Plio-Quaternary kinematics of fault-tip folding from modeling the structural and geomorphic record of deformation

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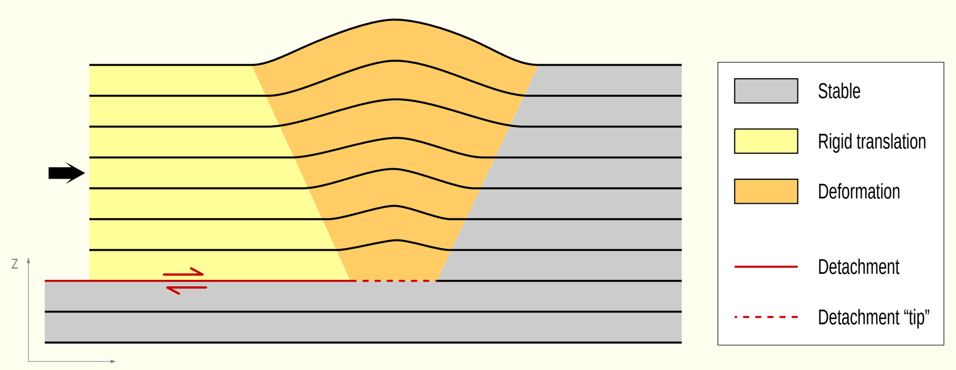
Introduction

It is rarely straightforward to interpret uplift rates recorded by geomorphic and structural markers in terms of horizontal shortening, e.g. in the context of piedmont folds, where thrust faults are often blind. Usually, this requires a spatially continuous record of the uplift, such as well-preserved alluvial or fluvial surfaces, as well as assumptions on the underlying pattern of deformation.

Here, using a simple kinematic model derived from analogical experiments (*Bernard et al.*, submitted) and applied first to the analysis of Pakuashan anticline in Taiwan (*Simoes et al.*, submitted), we are able to constrain the horizontal shortening history of a young fault-tip fold, as recorded by pre-growth and growth strata, deformed geomorphic markers and topography.

Modeling Approach



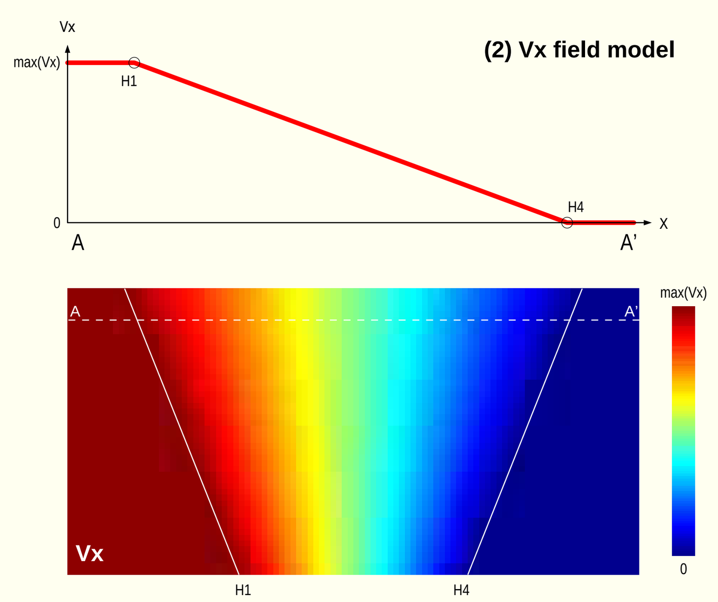
(1) Simple geometry of a fault-tip fold

In a fault-tip fold model (e.g. *Dahlstrom, 1990*; *Mitra, 2003*), rocks are deformed above the tip (or tip-area) of a sub-horizontal detachment fault. This model applies to "young" folds, since after a certain amount of shortening has been accommodated in this pattern, strain tends to localize, evolving toward a fault-bend fold (*Suppe, 1983*).

A simple kinematic model

Analogical modeling by *Bernard et al.* (submitted), using sandbox experiments, offers a reasonable first-order description, in cross-section, of the velocity field in the early stage of fault-tip fold development. In this model, the horizontal (Vx) and vertical (Vz) velocities, relative to the area below the detachment, vary linearly with X in a series of spatial domains bordered by hinge lines (H1, H2...).

