Modeling the shortening history of a fault-tip fold using structural and geomorphic records of deformation

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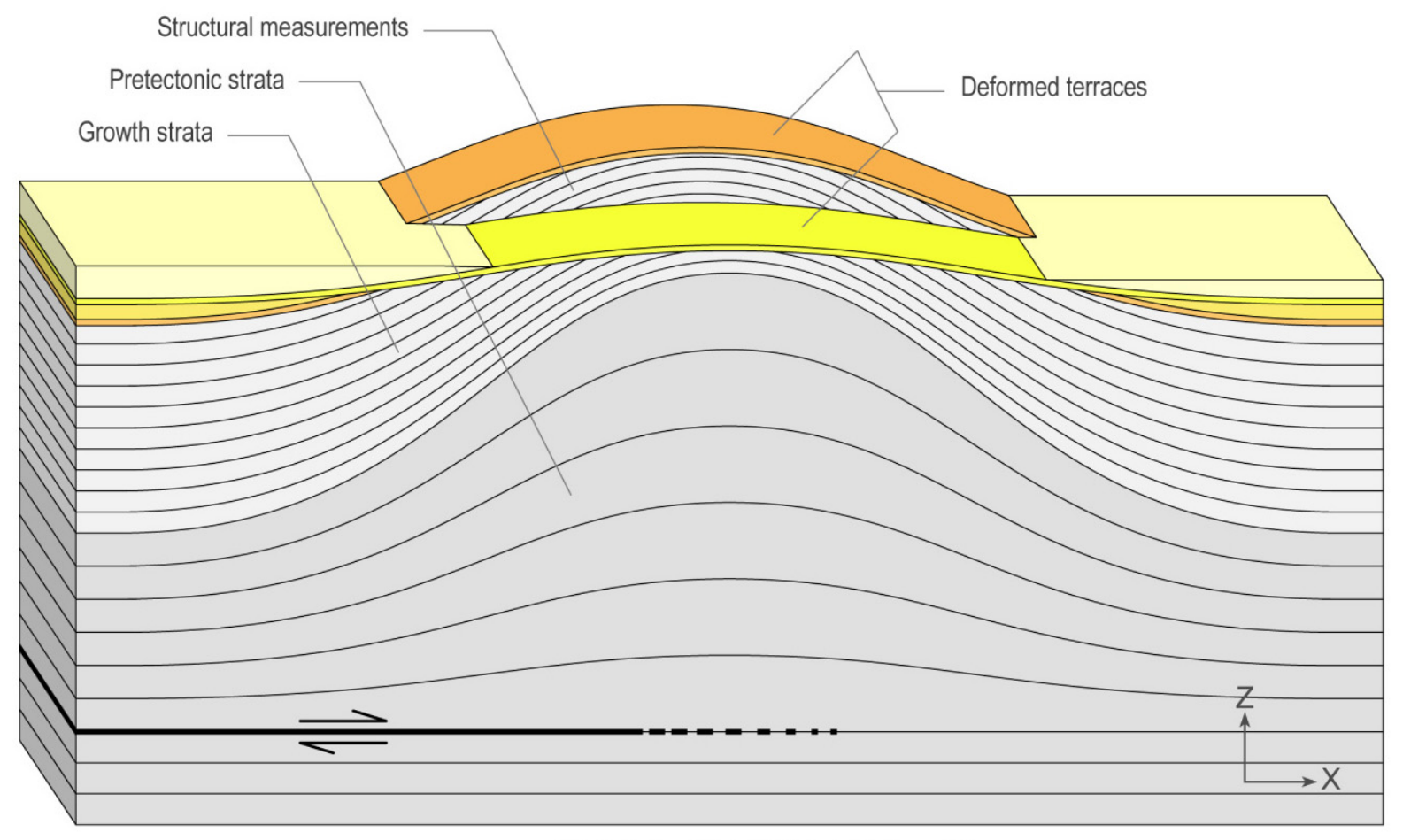
[Daëron et al., 2006, JGR, in press: *http://www.whooshingsounds.net/tecto/public/daeron-jgr-2006.pdf*]

Presentation

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 formulation of the displacement field derived from sandbox experiments (Bernard et al., submitted), we parameterize the spatial deformation pattern above the basal detachment of a fault-tip fold. Assuming a stationary spatial pattern of deformation, we simulate the gradual warping and uplift of stratigraphic and geomorphic markers, which provides an estimate of the cumulative amounts of shortening they have recorded. This approach allows modeling of isolated terraces or growth strata.

We apply this method to the study of two fault-tip folds in the Tien Shan, the Yakeng and Anjihai anticlines, documenting their deformation history over the past 6-7Myr. We show that the modern shortening rates can be estimated from the width of the fold topography provided that the sedimentation rate is known, yielding respective rates of 2.15mm/yr and 1.12mm/yr across Yakeng and Anjihai, consistent with the deformation recorded by fluvial and alluvial terraces. This study demonstrates that the shortening rates across both folds accelerated significantly since the onset of folding. It also illustrates the usefulness of a simple geometric folding model, and highlights the importance of considering local interactions between tectonic deformation, sedimentation and erosion.



FAULT-TIP FOLD

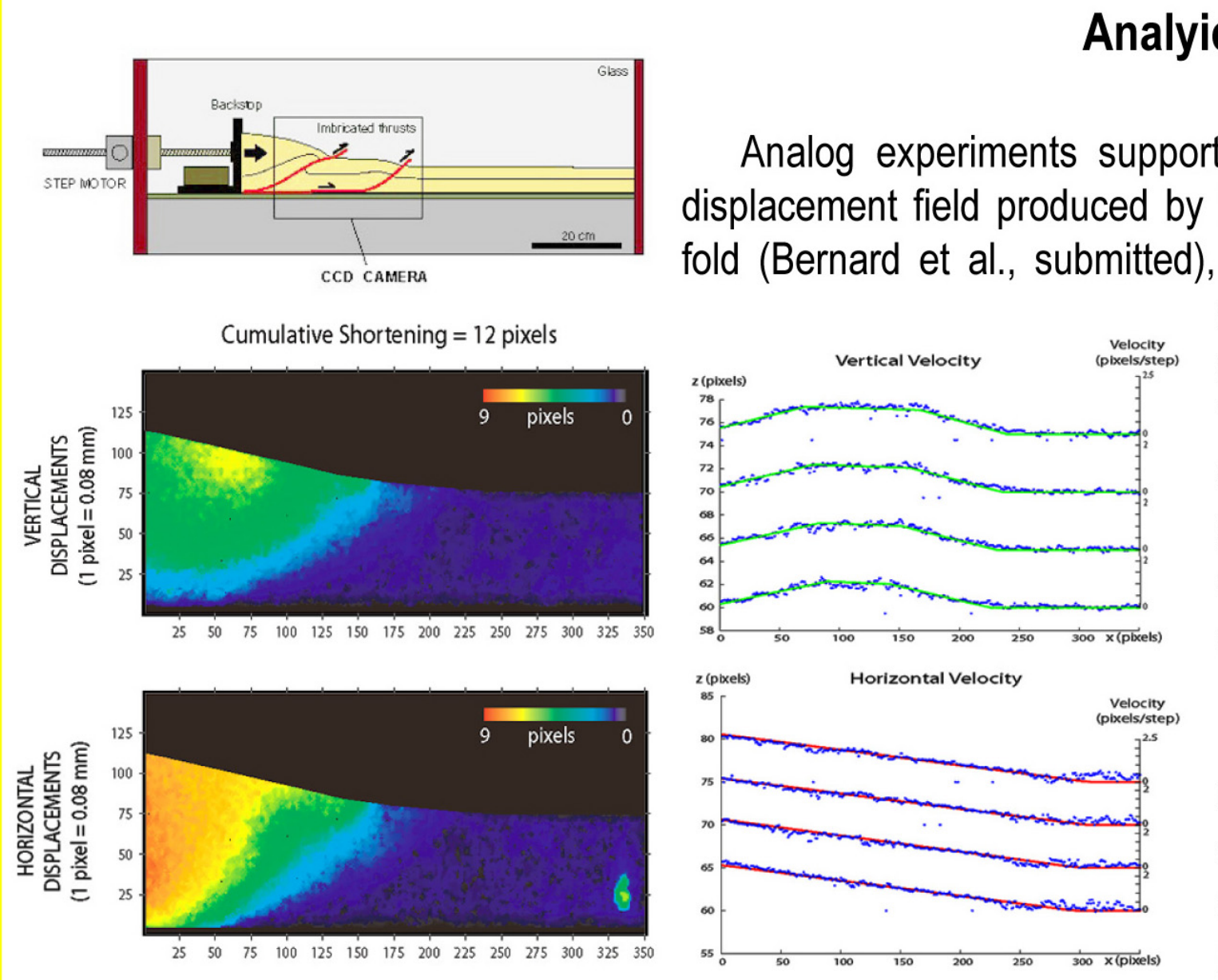
Fold geometry:

- Seismic data
- Geomorphic surveys

Time constraints:

