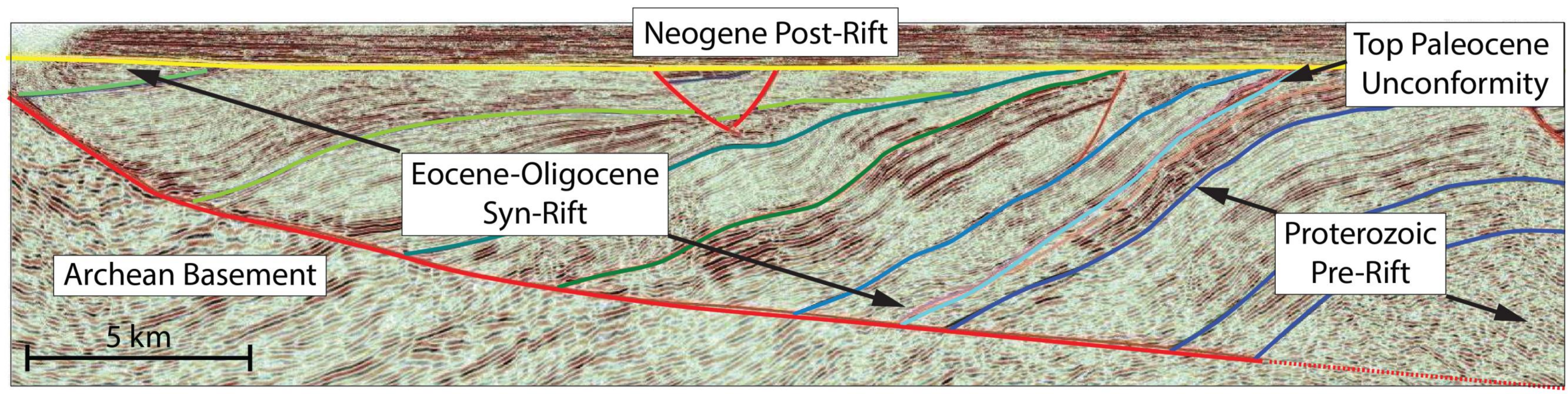
Kinematic Implications of Interpreted Angular Unconformities