Along a given horizontal line (AA'), from the first hinge H1 to the last hinge (here, H4), Vx varies from max(Vx), the slip rate of the detachment fault, to zero. Vx is thus entirely constrained by the detachment slip rate and the configuration of the first and last hinges in the model.



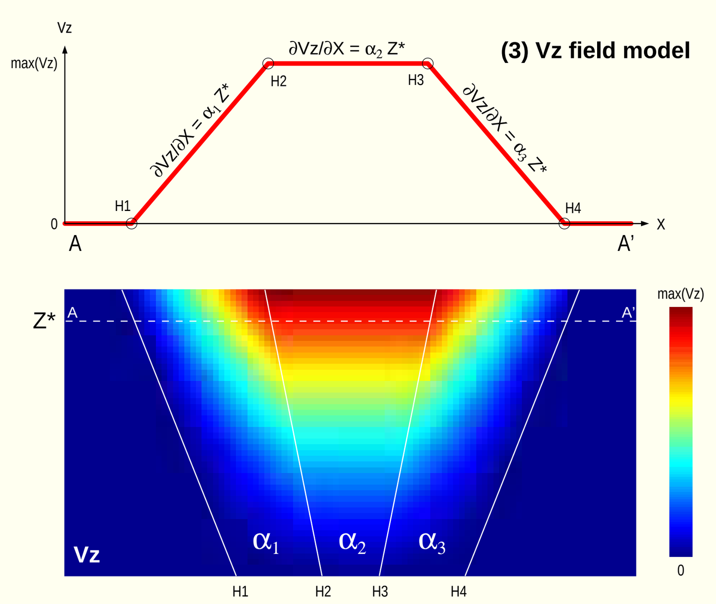
(2) Vx field model

Along the same line (AA'), Vz is continuous and varies linearly in each inter-hinge domain, with $\partial Vz/\partial X$ being proportional to the local height above the detachment:

$$\partial Vz/\partial X = \alpha.(Z-Z_{detach})$$

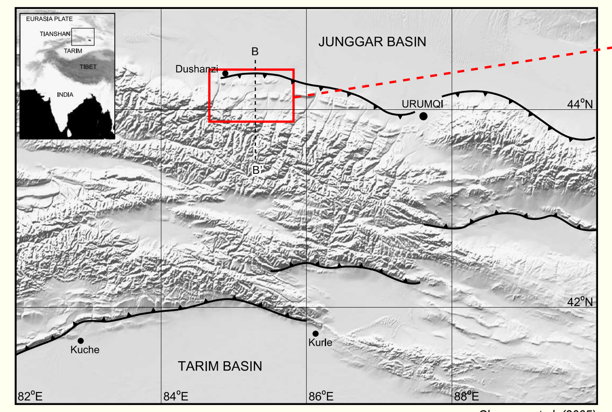
The parameter α is constant in each inter-hinge domain, but different domains have different values of α.

The results of Bernard et al. suggest that, to a first-order approximation, these hinges remain stable, throughout deformation, while material passes through them from on domain to another.