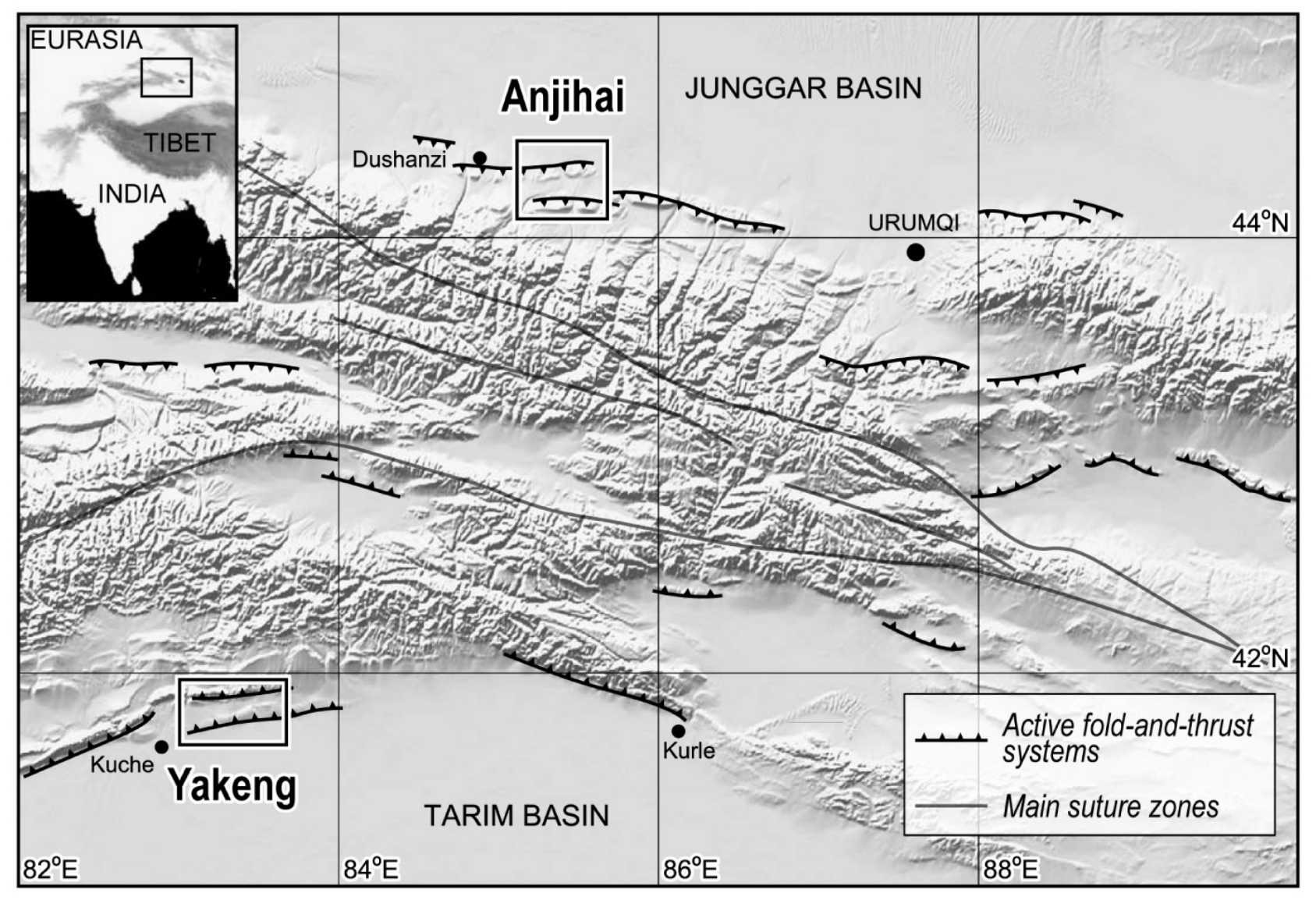
- Magnetostratigraphy
- OSL dating
- Cosmogenic dating
- Radiocarbon dating

Analyical formulation of fault-tip folding



Analog experiments support a simple analytical formulation of the displacement field produced by incremental shortening across a fault-tip fold (Bernard et al., submitted), and this formulation has been used to analyze the growth of Pakuashan anticline along the western foothills of Taiwan (Simoes et al., submitted). The displacement model's parameters, which govern the finite shape of the fold, can be estimated based on seismic imaging of deep pre-growth strata.

We use the same formulation to model the growth of two case examples of young fault-tip folds located in the fold-and-thrust belts that bound the Tien Shan range, in Central Asia.

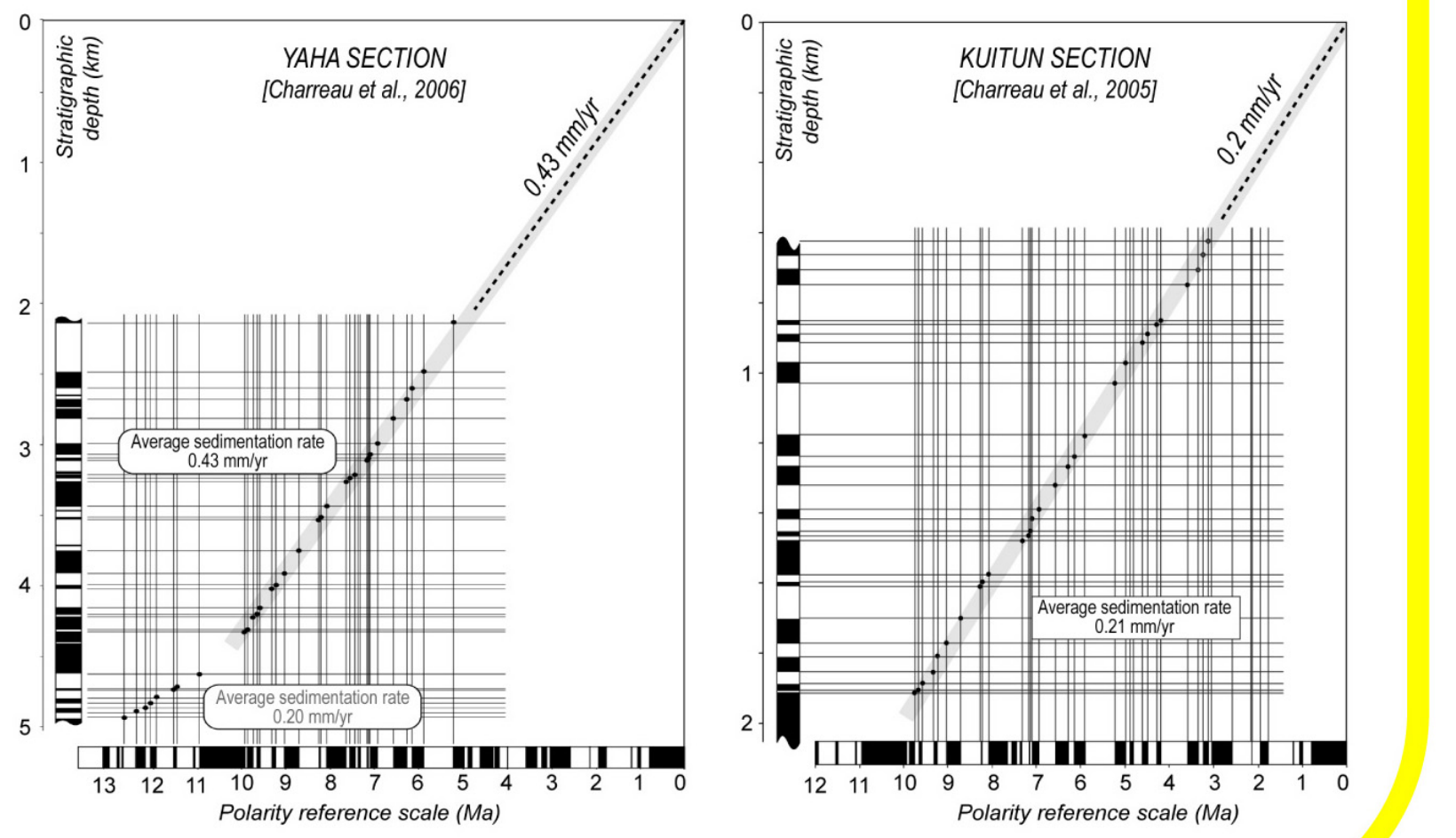


Regional setting

Simplified map of the eastern Tien Shan area. Black boxes mark locations of the folds modeled in this study. Black barbed lines show locations of identified zones of active thrusting and folding. Grey lines show approximate traces of the north Tien Shan and south Tien Shan suture zones.

