Do fault-cored anticlines grow by repeated earthquakes on the fault?

INDIANA UNIVERSITY

Wen-Jeng Huang and Kaj M. Johnson, Indiana University

INDIANA UNIVERSITY

Question:

Are anticlines built solely by slip on underlying blind faults during earthquakes?

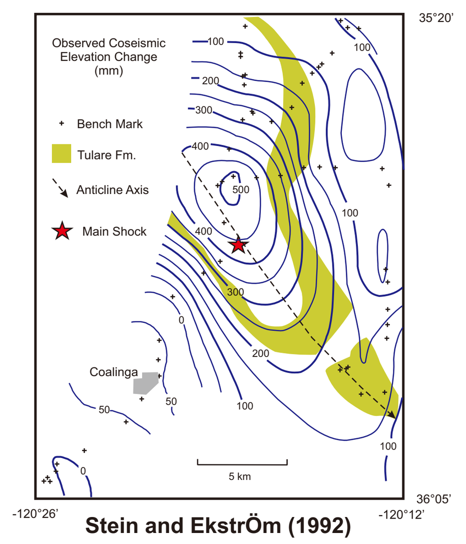
Answer:

Probably not. Mechanical layering under horizontal compressive loads **will buckle**, **amplifying** the fold produced by slip on the fault. We show that buckling of folds over blind faults may amplify the fold by **as much as a factor of nine**. Slip on the fault may contribute **only a fraction** of the total fold amplitude.

Motivation for studying the mechanics of folding over blind faults

The **geometry** of folds is routinely used to **estimate the amount of slip** on blind faults. The principal assumption is that the fold is built **solely by slip on the underlying fault**. The **similarity of coseismic uplift pattern with fold geometry** has been used to suggest that folds grow incrementally by **slip on the fault during earthquakes**. Blow are two examples of anticlines that grew during earthquakes.

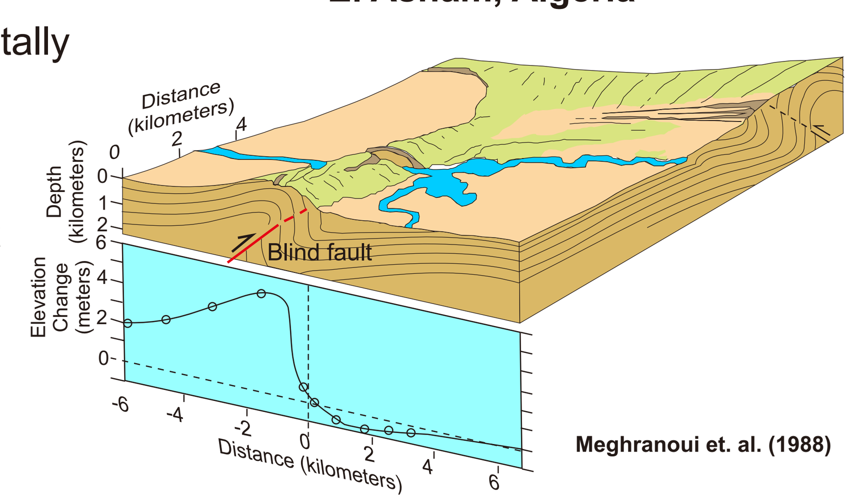
Coalinga, California



Stein and EkstrÖm (1992)

If anticlines grow incrementally by slip on the fault during earthquakes, then it is reasonable to use **elastic dislocation models** to not only estimate **coseismic slip** on the fault, but the **long-term slip rate** on the fault (e.g., Stein and King, 1984; Lin and Stein, 1989; Parsons et al., 2006).