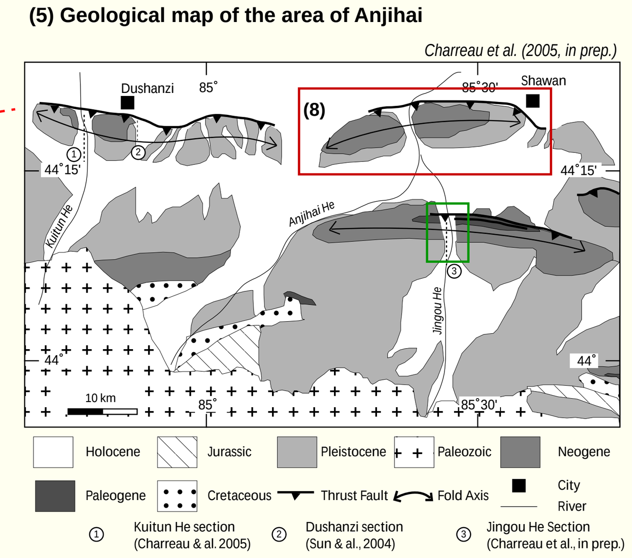


(3) Vz field model

Tectonic Setting



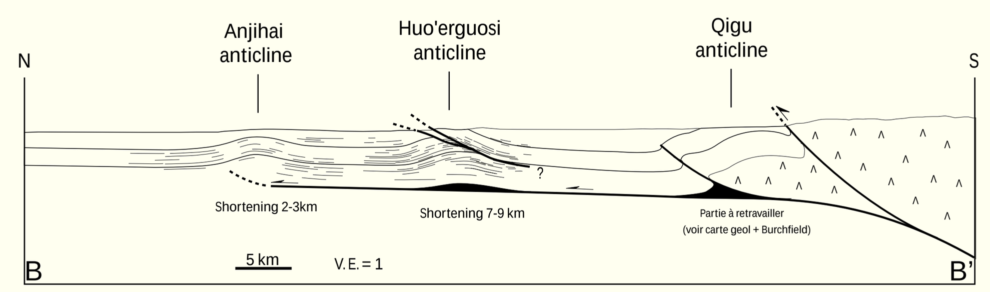
(4) Shaded topography of the eastern Tien Shan



(5) Geological map of the area of Anjihai

The Tien Shan is one of the largest mountain ranges in Asia, with summits above 7000m, and lies over an E–W distance of 2500km, between the Tarim and the Junggar basins. Located ~2000km north of the initial front of the India-Asia collision, it is among the most active intracontinental orogenic belts in the world, as evidenced by active faulting and high levels of seismicity. In the eastern Tien Shan, GPS measurements suggest shortening rates of 6—8mm/yr.

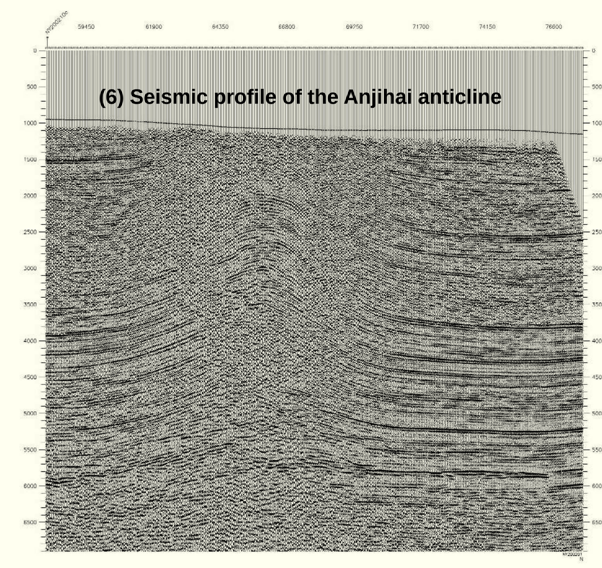
The range's N flank is mainly composed of Mesozoic to Quaternary sediments which have been folded in a set of east–west-striking ramp and fault-propagation anticlines (*Avouac et al.*, 1993).



Anjihai

The Anjihai anticline is frontmost in a series of folds lying N of the range front. The surface anticline (8) is ~7km wide, exposing conglomerates of the lower Pleistocene Xiyu and the Pliocene Dushanzi formations, unconformably overlain by Quaternary conglomerates and loess (7). On the S flanks of the surface anticline, prominent, S-dipping, Quaternary structural surfaces are preserved. Seismic profiles reveal a gentle, symmetric structure strongly suggestive of a detach-ment-driven fold.