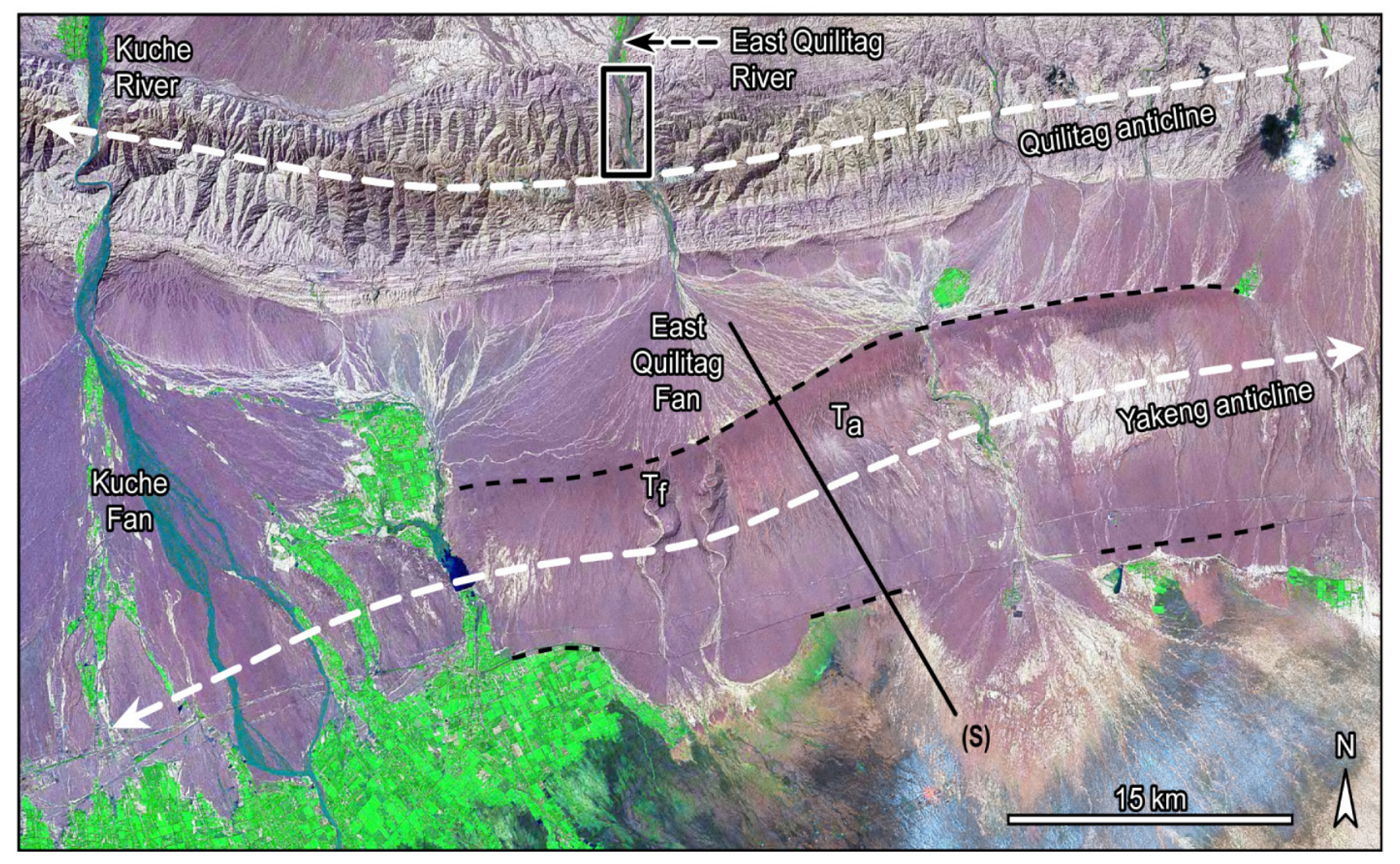
Sedimentation rates

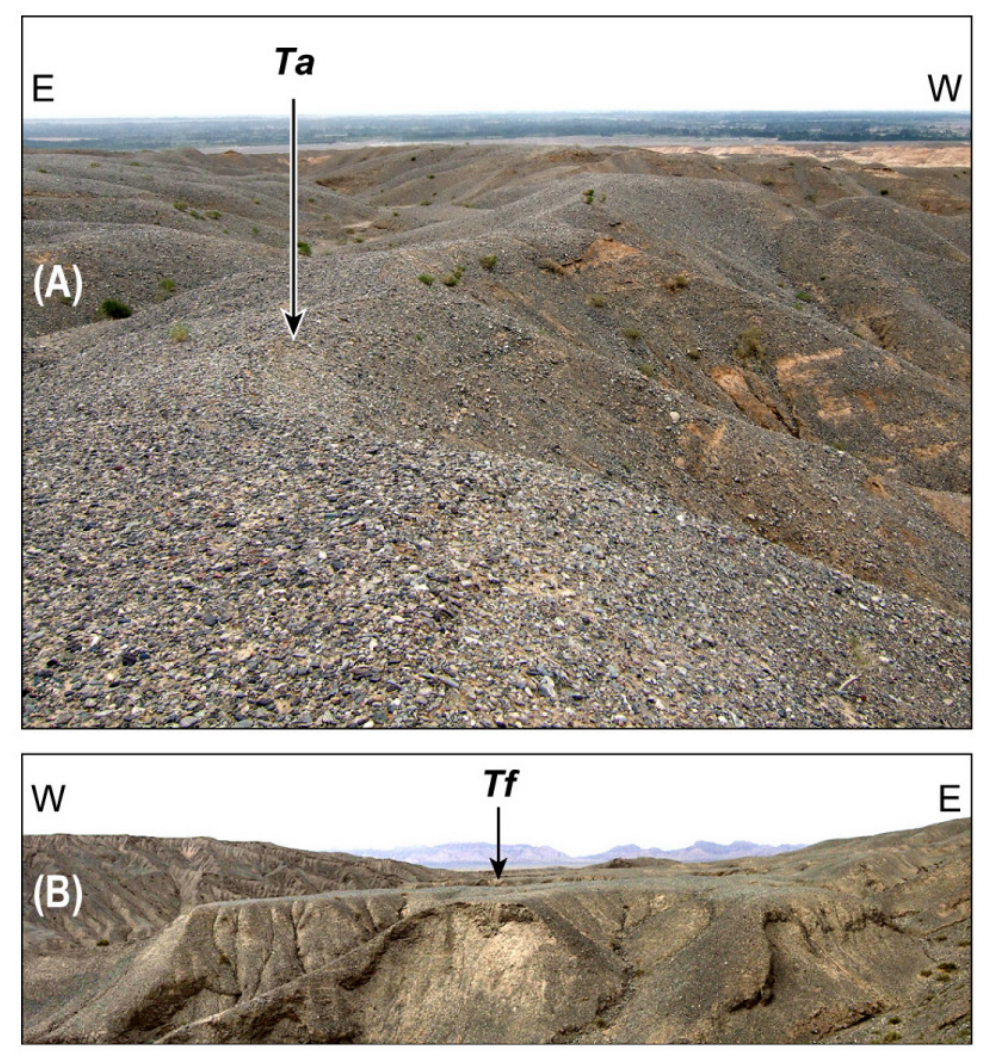
Our geometric modeling does not directly provide timing information. It does, however, constrain cumulative shortening as a function of stratigraphic depth, which can then be converted to ages using the recent magnetostratigraphic studies of Charreau et al. [2005, 2006] and Charreau [2005]. These studies show evidence for remarkably constant sedimentation rates over the past 10.5 Myr. Between the modern surface and the stratigraphic level of the top of each section, constrained by seismic profiles [Deng fa et al., 2005], average sedimentation rates are very similar to the respective magnetostratigraphic rates since 10-11 Ma. The available local magnetostratigraphic data imply that, at the two sites discussed in this study, old sedimentation rates (10.5 5.2 Ma at Yaha and 10.5 8.5 Ma at Jingou He) may be extrapolated over millions of years, possibly up to Late Pleistocene times, consistent with recent rates of ~0.43 mm/yr near Yakeng and ~0.27 mm/yr near Anjihai.