Hongshan Hill:
Period of Inversion Implied by Regional Angular Unconformity

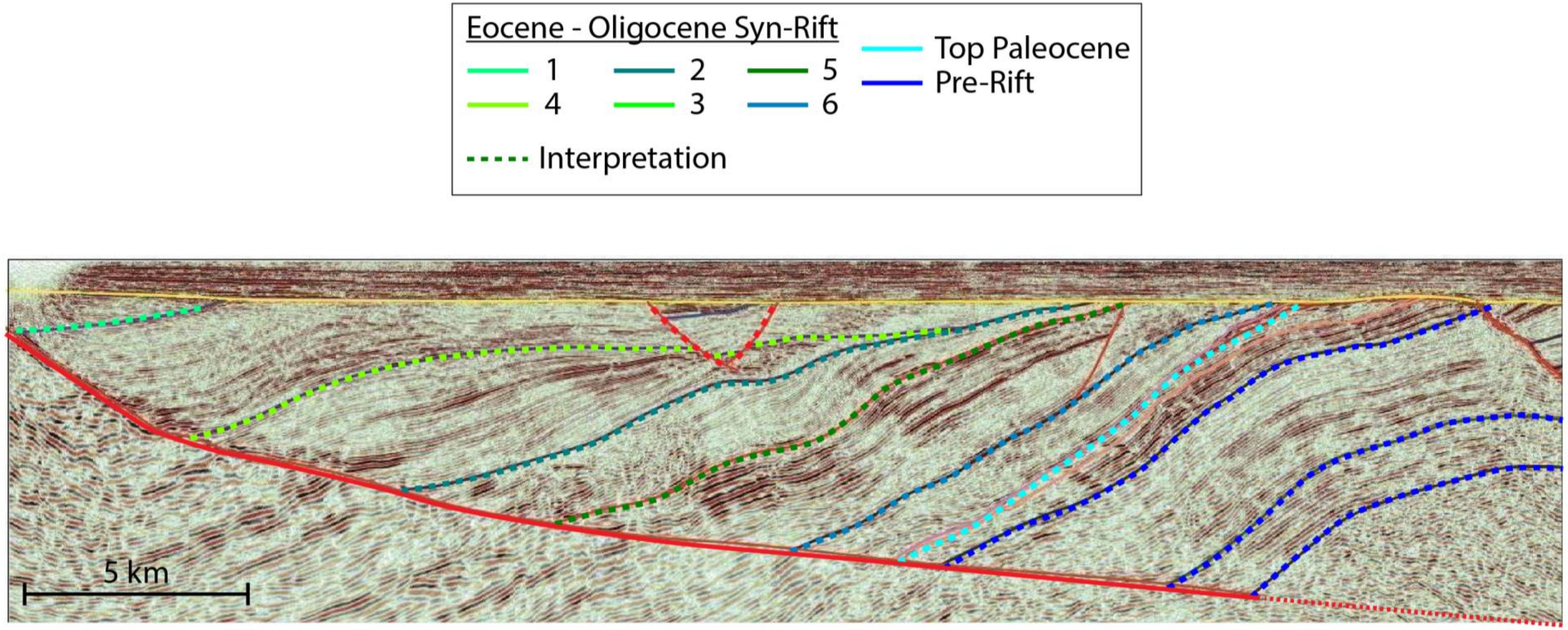


Bohai Rift Basin:
Complete Footwall Erosion

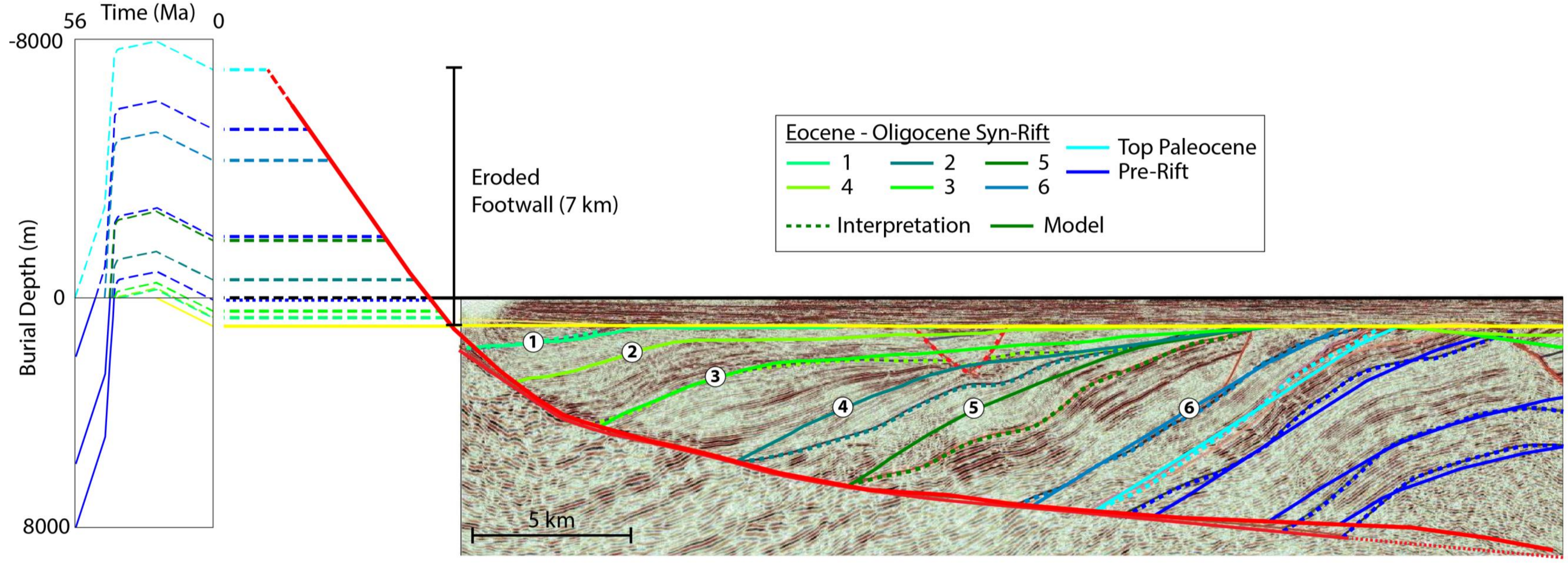