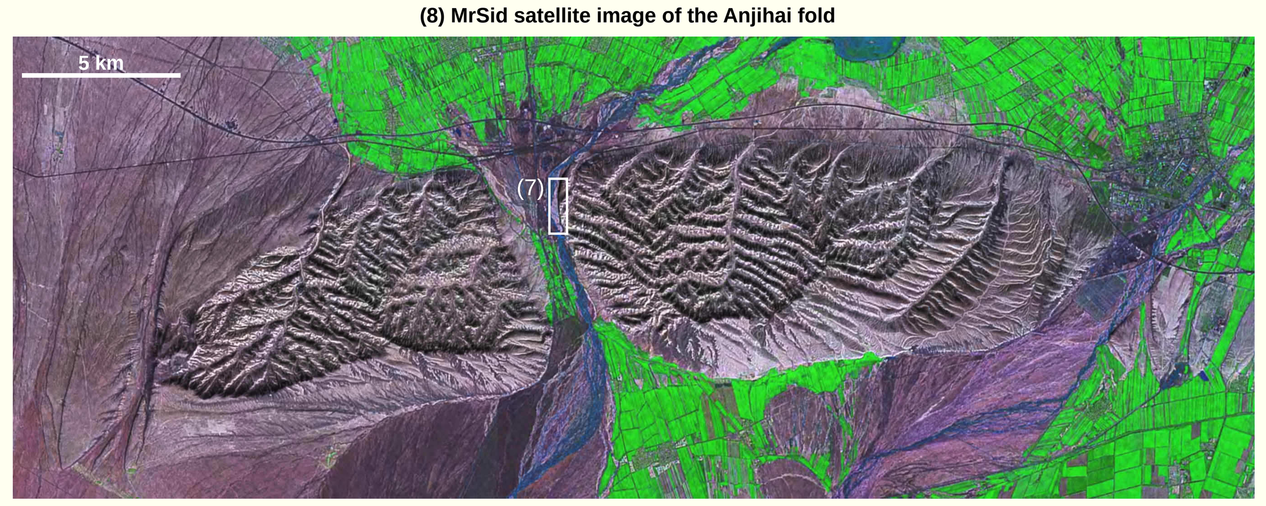
Our aim is to address whether such a "simple" fold can be adequately modeled using the "sandbox" kinematic model outlined by *Bernard et al.*, and to explore how such a model can help us combine the available structural and geomorphic data to constrain the shortening history recorded by the fold.