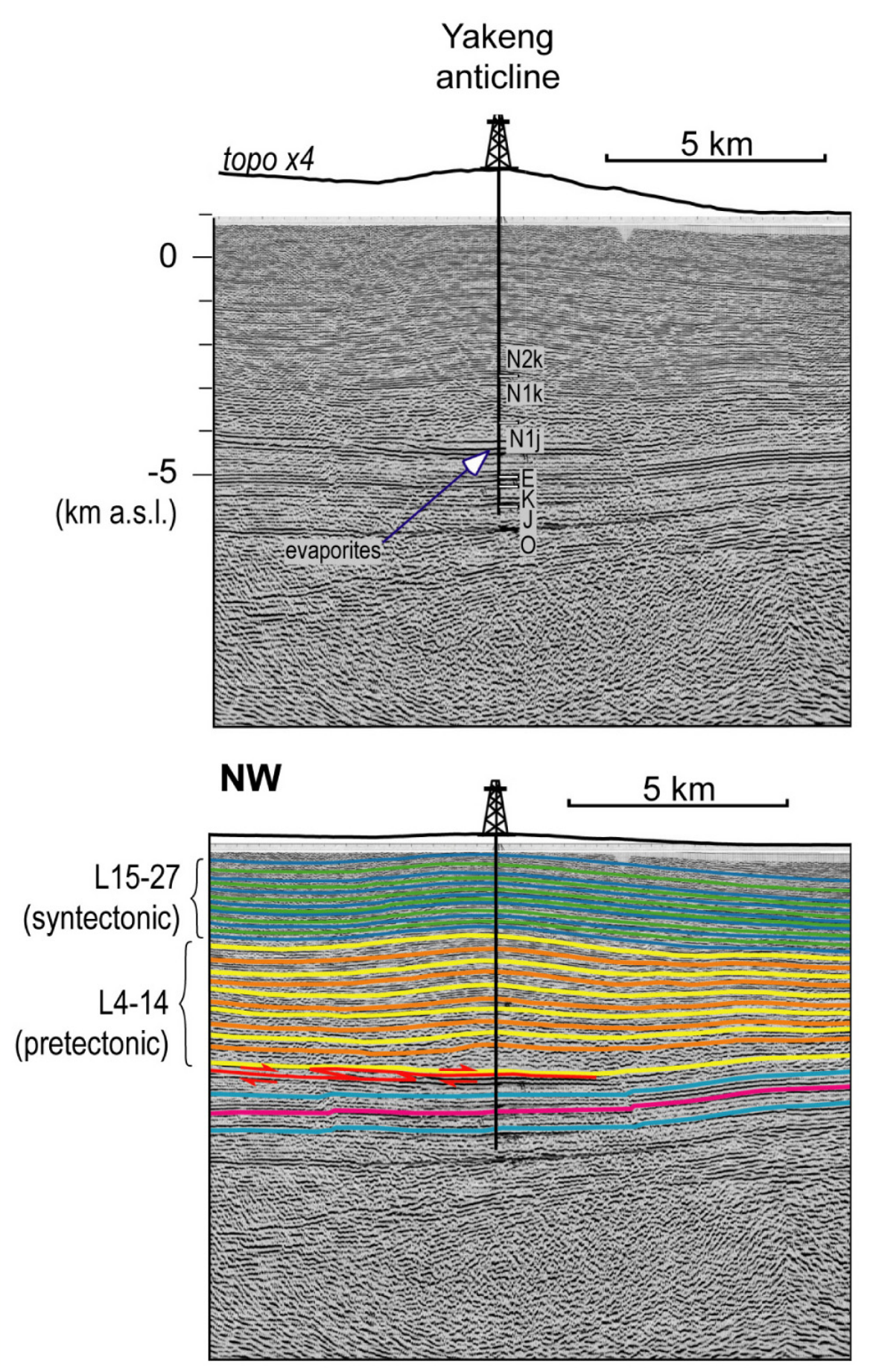


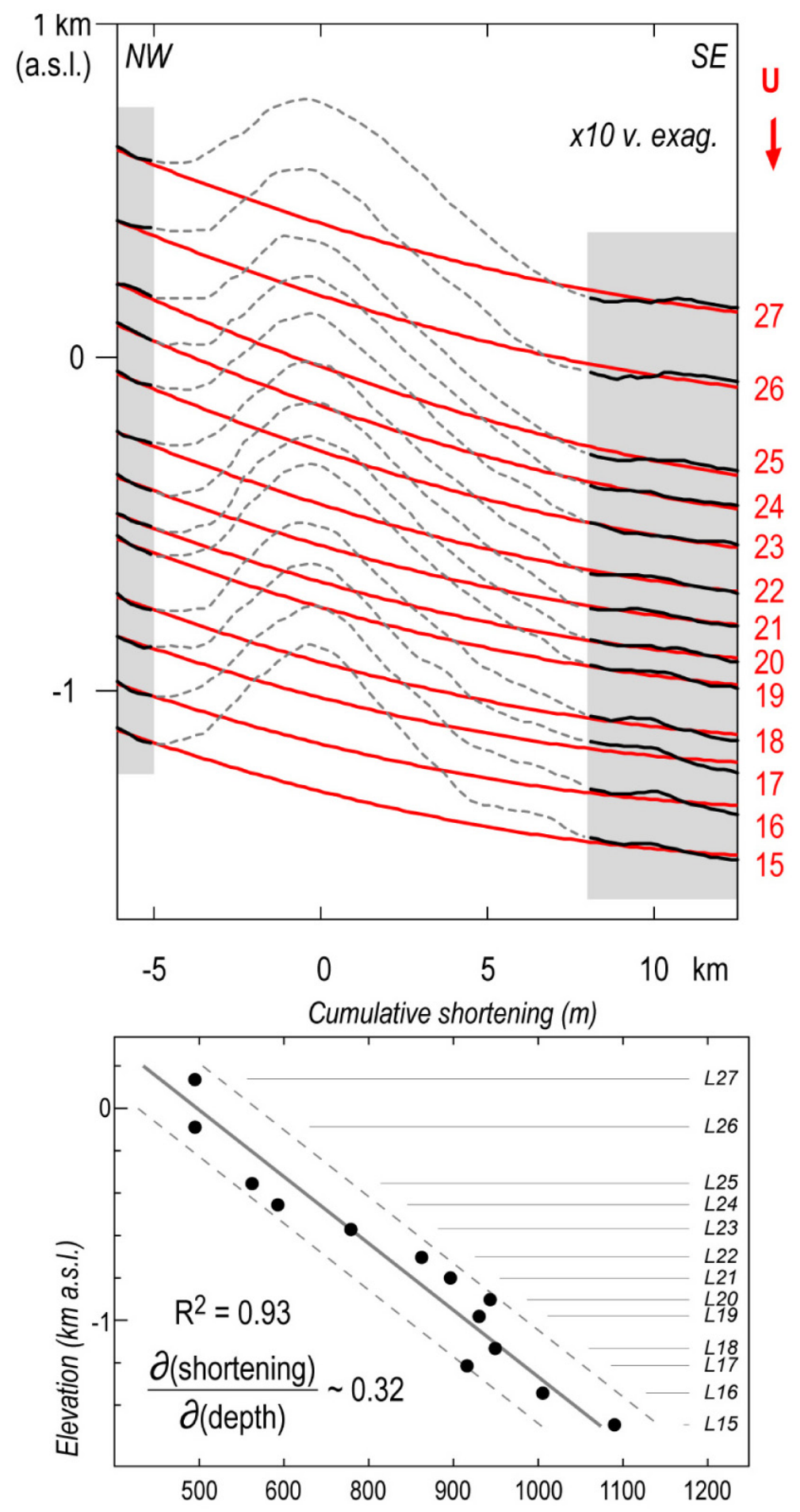
Yakeng fold

At the surface, the Yakeng anticline manifests as a gentle ridge resulting from the folding of a large-scale, south-dipping alluvial terrace (Ta). This structural surface is generally well preserved, although south-flowing rivers dissect it in a number of locations, forming steep, narrow gorges. One of these rivers, (East Quilitag river) formed and abandoned a partially preserved fluvial terrace (Tf). Since then, ongoing deformation has folded and uplifted Tf, bringing it about 25 m above the modern river (Poisson, 2002).