El Asnam, Algeria

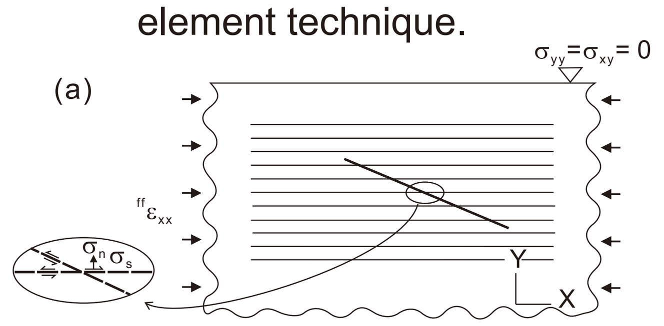


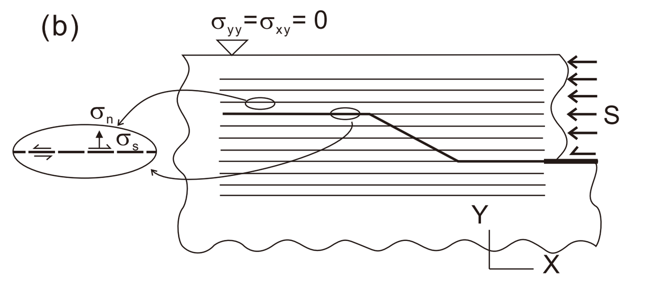
Meghranoui et. al. (1988)

In fact, the **fold form** of fault-cored anticlines are sometimes **modeled with slip on a buried dislocation** in an elastic half-space (e.g., Myers et al.,2003; Mynatt et al., 2007).

Amplification by buckling

We show that folds over blind faults can be **greatly amplified** by **buckling of strata** under compression. To demonstrate this, we construct a **mechanical model** using a boundary element technique.





The **thin** and **solid straight lines** in the left figure represent **bedding planes** and the **heavy lines** represent **faults**. Bedding planes and faults are discretized into patches with equal length. They are assumed to be **frictionless** and **cohesionless**.

From the solution for a 2D edge dislocation, we can relate the vector of shear stresses, σ_s, at the center of each patch to the vector of slip, s, on all the patches through the matrix, G_σ,

$$\sigma_s = G_\sigma s$$

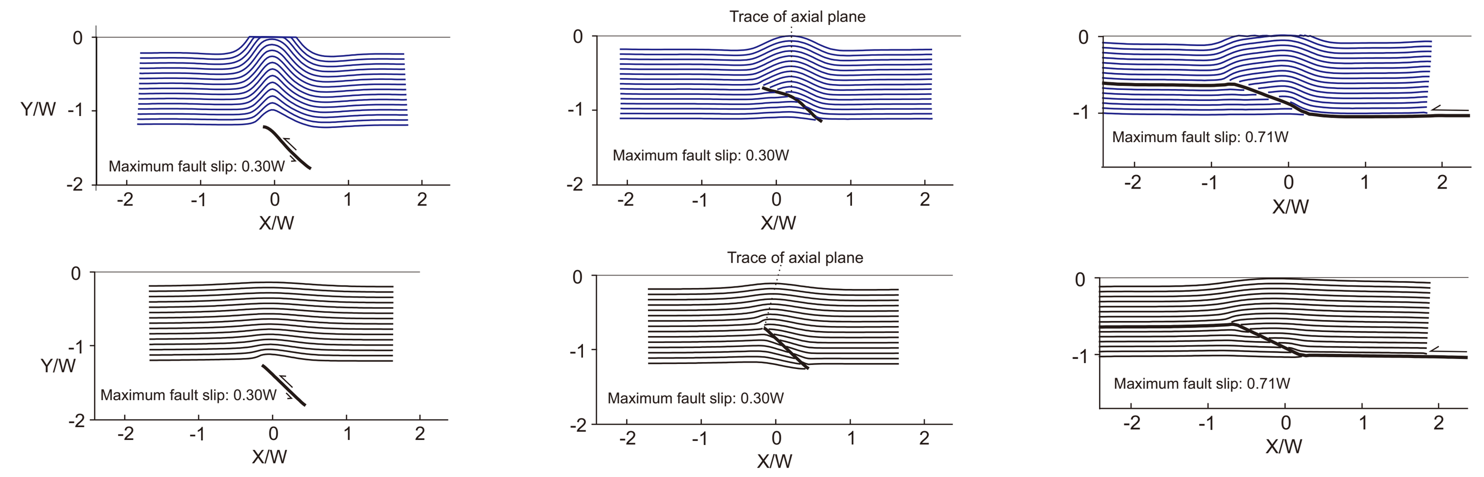
In **each increment of** shortening, we solve for slip, s. Using this slip, we calculate **new** geometry of the bedding planes and the fault.