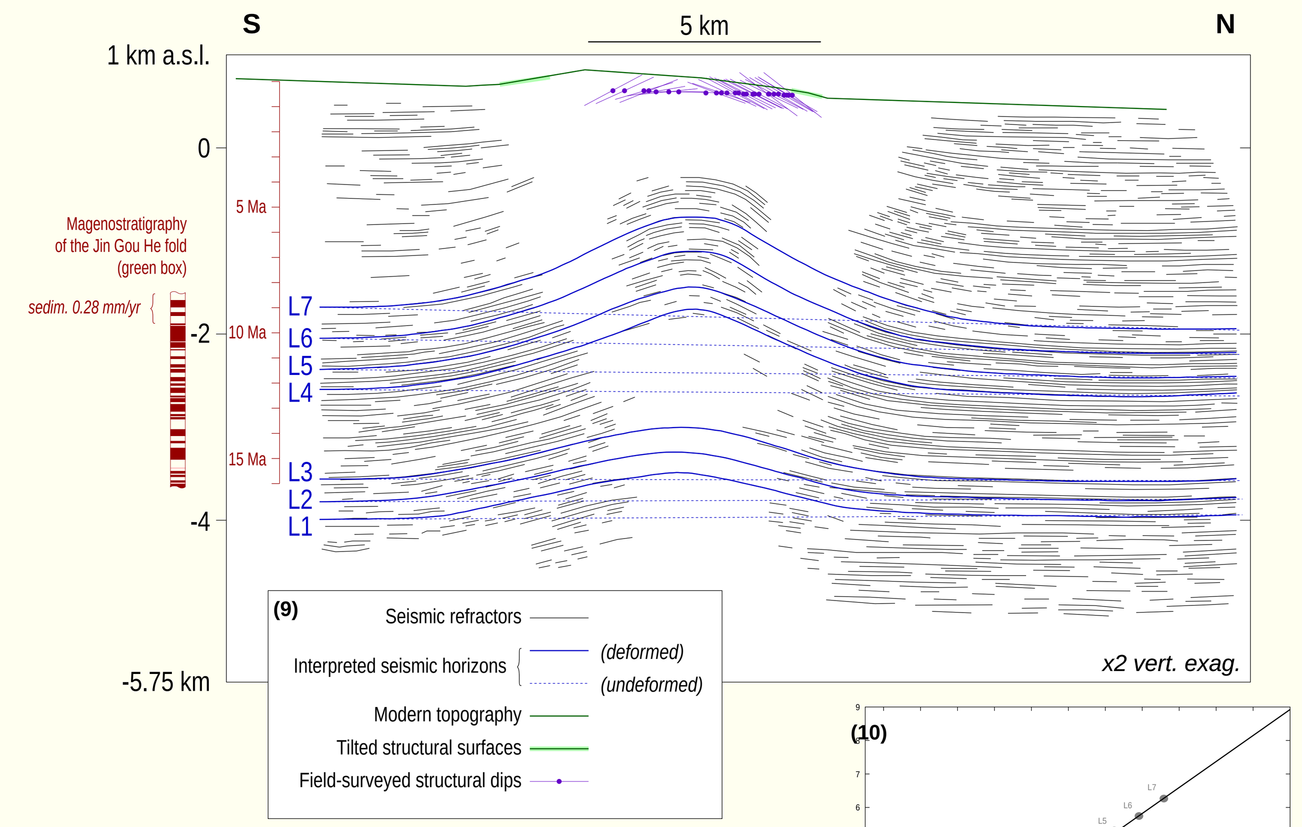


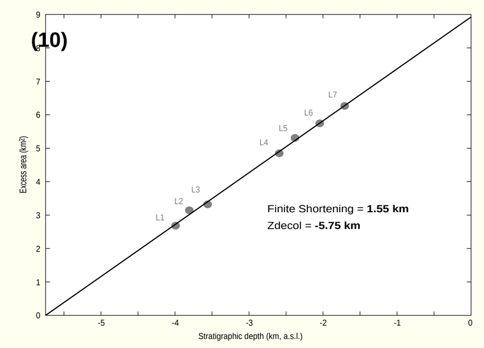
(6) Seismic profile of the Anjihai anticline

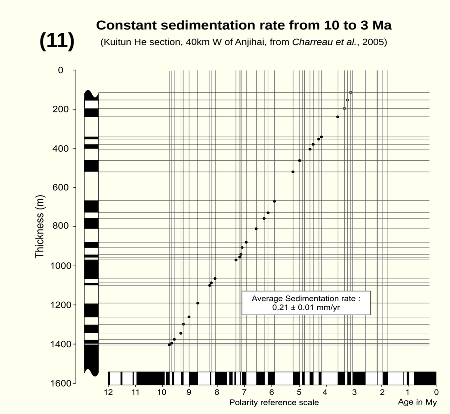
(7) Field view of the N-dipping Dushanzi formation, overlain by Quaternary gravels and loess

(8) MrSid satellite image of the Anjihai fold









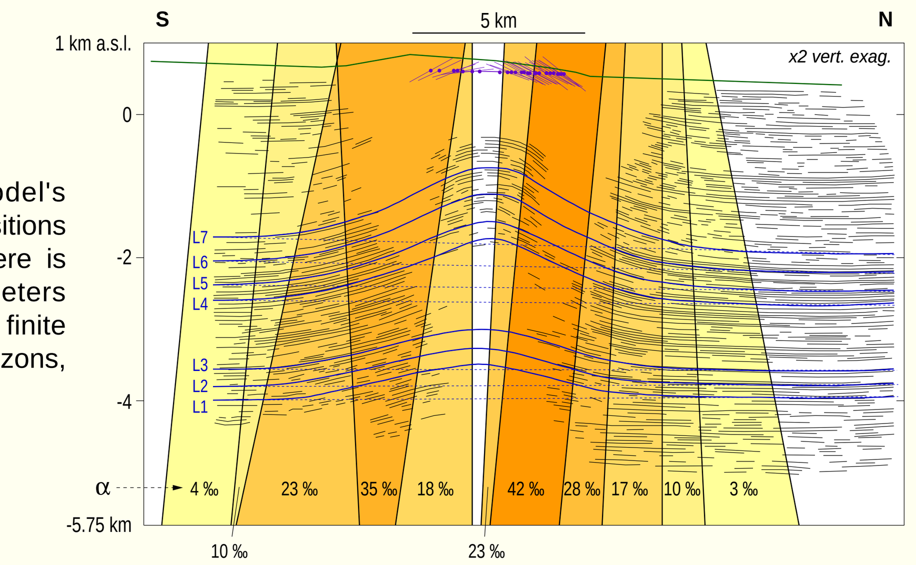
Model Data

- A N-S profile of the fold's topography was measured using SRTM and SPOT DEMs.

- Seismic data, courtesy of Petrochina (Dengfa & Suppe, 2005), provide constraints on the deeper structure of the fold. A number of horizons (L1–7) can be mapped (9). Using these horizons (10), we estimate that fold initiation postdates L7 and that the finite amount of shortening absorbed by the fold is ~1.5km.

