Kinematics of Changhua blind thrust and growth of Pakuashan Anticline, West Central Taiwan

Martine Simões [1 2], Jean Philippe Avouac [1], Yue-Gau Chen [3], Ashok K. Singhvi [4], Chien-Yin Wang [5], Manoj Jaiswal [4], Yu-Chang Chan [6], Sylvain Bernard [2].

[1] California Institute of Technology, Tectonics Observatory, Pasadena, CA, USA; [2] Ecole Normale Superieure, Laboratoire de Geologie, Paris, France; [3] National Taiwan University, Department of Geosciences, Taipei, Taiwan; [4] Physical Research Laboratory, Planetary and Geosciences Division, Ahmedabad, India; [5] National Central University, Jonghli, Taiwan. [6]Academia Sinica, Institute of Earth Sciences, Taipei, Taiwan.

Location of our study area

* Deformation front of West Central Taiwan
* Changhua fault: blind thrust - Pakuashan and Tatushan anticlines: fault-tip folds.
*Slip rate and age of deformation initiation unknown

however... evidence that fault locked!

Need to understand kinematics of fold growth:

→ insights into contribution of this fault to crustal shortening across the range

→ seismic hazard assessment.

Purpose of this study

Constrain kinematics of deformation of a fault-tip fold

* Finite deformation: Seismic profiles, well logs
* Incremental deformation: DEM mapping of lateritic surface, Geometry of deformed growth-strata ,OSL dating of these levels

→ shortening cumulated since deposition

Cumulated shortening vs. age of strata: growth history of the fold

→ * age of deformation initiation
* slip rate

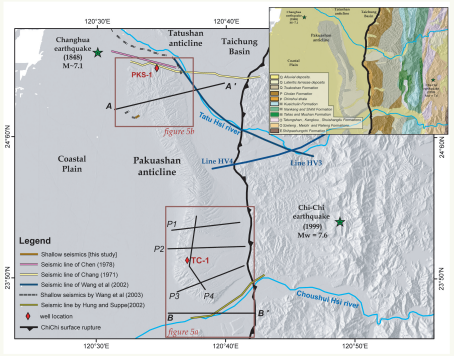


Figure 1: Map of the Western Foothills of Central Taiwan. The Pakuashan anticline formed at the tip of the blind Changhua thrust fault, which might have produced the 1848 Changhua (M~7.1) earthquake (Tsai, 1985). Remnants of lateritic fluvial terraces dated in this study to 194+/-4 ka (Pakua1-TL, figure 2a) cap the anticline. Their warping attests to active folding. Also reported are locations of PKS-1 and TC-1 wells, along with the seismic lines of (Chang, 1971; Chen, 1978; Hung and Suppe, 2002; Wang, et al., 2003; Wang, et al., 2002) the location of the shallow seismic investigations presented in this study is also indicated. In the northern area, all the data were projected on a N78 +/- 3E direction indicated by line A-A'.To the south they were projected on a N90 +/- 3E direction along line B-B'. Boxes show the two field areas mapped in more detail in figures 2a and b. Inset: geological background of the Western Foothills of Central Taiwan - E: Eocene; O: Oligocene; M: Miocene; P: Pliocene and Pleistocene; Q: Quaternary.

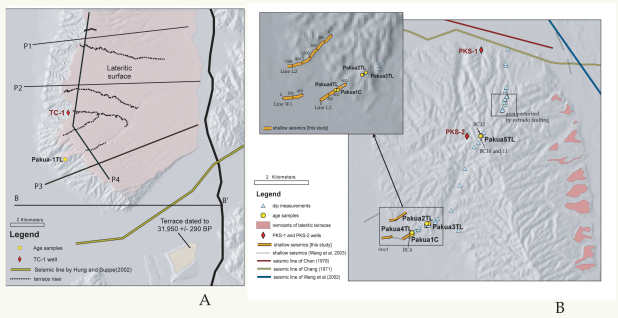


Figure 2: Maps of southern (A) and northern (B) Pakuashan area. See boxes in Figure 1 for location:
(A) Southern Pakuashan area along the Choushui river. The finite structure of the fold was retrieved from the seismic profile of [Hung and Suppe, 2002], and the TC-1 well [L-H. Hung, pers. comm., 2005) ~7km further north. The strath level from the tilted fluvial terrace dated to 30.950 +/- 290 BP by radiocarbon [Chu, et al., 2002] was surveyed in the field . Also, we were able to date one of the lateritic fluvial surfaces preserved on the backlimb of the fold in this area (Pakua1-TL: 19 +/- 4 ka). its geometry was extracted from the 40m-DEM for our analysis. All data were projected along line BB'.
(B) Northern Pakuashan area. Field measurements and sampling were performed along highway 74. Labels refer to the sites mentioned in the text. Also shown is the area where some normal faulting in the backlimb has been observed, most probably related to some extrados deformation. Age samples could only be collected in the footcloth of the anticline. The shaded relief, made from the 40m- DEM, outlines the location of remnants of the lateritic terraces that used to cap the fold. Shallow seismic investigations have been carried in the westernmost portion of our field area (inset). All these measurements were projected on a N78+/-3°E direction indicated by line A-A' of figure 1.