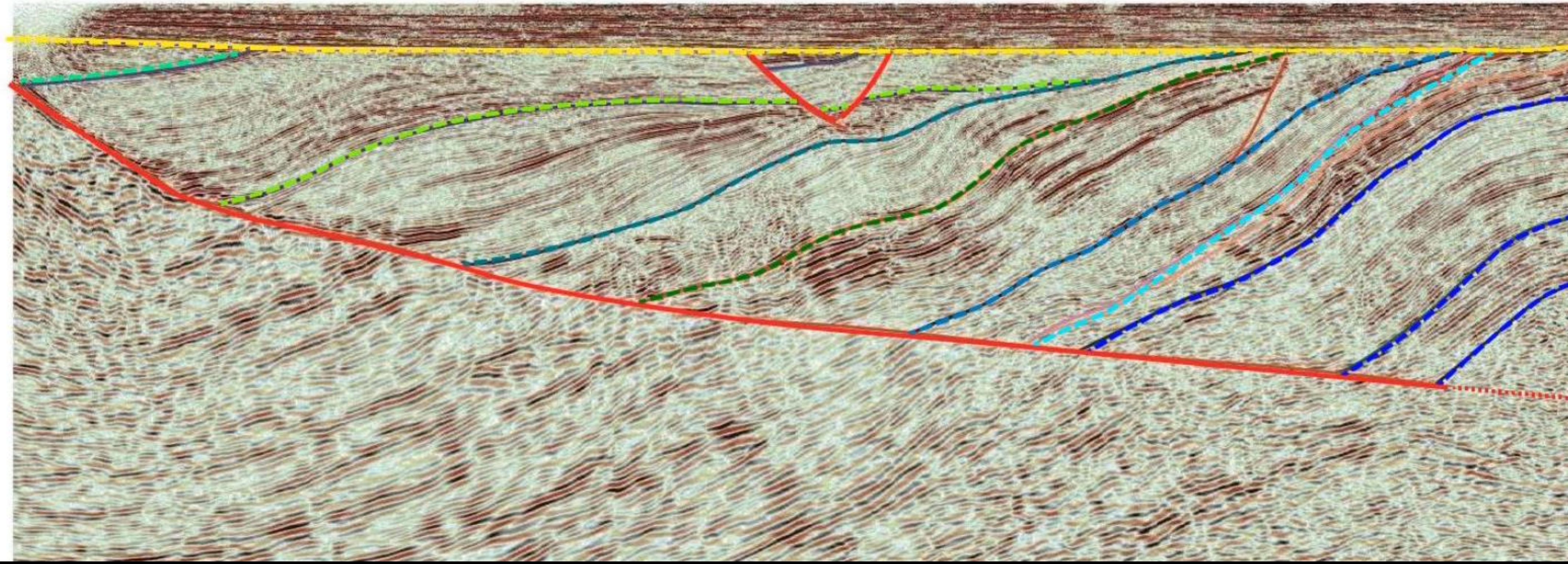
Bohai Rift:

Model Fit to Interpreted Growth Fold Geometry and Cut-off Depths
Footwall Correlations Treated as Free Variable