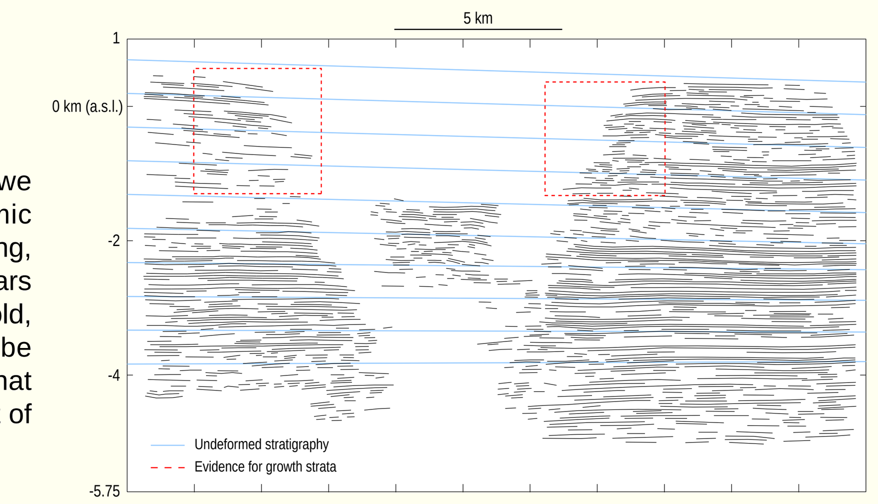
- Magnetostratigraphic data (9,11) from nearby folds suggest that the sedimentation rate at Anjihai remained constant from 10 to 3Ma, around 0.28mm/yr (*Charreau et al.*, 2005).

(12)



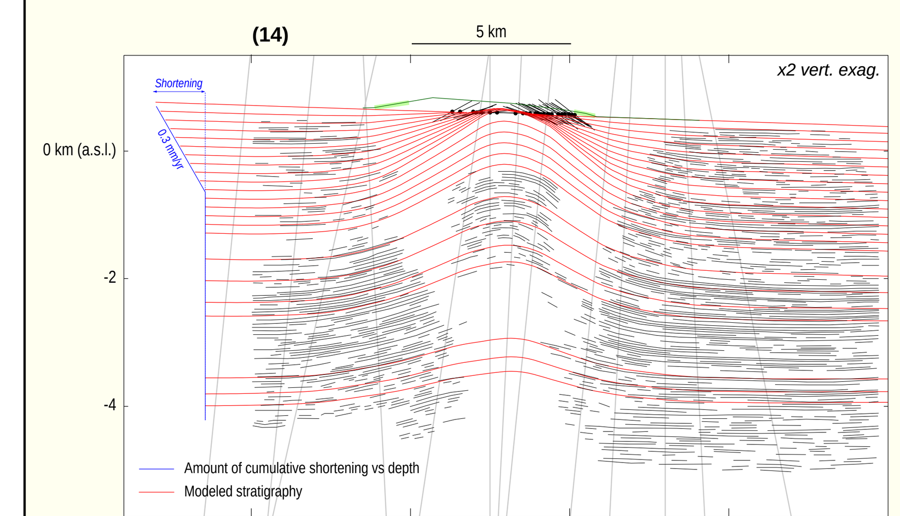
One can vary the model's parameters (number and positions of the hinges, α-values). Here is one combination of parameters which can account for the finite geometry of the seismic horizons, given a shortening of 1.55km.

(13)



If, using these parameters, we retro-deform all the seismic reflectors by 1.55km of shortening, evidence of growth strata appears clearly in the flanks of the fold, where reflectors have then be tilted too far back, implying that they underwent a lesser amount of shortening.

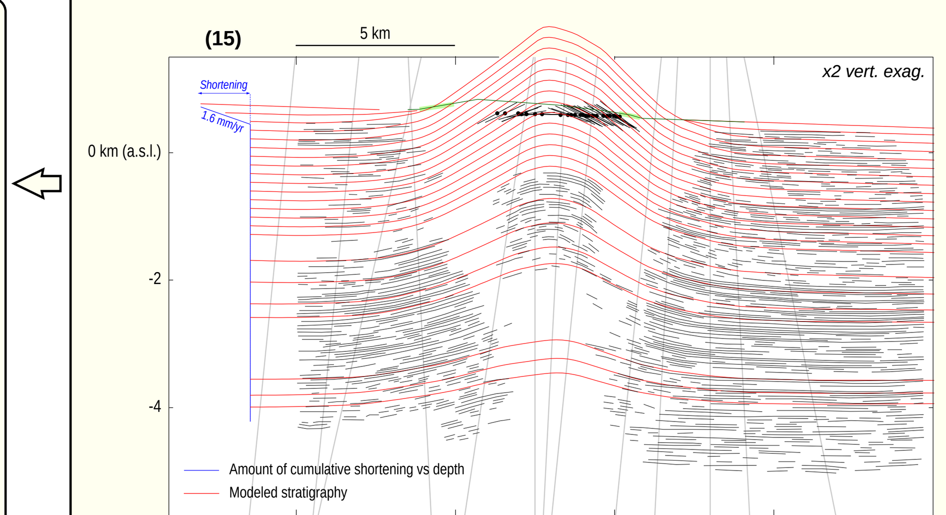
(14)