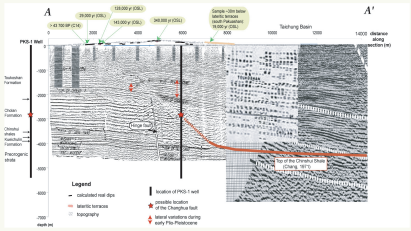


Figure: Cross-section in a N78 direction along line A-A' (northern Pakuashan) (see figures 2 and 5b for locations).
The deeper structure of the Pakuashan anticline is documented by seismic profiles [Chang, 1971; Chen, 1978; Wang, et al., 2003; Wang, et al., 2002] and by the logs from the PKS-1 and PKS-2 wells [Chang, 1971] (only data from PKS-1 were reported for simplicity). The possible position of the Changhua thrust ramp along the PKS-1 well is indicated (red star) and corresponds to a repetition of the Cholan Formation [Chen, 1978]. The thick red line beneath the Taichung Basin locates the top of the Chinshui Shale as proposed by [Chang, 1971]; this level is the most probable candidate for the decollement level beneath Pakuashan. The hinge fault may have been active since the Miocene, through the early Plio-Pleistocene; indeed, huge lateral variations at the base of the Toukoshan Formation (thick red arrows) suggest that the geometry of these strata may still be affected by this normal fault.

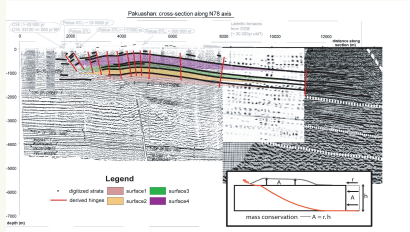
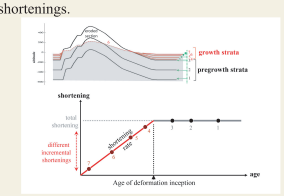


Figure: Analysis performed on the seismic profiles projected along line A-A' (northern Pakuashan) (see Figures 2 and 5b for location). Only the best reflectors above the early Plio-Pleistocene were digitized: indeed the base of the Toukoshan Formation might still be affected by the hinge fault (thick red arrow; see caption or figure above) so that its geometry may not be used simply to retrieve the kinematics of deformation across the Pakuashan anticline. Four main strata, labeled as layers 1 to 4 from bottom to top, could be traced almost entirely across the whole structure. They defined surfaces above a baseline, whose area A is directly linked to their height above the decollement h as well as to their cumulated shortening r if we assume mass conservation ; surfaces labeled 1 to 4 correspond respectively to layers 1 to 4 on the figure. In addition to that, the baseline gives some information on the initial geometry of the strata: the original dip, indicated with the layer label, increases with depth, as expected from the compaction of sediments within the Taichung Basin. The position of the hinges could also be assessed easily from this analysis, mostly on the backlimb of the fold as well as along the axial line; it is probably not as precise for the frontal portion of the anticline since the resolution of the seismic profiles is poor. The warping of the layers to the east is attributed to the Chelungpu fault and is thus not considered in our modeling.

Modeling approach

Need for a model to reconcile finite and incremental shortenings.



→ New modeling approach: analytical formulations for fold growth derived from sandbox experiments [Bernard et al, in prep]

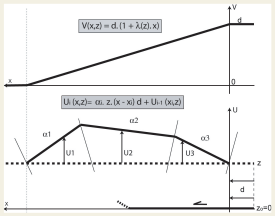


Figure: Sketch illustrating the parameters used within our analytical approach (Bernard et al (in prep.)). After an incremental shortening d, a layer originally at an altitude z above the decollement, gets to be deformed. The pattern of vertical displacements U can be described in terms of different continuous domains delimited by hinges.the horizontal axis is then assumed to have its origin along the 1st hinge. Within each domain, U can be simply expressed by the relation indicated in the lower part of the figure. αi characteristic of each domain,and ci is a constant that allows for continuity from one hinge to the next one. This expression implies that, for an incremental shortening d, since is constant in each domain, uplift increases with the initial altitude z of the level; our seismic profiles in the natural case of the Pakuashan anticline seem to follow this scheme. Hinges for vertical and horizontal displacements are assumed to be identical. Horizontal displacement V decreases linearly from d in the hinterland to 0 at the front of the fold; the simple expression describing V is indicated in the upper part of the figure.