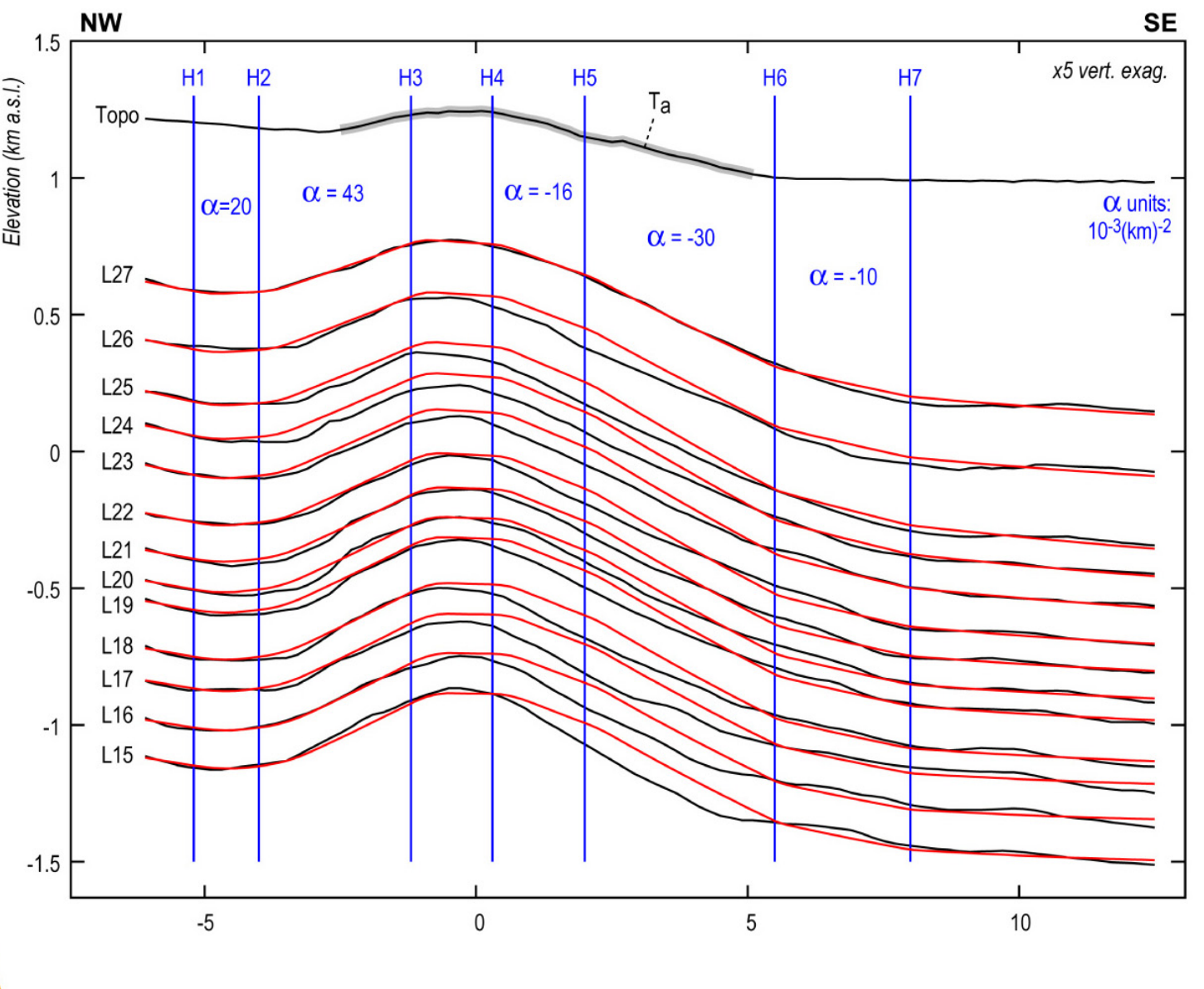


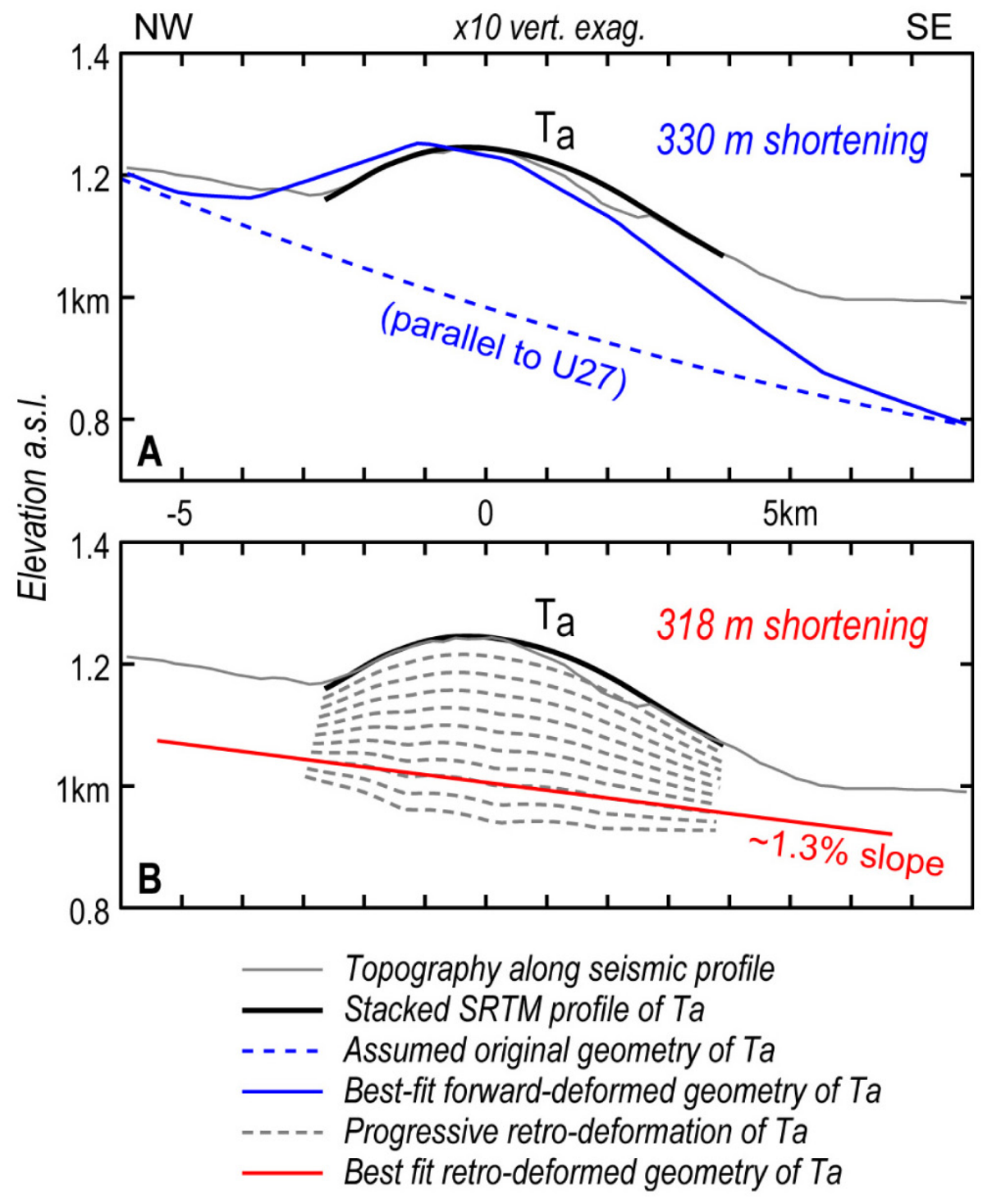


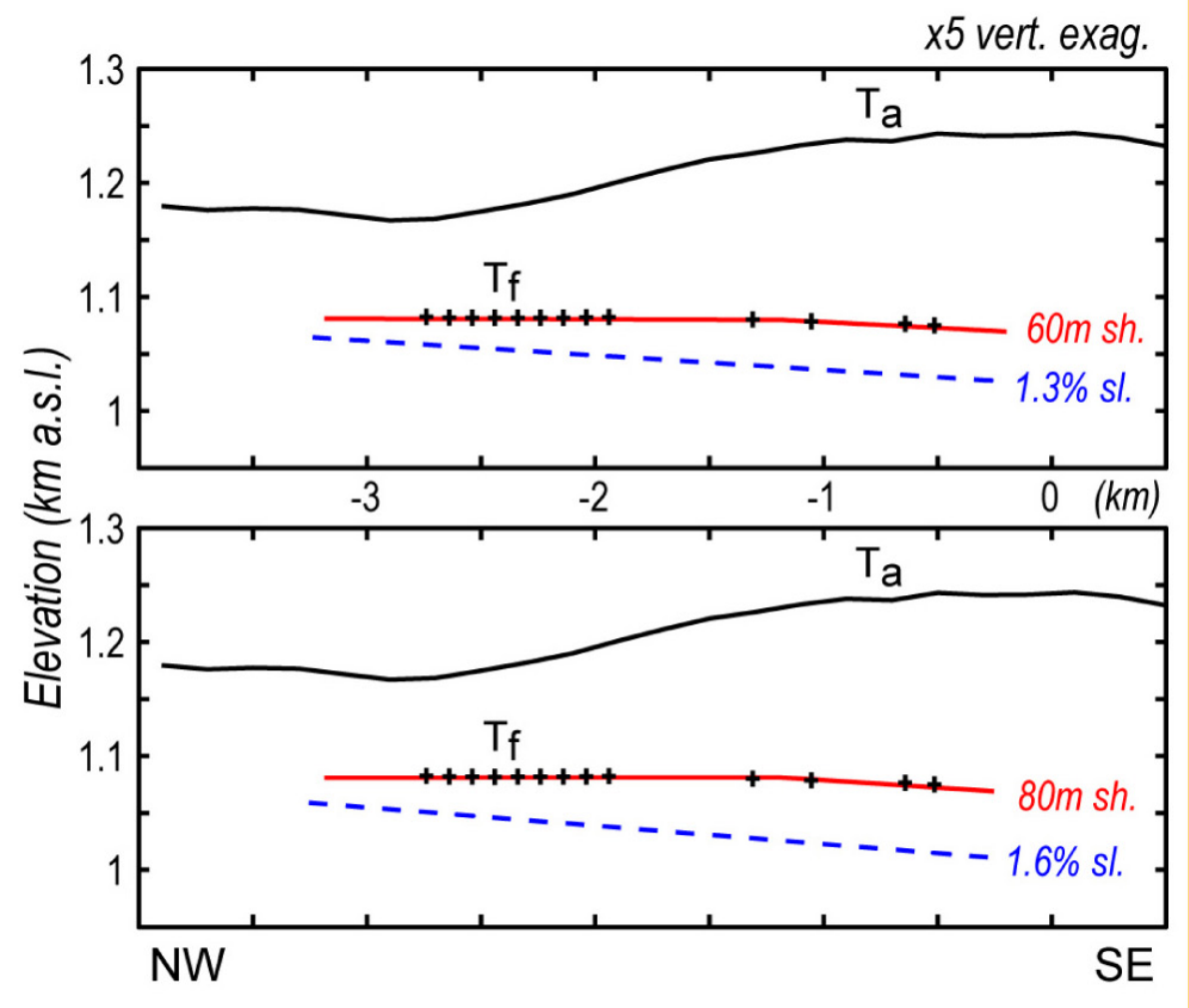


Seismic imaging (Hubert-Ferrari et al., 2005) reveals that the width of the structural fold is more than twice that of the emergent Ta, because the latter is buried under sediments on the outer flanks of the anticline. At depth the amplitude of folding generally decreases downwards, consistent with the geometry of a fault-tip fold growing above a 6-km-deep basal detachment coinciding with reflector L4, in the evaporites of the Oligo-Miocene Jidikeh formation. Gonzalez-Mieres and Suppe (2006), using measurements of thickness relief area, estimated the mean finite shortening to be 1.2km, and showed that folded reflectors L5 to L14 are pretectonic.

Based on the assumed original geometries of the syntectonic seismic reflectors, we estimate their respective amounts of cumulative shortening, and use these values to estimate deformation model parameters consistent with the observed finite geometry. The resulting folding model is used to estimate the cumulative shortening experienced by the geomorphic markers Ta and Tf.