Simulations

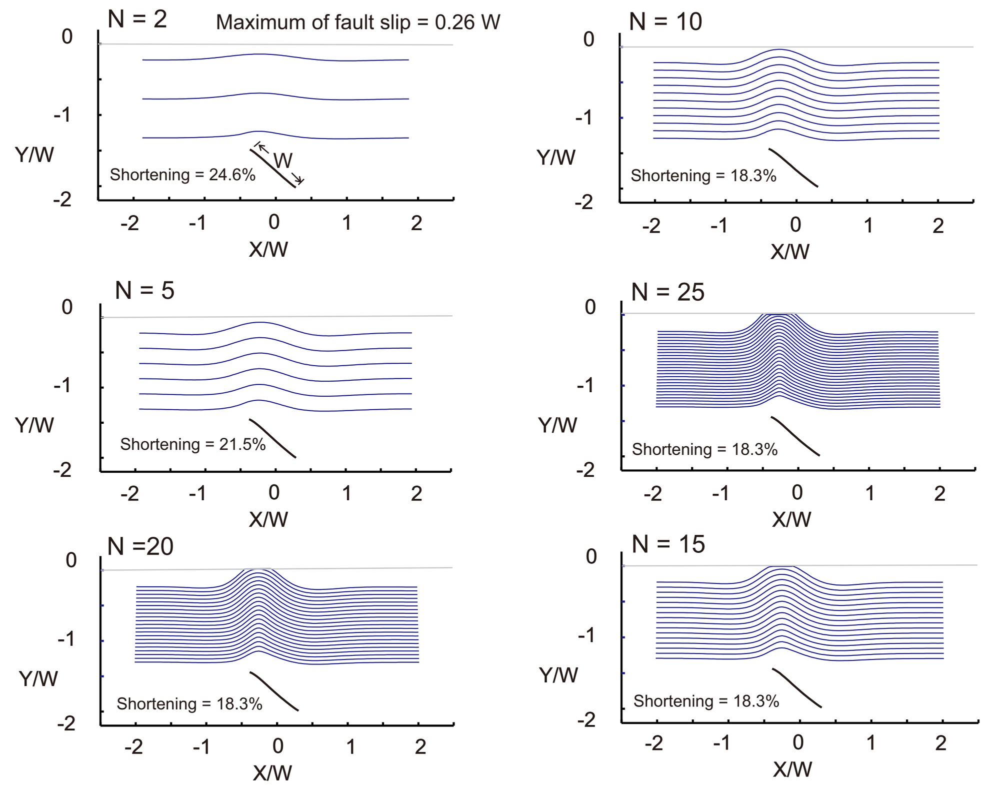
Mechanical layering has a large influence on fold form. Amplitude of buckle folds is much larger than amplitude of passive folds. We compare the case that layers are bonded (passive folding) with the case that layers slip freely at contacts (buckle folding).