It does not appear possible to account for these growth strata using a simple, 1-stage scenario with a constant rate of shortening. Since the total shortening is constrained, we can only vary the stratigraphic depth of fold initiation.

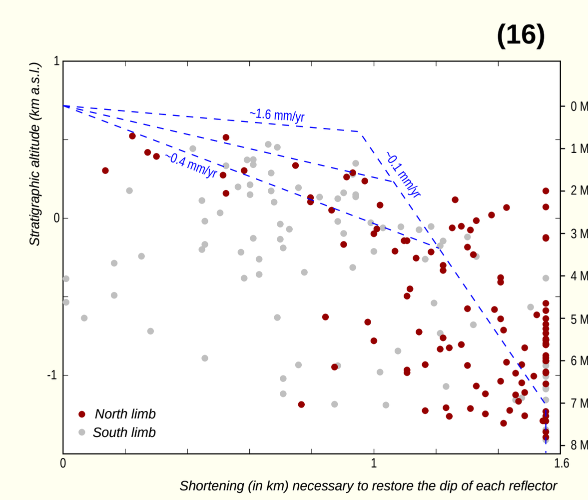
- In the hypothesis of an early initiation (14), the resulting slow shortening rate results in a maximum uplift rate which is insufficient to overcome the local sedimentation rate, and thus generating almost no topography.

(15)



- In the hypothesis of the earliest initiation capable to generate topography with the observed width (15), most of the observed growth strata become pretectonic strata in the model, yielding significative tilt misfits.

(16)