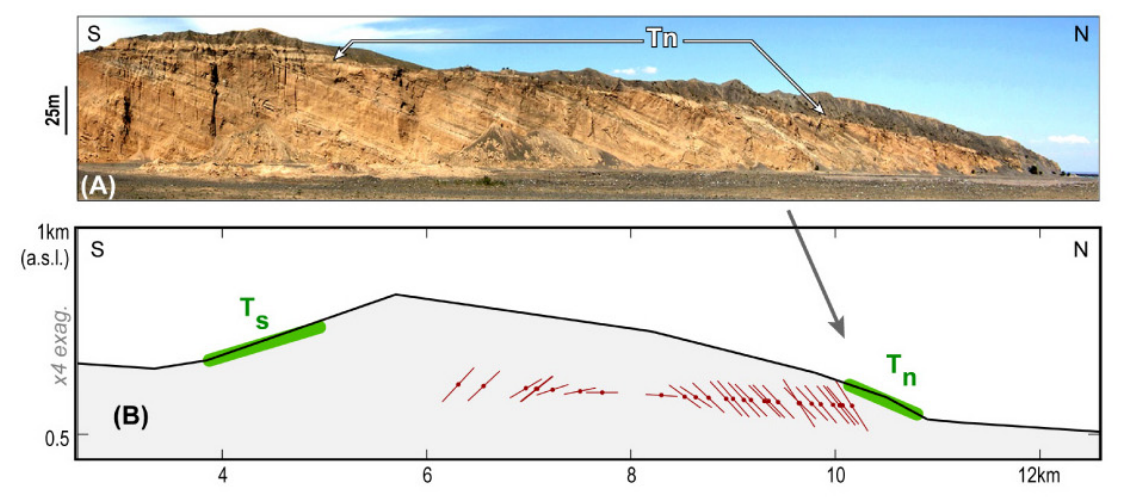


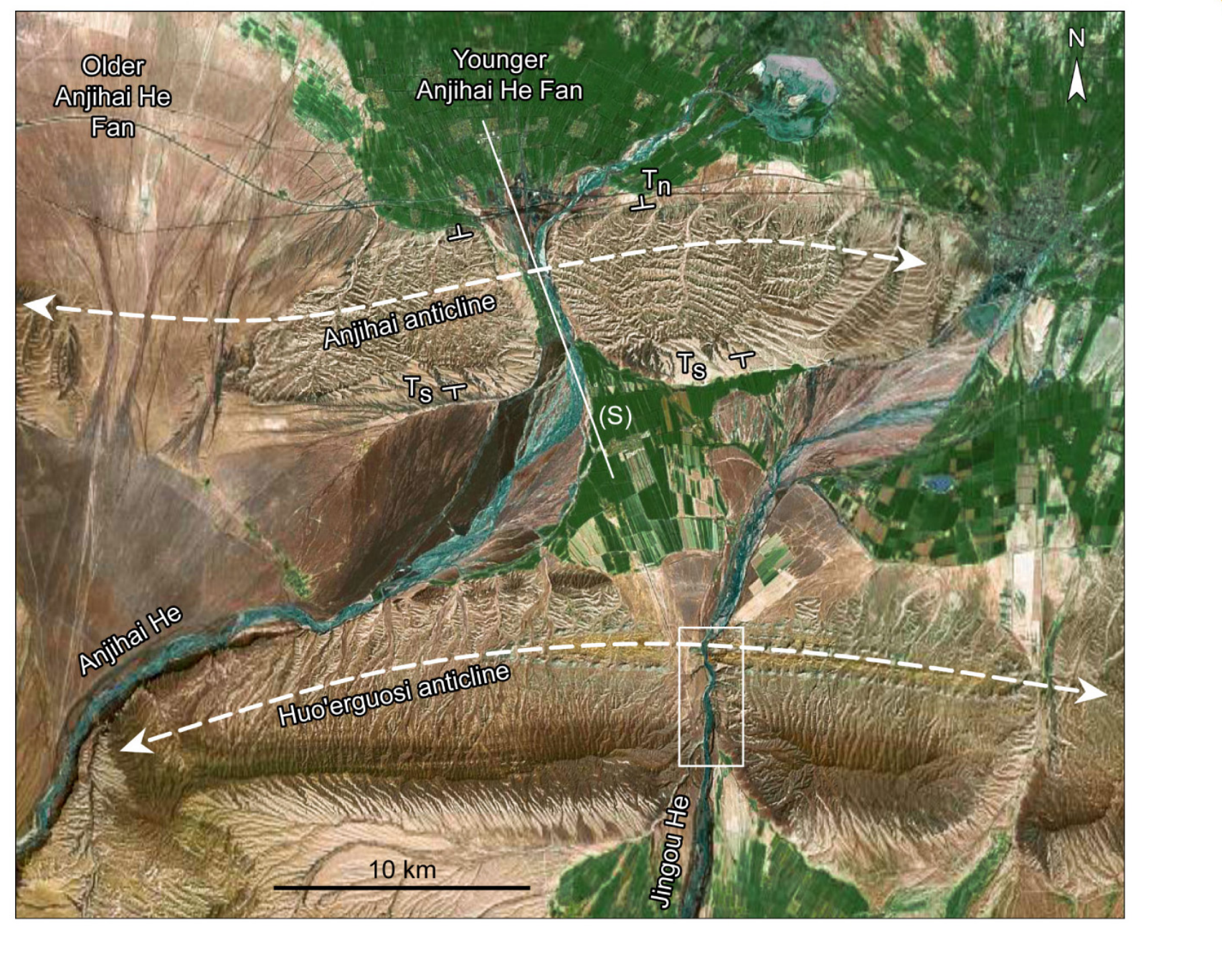


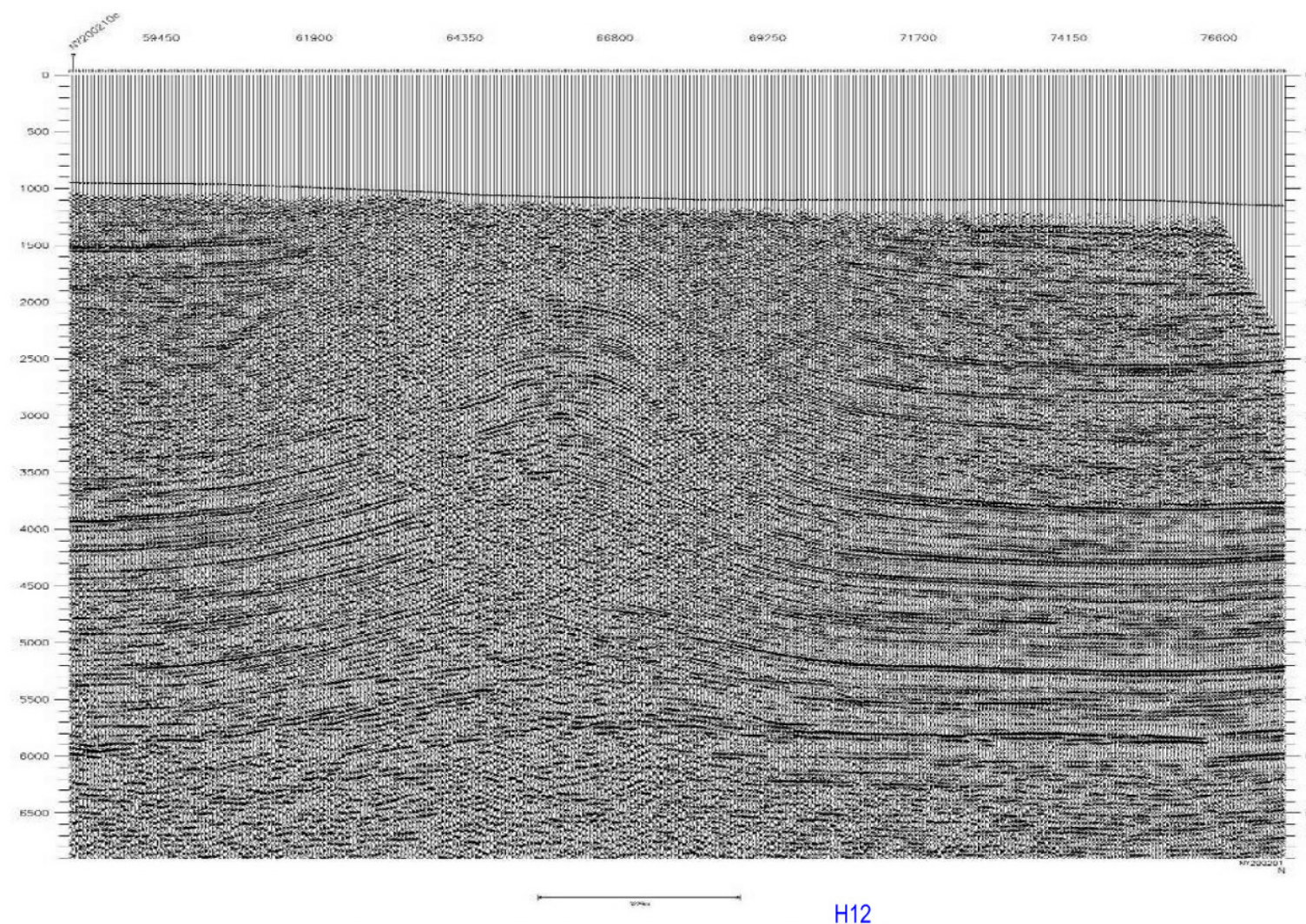


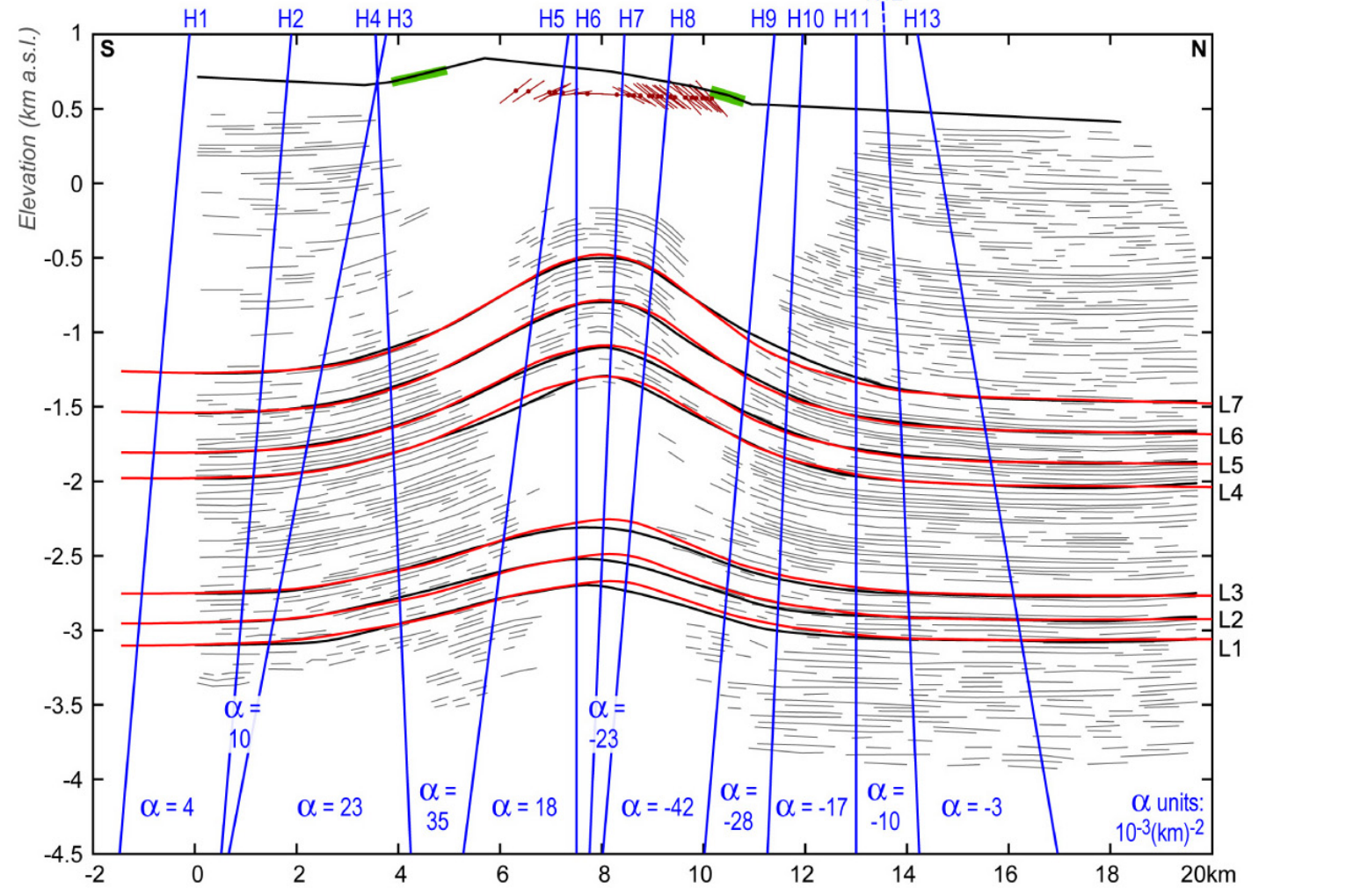
Anjihai fold

The surface fold is about 7 km wide, and exposes conglomerates of the Xiyu (highly diachroneous, Neogene to Quaternary) and Dushanzi (Neogene) formations, unconformably overlain by Quaternary conglomerates and loess. On the flanks of the anticline, such Quaternary structural surfaces are well-preserved, forming triangular cuestas with slopes of 7–10%. We interpret these surfaces (noted Tn and Ts) as folded strath terraces which passively record deformation since their abandonment. Along the steep walls of the river-gap, the shallow structure of the fold is beautifully exposed, with dip angles up to 25º.