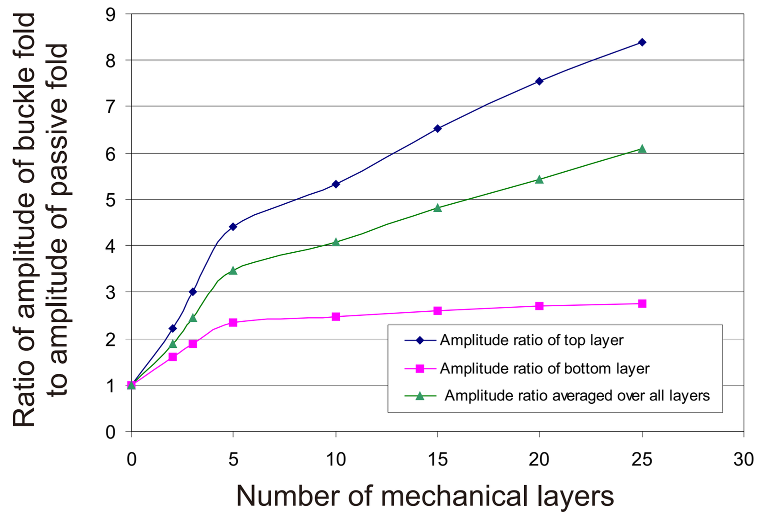
Buckle folding

Passive folding



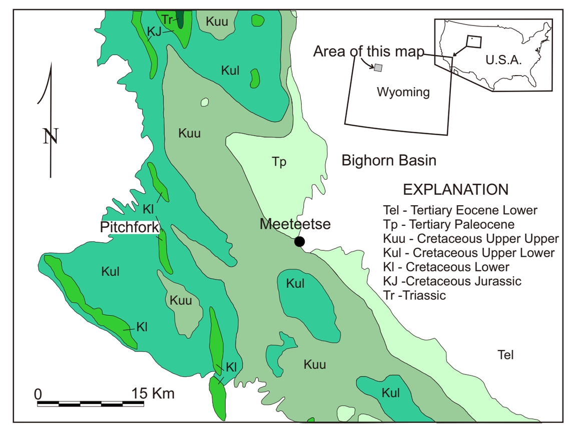
Simulations below illustrate the influence of layer thickness on fold amplitude.

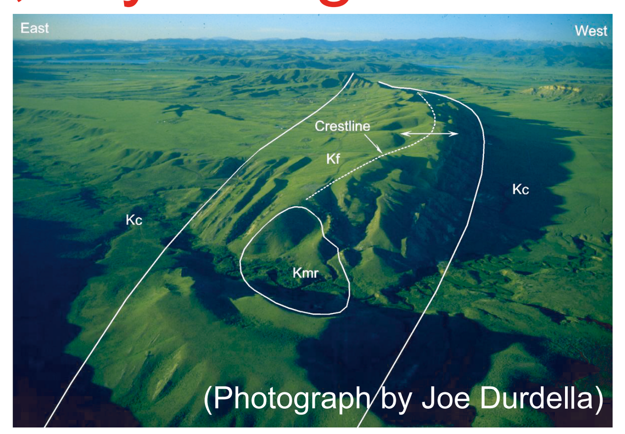




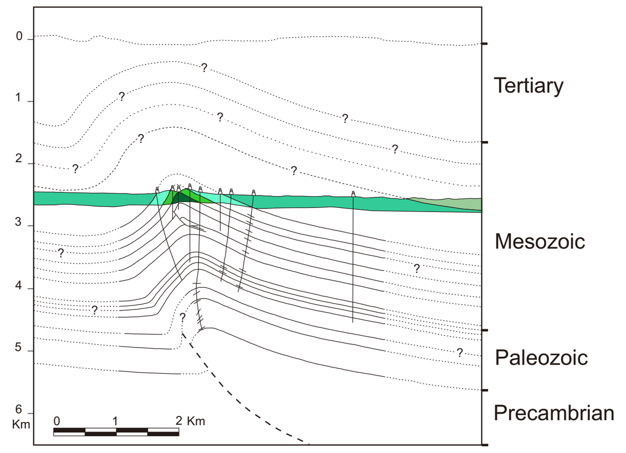
The figure above compares the amplitude of passive folds with the amplitude of buckle folds. The rate of fold growth increases with the number of layers.

Pitchfork Anticline, Wyoming





(Photography by Joe Durdella)