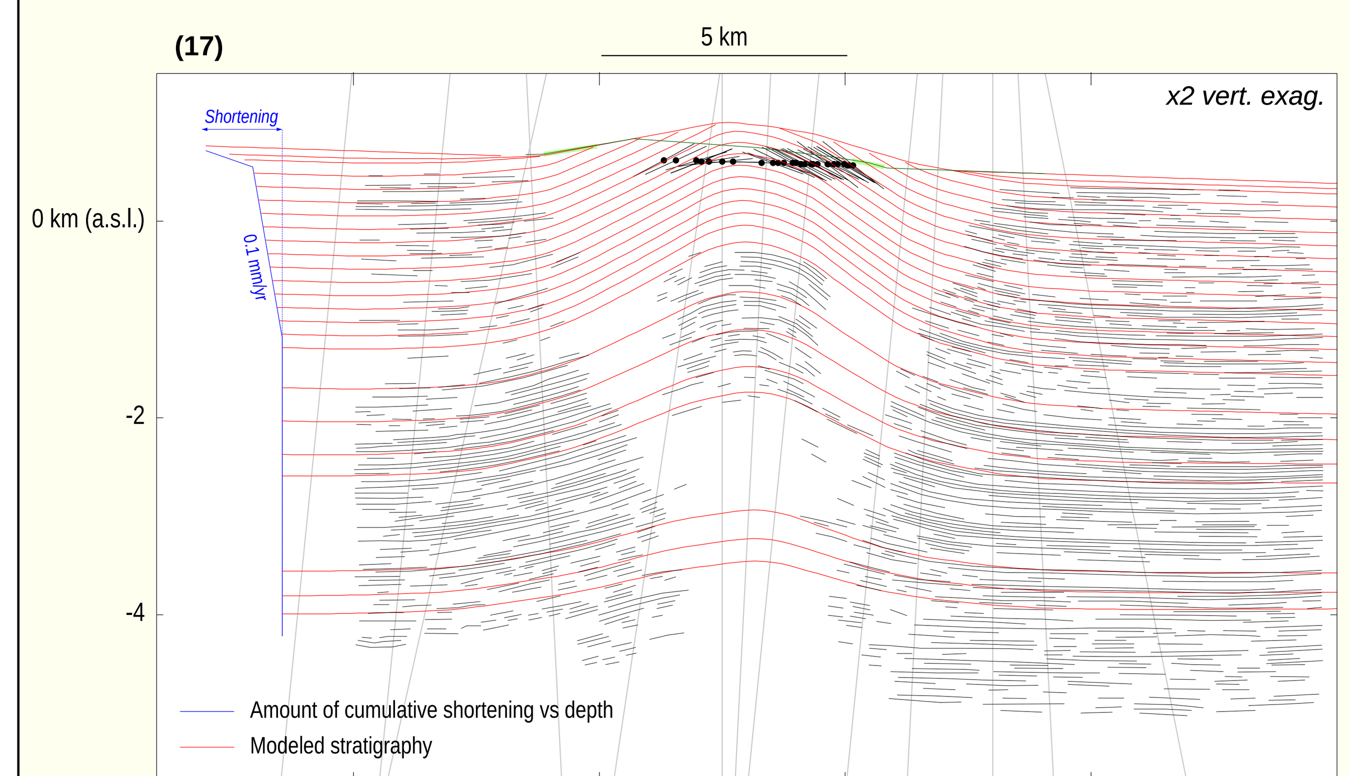


A more likely scenario (17) should then include a first phase of "early", "slow" shortening accounting for the continuous tilting of the growth strata, followed by more rapid shortening rates capable generating uplift rates larger than the sedimentation rate.

To constrain the former rate, we plot here, vs depth, the amounts of shortening necessary to tilt bach each growth strata reflector in an undisturbed configuration (16). In spite of some noise, this suggests that initiation of the fold started somwhere between 0.3 and 1km b.s.l., i.e. sometime between 7 and 4Ma.

The onset of the latter phase is not constrained by seismic data. In order to use the acquired dip of the Quaternary structural surfaces on the flanks of the fold to constrain this phase, we have to assume an age for these surfaces. Realistic ages within the past 1Myr yield shortening rates of about 1.5mm/yr, consistent with other active folds elsewhere along the range front.

(17)



Conclusions

- Using a reasonably small number of hinges, it is possible to reproduce the finite deformation of a fault-tip fold using the modeling approach proposed by Bernard et al.
- Given such a model, any uplifted and tilted stratigraphic marker can be interpreted in terms of the amount shortening it went through, providing constraints on the history of shortening as a function of stratigraphic depth.
- Even in a "simple" fold like Anjihai, this modeling documents a shortening history somewhat more complex than expected.
- These results are not model-dependent, and could be attempted using other descriptions of the velocity field as a function of incremental shortening.

In order to further investigate the shortening history of this particular fold, we might:
- date the Quaternary structural surfaces (e.g. using OSL) on the flanks of the surface anticline;
- aquire new, high-resolution shallow seismic data from the flanks of the fold, where the dips are maximal;
- perform more structural measurements, esp. in the S flank of the fold;
- directly constrain the age of the growth strata using magnetostratigraphy.

Avouac, J. P., et al. (1993), *Active thrusting and folding along the northern Tien Shan and late Cenozoic rotation of the Tarim relative to Dzungaria and Kazakhstan*, JGR, 98, 6755-6804.
Bernard, S., et al. (submitted), *Investigating kinematics of folding from sandbox experiments*.
Charreau, J., et al., *Magnetostratigraphy and rock magnetism of the Neogene Kuitun He Section (Northwestern China): Implications for Late Cenozoic uplift of Tianshan mountains*, EPSL, 2005.
Dahlstrom, C. D. A. (1990), *Geometric Constraints Derived from the Law of Conservation of Volume and Applied to Evolutionary Models for Detachment Folding*, AAPG Bulletin, 74, 336-344.
Mitra, S. (2003), *A unified kinematic model for the evolution of detachment folds*, Journal of Structural Geology, 25, 1659-1673.
Simoes, M., et al. (submitted), *Kinematic analysis of the Pakuashan fault-tip fold, West Central Taiwan: shortening rates and age of folding inception*, JGR-Solid Earth.
Suppe, J. (1983), *Geometry and kinematics of fault-bend folding*, American Journal of Science, 283, 684-721.