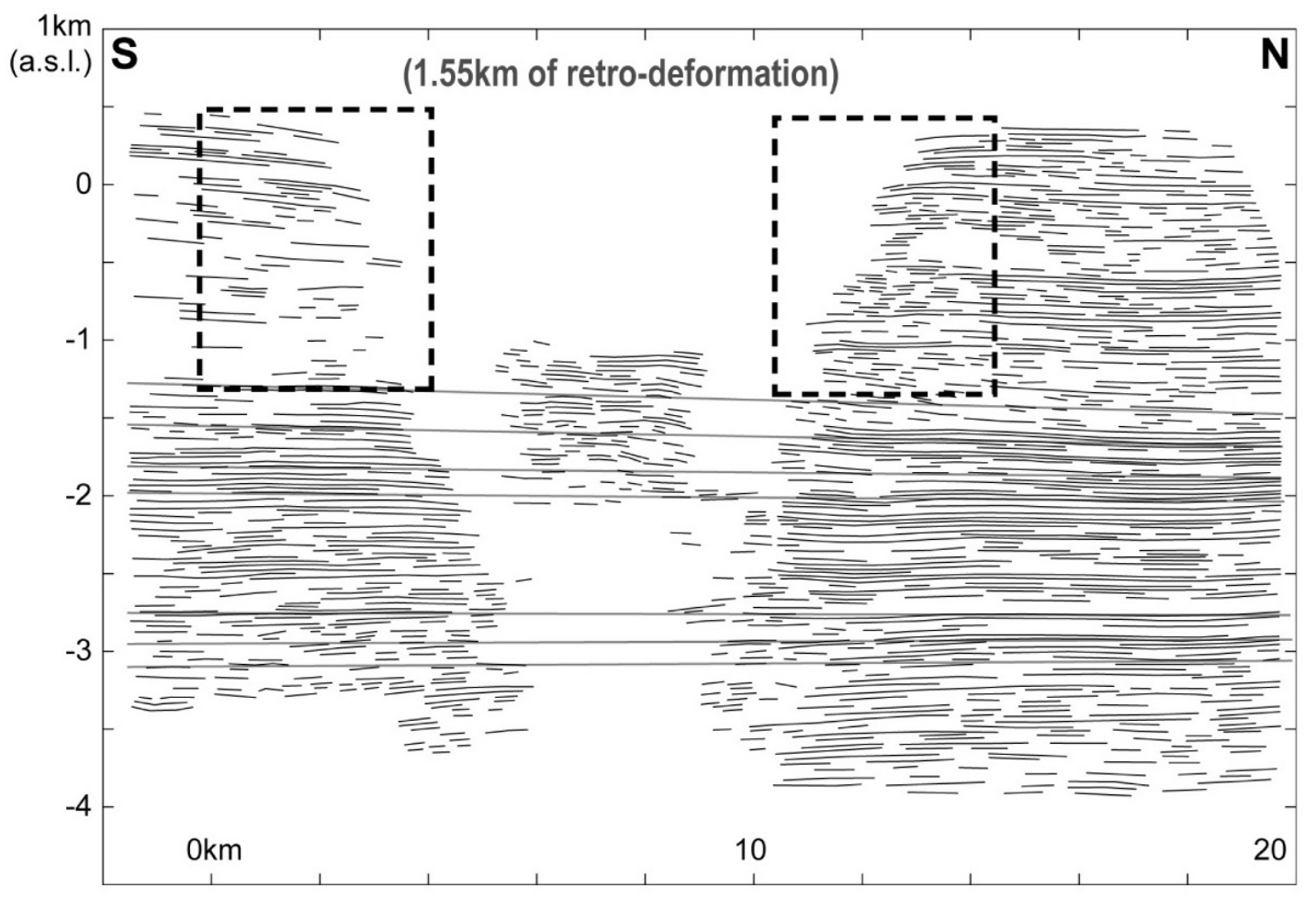








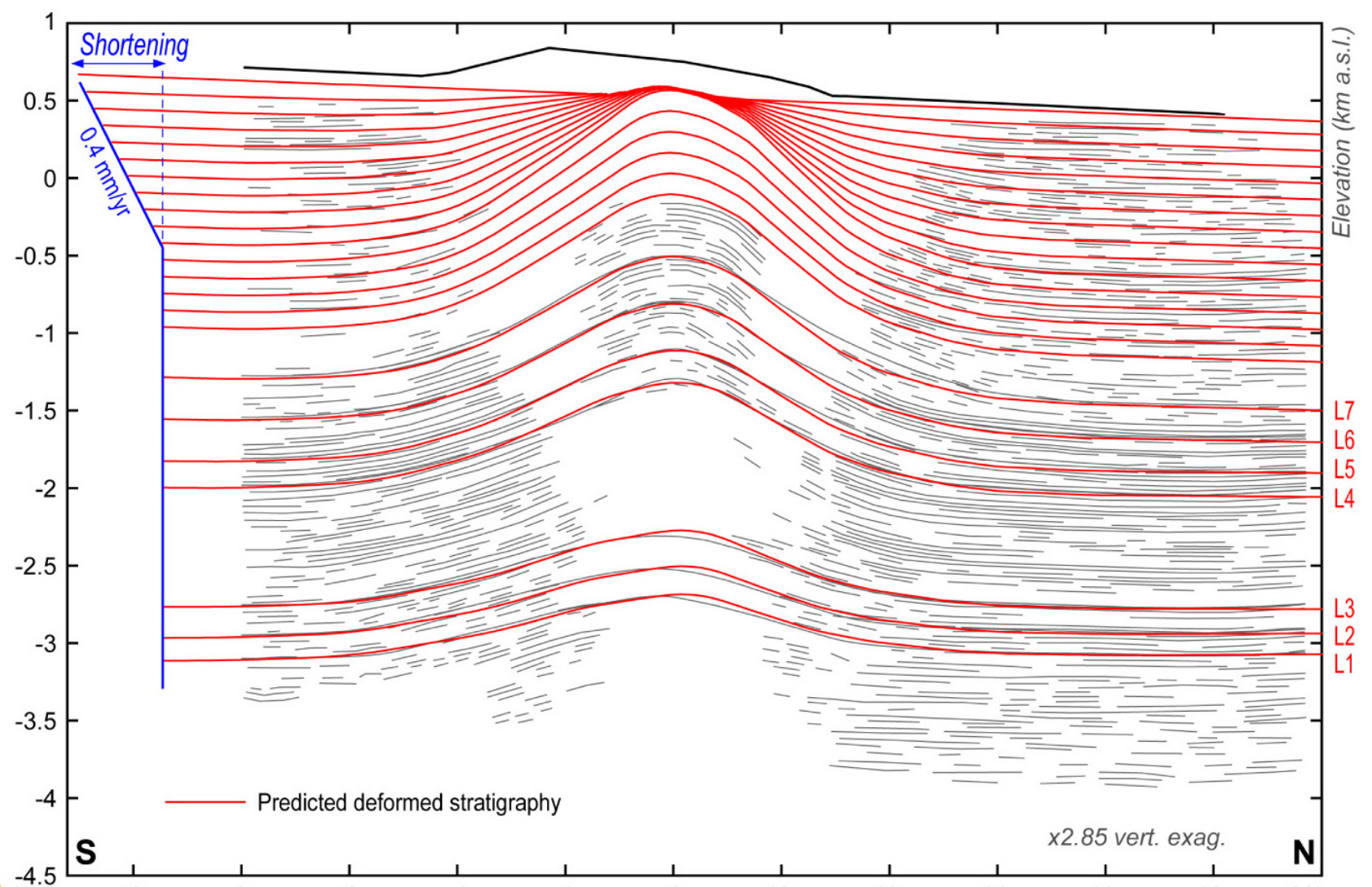
The seismic profile reveals a smooth, rather symmetric sub-surface structure strongly suggestive of detachment-driven folding, although the lower part of the section might be suggestive of small-scale ramping near the fold's core. Our line-drawing interpretation of the seismic data allows mapping 7 distinct markers across the fold (L1 to L7). For all seven markers, the structural relief areas are well-correlated with depth, consistent with ~1.5 km of finite shortening over a basal detachment located ~5 km below the surface. We conclude that the sediments below L7 are pretectonic strata.