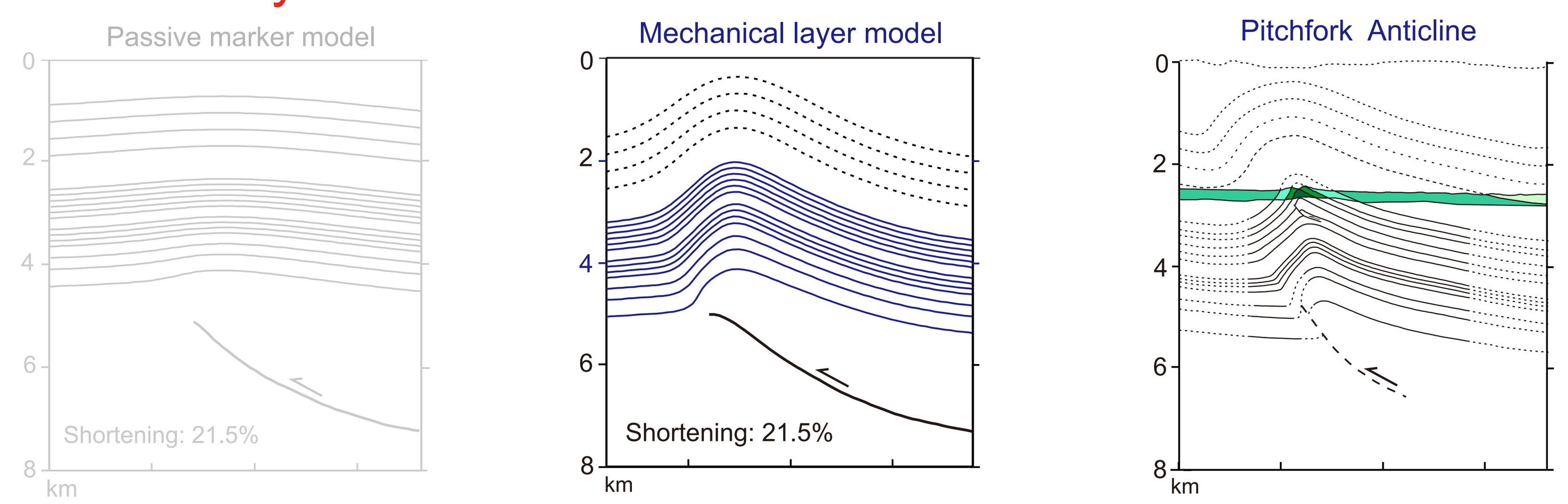


(Durdella, 2001)

Pitchfork Anticline is one of many anticlines in the Bighorn Basin in Wyoming that formed during the **Laramide orogeny**.

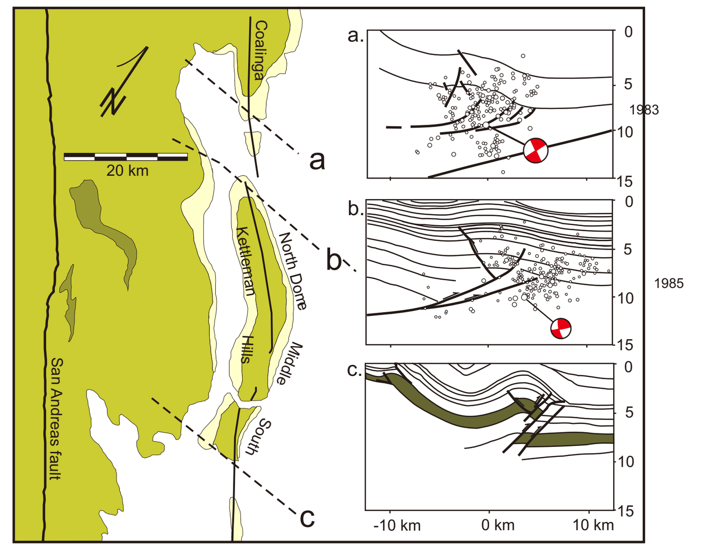
- Geometric features: Durdella (2001, p. 37)
  1. The limbs are **rounded** rather than planar.
  2. The stratigraphic **throw** in the anticline increase by about **50%** from the top of the Precambrian basement to the top of Cretaceous units near the current ground surface.
- The Pitchfork Anticline displays geometric features **consistent** with buckle folding.