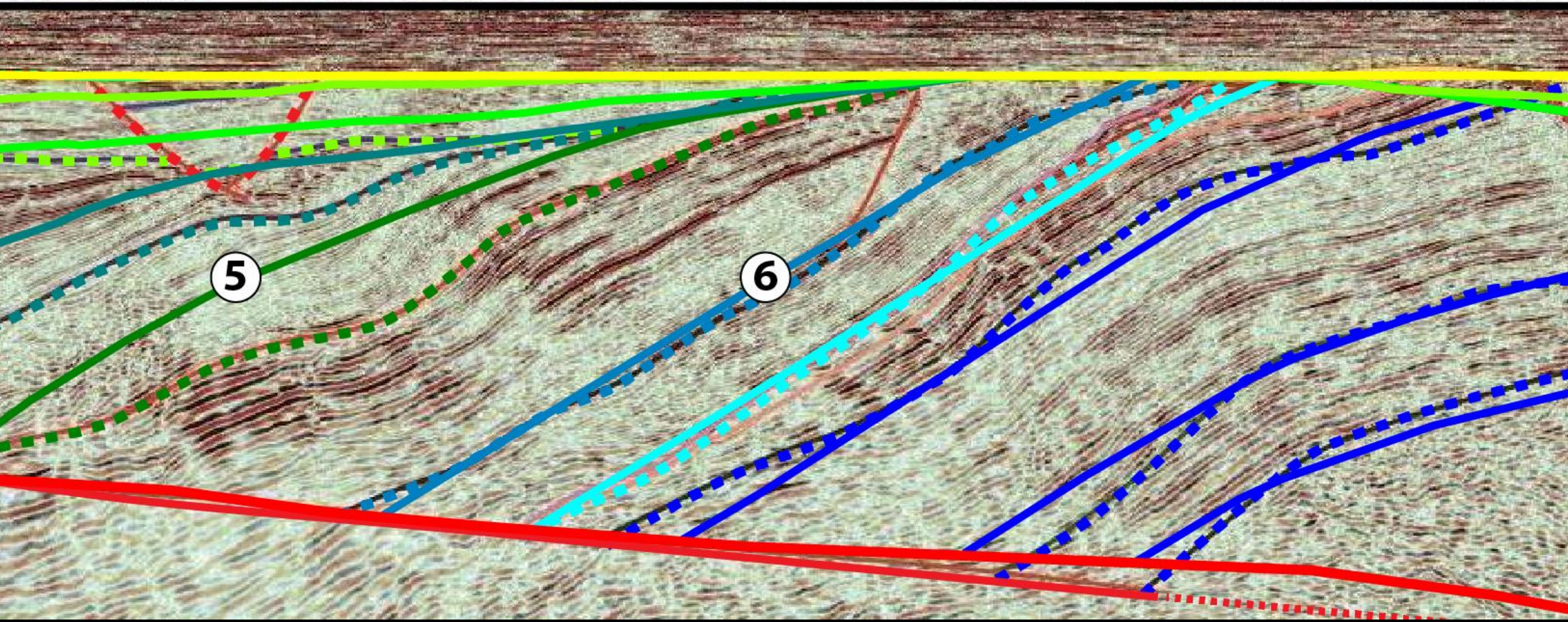


Bohai Rift:
Model Burial History Suggests 7 km of Erosion





Bohai Rift Model Mis-fit:
Influence of Fluvial Processes on Structural Geometry?



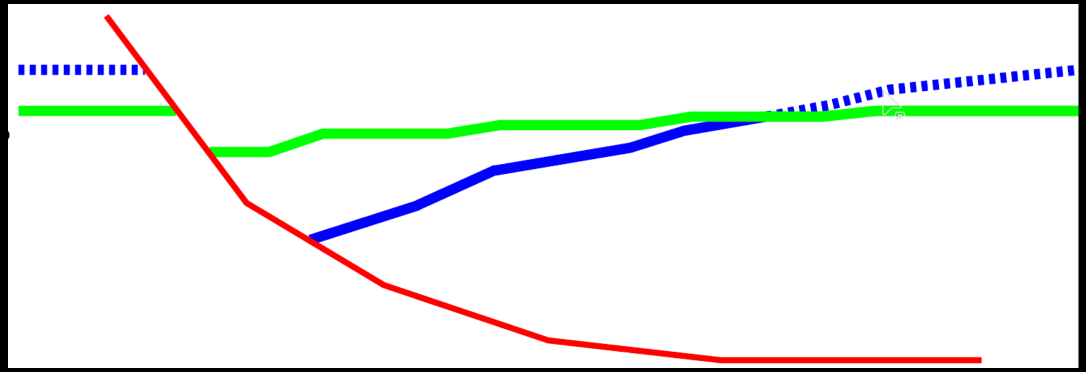
Seismic stratigraphy unrelated to folding on main fault between model surfaces 3 – 5

Conclusions

- Parameterizing forward models by age allows us to recreate regional depositional histories that include burial and erosion
- Regional erosion is modeled by placing younger horizons at greater footwall depths than older horizons

Regional Unconformity:

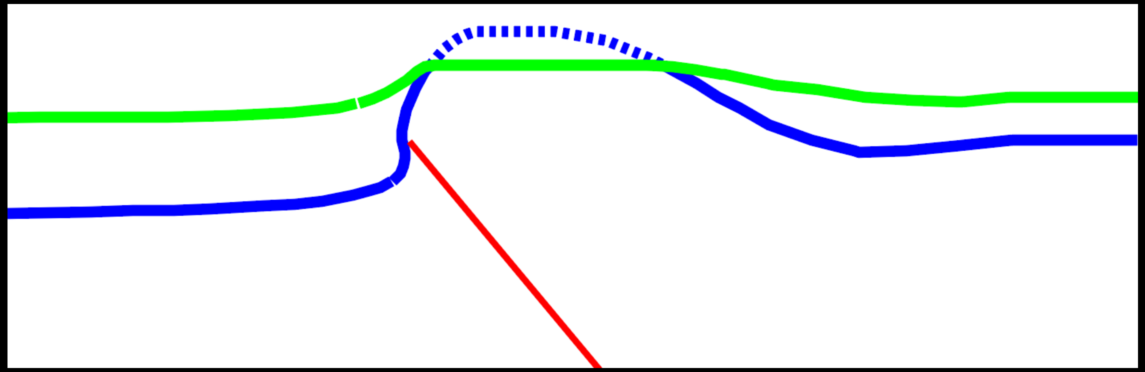
Pinch-out away from controlling fault



Only develop during extension
Implies missing section in footwall

Local Unconformity:

Pinch-out towards controlling fault



Only develop during contraction
No missing section in footwall

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Following presentation of this paper at AAPG ACE 2018, the material was published in the Journal of Structural Geology:

Eichelberger et al. (2018), Incorporating simple erosion into structural forward models: The effects of regional erosion on growth strata geometry. Journal of Structural Geology, 116, p. 146 – 158. https://doi.org/10.1016/j.jsg.2018.08.011