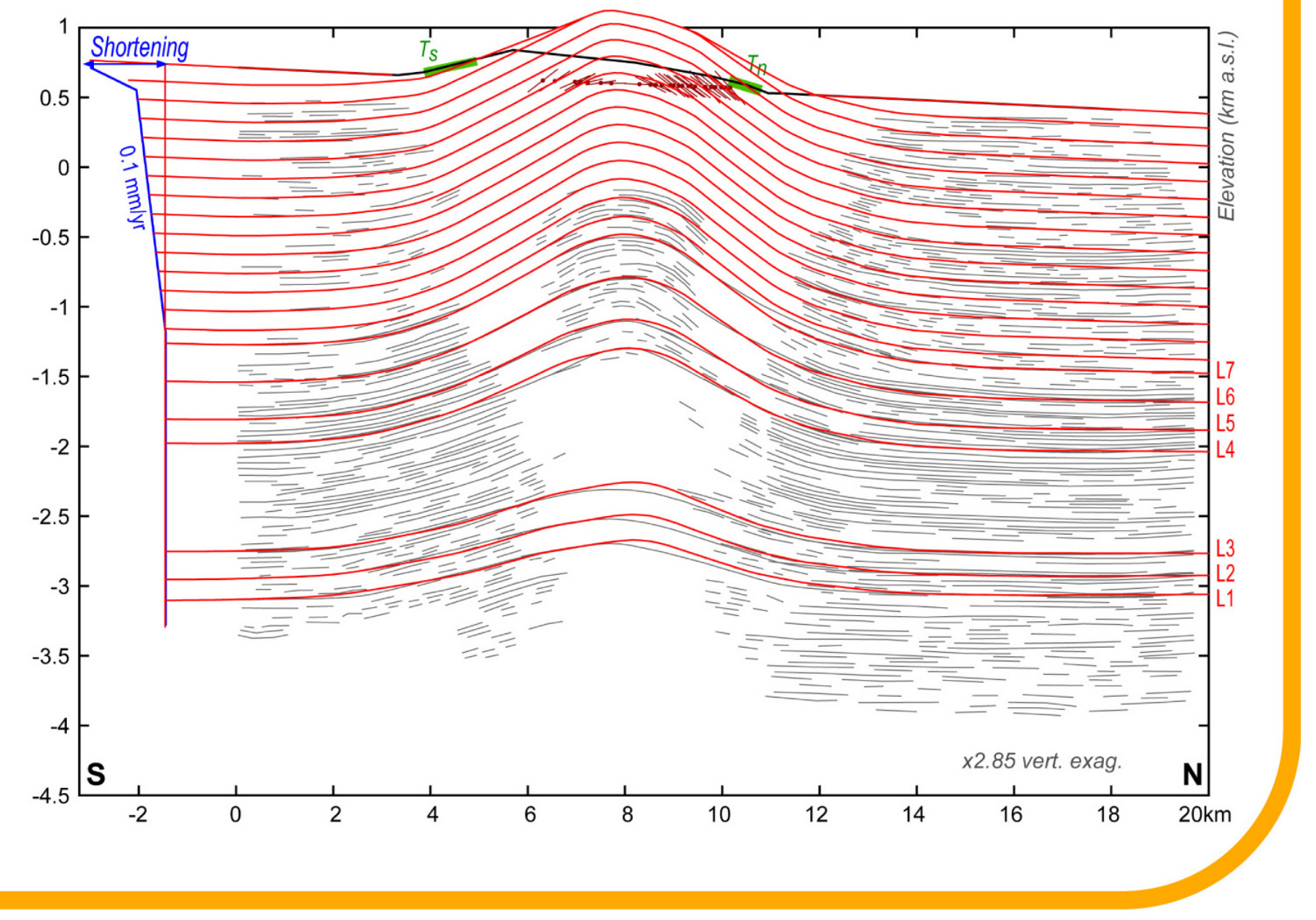


Imposing a finite shortening of 1.55km and a basal detachment depth of 4.5 km b.s.l., we can model the observed finite geometry of the pretectonic markers using a 13-hinge deformation model. The agreement between the predicted and observed dip angles is evidenced when all present-day seismic reflectors are"un-shortened" by 1.55km. Below L7, the retro-deformed reflectors are uniformly flat, whereas above L7 they adopt a syncline-like geometry, implying that these reflectors therefore correspond to growth strata.

Simple scenarios of shortening (constant shortening & sedimentation rates) provide a good fit to the seismic data alone. However, all of these models predict that the fold should have no or negligible topographic relief, because the sedimentation rate generally exceeds the uplift rate. This is clear indication that the ratio of shortening to sedimentation rates has recently increased.

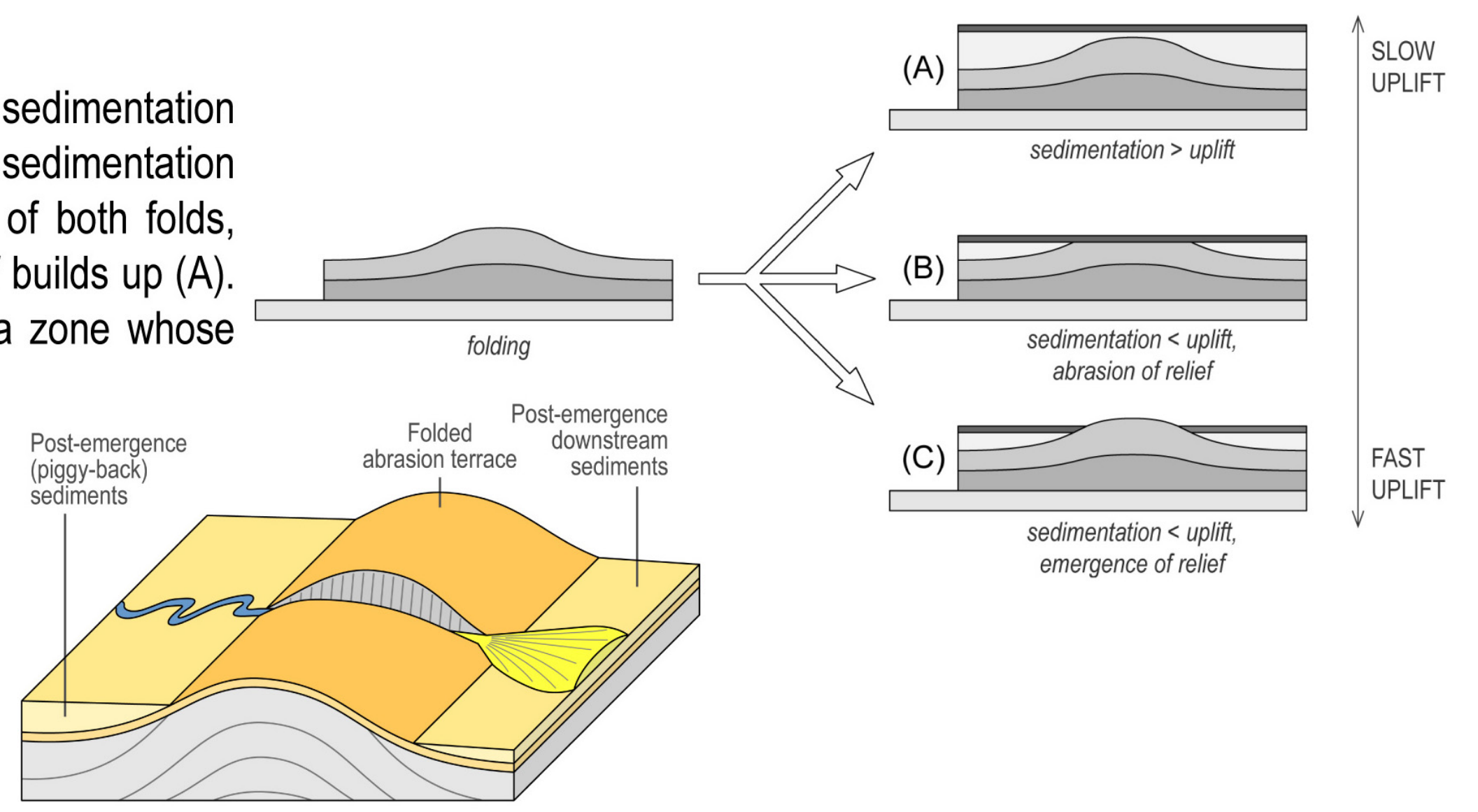
Two-stage scenarios involving a recent acceleration of shortening yield a better fit to the combined subsurface + surface data set. Additional data is still needed to quantify this acceleration.





Discussion

The study of these case examples highlights some simple interactions between folding, sedimentation and erosion. Topographic relief can only accrue where and when tectonic uplift is faster than sedimentation (see also discussion in Simoes et al. [2006]). Thus, in the early phases of the histories of both folds, syntectonic sedimentary units extend continuously across the fold, and no topographic relief builds up (A). As shortening rate increases, maximum uplift rates overcome the sedimentation rate, in a zone whose width is a function of the spatial distribution of uplift. As long as the hydrographic system has enough erosion power to sweep laterally back and forth and abrade rocks as they are uplifted, relief remains negligible, and an abrasion surface is emplaced, unconformably overlying older units (B), as observed on the northern flank of Anjihai. If the river is forced to entrench in a narrow gorge because it does not have enough stream power to abrade laterally all the uplifted rocks, relief starts building up above the core of the anticline (C), producing something similar to the current situation of Yakeng. Eventually, the fold ridge is expected to undergo secondary erosion driven by its own relief, as observed in the exposed core of Anjihai.



Topographic relief width is thus a function of the spatial distribution of uplift and the sedimentation rates. Shortly after the initiation of relief, the fold width should equate to the width of the area where the uplift rate is greater than the sedimentation rate. Using our parameterized deformation models for the Yakeng and Anjihai folds, we can plot the predicted emergence width as a function of the ratio between the shortening and sedimentation rates. The ratios consistent with the observed fold widths are 5.0 for Yakeng, and 4.15 for Anjihai. Combining the predicted ratios with relevant magnetostratigraphic sedimentation rates yields first-order estimates of the mean shortening rates since relief emergence, 2.15 mm/yr at Yakeng and 1.12 mm/yr at Anjihai, both much faster than the long-term averages. While the precision and reliability of this fold-width method will depend on our ability to understand the complexities of the post-emergence sedimentation regime, surface fold width stands out as a remarkably sensitive measurement, governed as it is by competition between two important geomorphic processes.