Mechanical analysis of Pitchfork Anticline



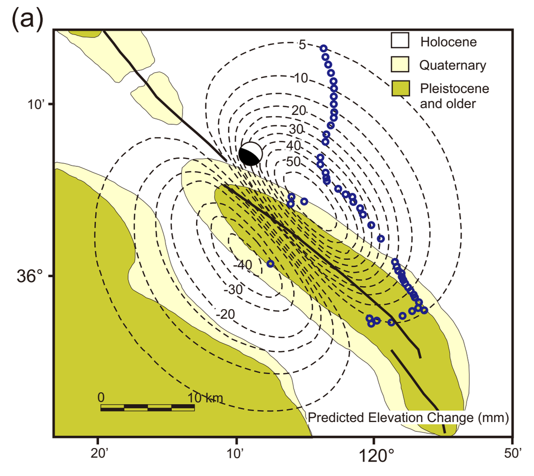
- Durdella (2001) considered a **single, listric fault** with **imposed slip** beneath passive layering, unaccompanied by shortening (elastic dislocation model). It was **unsuccessful** in producing even a rudimentary fold of the shape of Pitchfork Anticline.
- We **simulate** Pitchfork Anticline with our **fault-cored buckle fold boundary element model** with a **basement fault** underlying a stack of mechanical layers under horizontal **compression**.
- The model reproduces many of the **features.** The fold is similarly **localized**, the anticlinal hinge is relatively **tight**, and the backlimb is **rounded.**

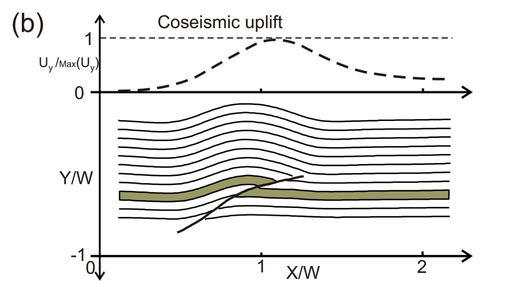
Kettleman Hills, California



- Study of an **actively growing** anticline at Kettleman Hills in central California.
- data directly relating slip on the fault to the growth of the folds.
- Surface displacements were recorded from a moderate earthquake in 1985.
- Figure in the right shows profiles across the chain of folds constructed from **well** and **seismic reflection** data (Stein and Ekström,1992; Wentworth and Zoback, 1989; Meltzer, 1989).

Mechanical analysis of Kettleman Hills Anticline





Observation:

Coseismic uplift is **centered** on the forelimb of anticline rather than the hinge line.

Model:

The axial trace of anticline is located **behind** the fault tip but the peak coseismic uplift is above the fault tip, **centered** on the forelimb.

Interpretation:

The similarity between the observation and model suggest Kettleman Hills Anticline formed by combined mechanisms of fault slip and buckling.

References:

Durdella, M. J., 2001, Mechanical Modeling of Fault-related Folds: West Flank of the Bighorn Basin, Wyoming: M.S. Thesis, Department of Earth and Atmospheric Sciences Library, 128 p.

King, G. C. P, and R. Stein (1983), Surface folding, river terrace deformation rate and earthquake repeat time in a reverse faulting environment: the Coalinga, California, earthquake of May 1983, California Division of Mines and Geology, Special Publication 66, 165-176.

Lin, J. and R. S. Stein (1989), Coseismic folding, earthquake recurrence, and the1987 source mechanism at Whittier Narrows, Los Angeles Basin, Calfornia, J. Geophys. Res., 94, 9614-9632.

Meghraoui, M. and H. Philip, F. Albarede, and A. Cisternas (1988), Trench investigations through the trace of the 1980 El Asnam thrust fault: Evidence for paleoseismicity, Bulletins of the Seismological Society of America, v.78, no. 1, 979-999, April.

Meltzer, A. (1989), Crustal structure and tectonic evolution; Central California, Ph. D. dissertation, 95-167, Rice Uni. at Houston, Texas.

Myers, D. J., J. L. Nabelek and, R. S. Yeats (2003), Dislocation modeling of blind thrust in the eastern Los Angeles basin, California, , J. Geophys. Res., 108 (B9),2443,doi:10.1029/2002JB002150.2003.

Mynatt, I., G. E. Hilley, and D. D. Pollard (2007), Inferring fault characteristics using fold geometry constrained by air borne laser Swath mapping at Raplee Ridge, Utah, J. Geophys. Res., 34, L16315, doi:10.1029/2007GL030548, 2007.

Stein, R.S., and G. Ekstrom, 1992. Seismicity and geometry of a 110-km-long blind thrust fault 2. Synthesis of the 1982-1985 California earthquake sequence, Journal Geophysical Research, 97, 4865-4883.

Wentworth, C. M. and M. D. Zoback (1989), The style of late Cenozonic deformation at the eastern front the California Coast ranges, Tectonics, 8, 237-246.