Assume that applicable to broader scale and when medium layered!

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This first time application to a natural fold proves to be successful!

Analysis of Pakuashan: example of the northern portion of the fold

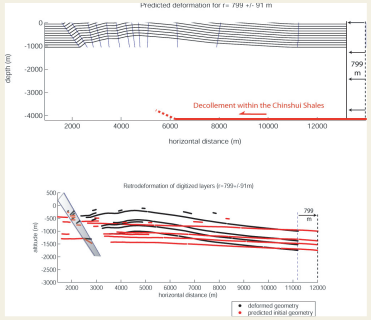

Figure: Application of the analytical approach proposed by [Bernard, et al., subm.] to northern Pakuashan along line A-A' (see Figure 1 for location).The model parameters assume a total shortening of 799 +/- 91m along A-A', with a decollement located within the Chinshui Shales.
(A) Predicted deformation for initially horizontal levels.The geometry of the blind thrust is schematic and is only shown to indicate the most probable decollement level.
(B) Retrodeformation of strata digitized from the projected seismic profiles using the simple analytical formulations used in (A). The original geometry inferred from this analysis predicts initial dips that range from 2.1 to 1.8° given the uncertainties on the model.this is in good agreement with the analysis performed on the seismic profiles .The misfit between the model and the observations is not negligible at the front of the fold (shaded area).this could result from model uncertainties as well as from the seismic profiles that show very poor resolution in this area. The deeper level in this shaded area shows a predicted initial dip too steep: this is an artifact of the model since the observation of the seismic profiles suggests that the two last hinges do not apply to the stratum.

Parameters for model derived from analysis of finite deformation documented on seismic profiles and well logs

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799 +/- 91 m of finite shortening across the northern and southern Pakuashan anticline on the A-A' direction (direction of trnasport in Taiwan)
Decollement within the Chinshui Shales

Predicts well the deformation pattern observed for the Pakuashan anticline

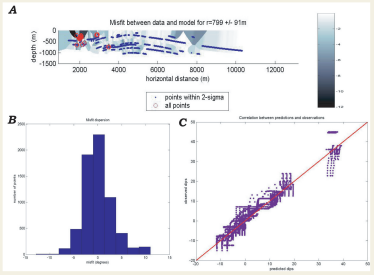

Figure: Misfits between measured dip angles and those predicted by the model for northern Pakuashan. The cumulated shortening and the corresponding depth of the decollement considered are respectively 799 +/- 91 m (along direction A-A', oblique to the direction of transport) and 4261m.
(A) Residuals between predictions and data (colorbar in degrees). The highest residuals take place at the front of the fold, between the two last hinges, where the model predicts dip angles smaller than those observed. Misfits also appear high in the shallow portion of the backlimb; however, since there were no data from the seismic profiles in this zone, these misfits are only artifacts from the interpolation on the residuals. Also, for a more accurate comparison, layers digitized from the seismic profiles were plotted on this diagram in blue where residuals are within the 2-sigma uncertainties of their distribution, in red where they lie outside these values. It appears that, apart from the frontal portion of the anticline, most of the misfits occur along the axial lines of the hinges, or where strata are not well defined in the seismic profiles.
(B) Misfit distribution. The values for the misfit represent the residuals calculated when the predicted dips are substracted from the observed dips at any data point. Residuals are centered on 0.12°, with a standard deviation of 3.08° which conforts the validity of our approach to describe the kinematics of the Pakuashan anticline. High positive misfits correspond to the frontal part of the fold.
(C) Correlation between data and model. The coefficient of correlation is 0.9732 . Negative dip angles plunge to the east (backlimb) while positive values correspond to dips to the west (forelimb).

Misfit: standard deviation of ~3 degrees (slightly higher for southern Pakuashan)

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Very good correlation between model predictions and observations

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misfit mostly along hinges and on the most frontal part of anticline

Final results combining north and south Pakuashan

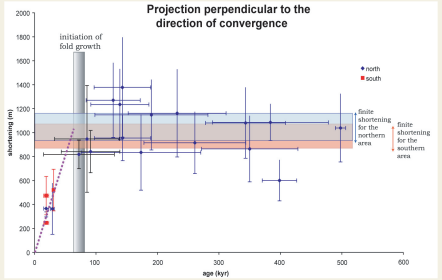

Figure: Final results combining the analysis for northern and southern Pakuashan in the direction of convergence N118E. The kinematics inferred from both areas are consistent with each other and suggest a shortening rate of 15.9 +/- 1.4 mm/yr and an age of deformation inception of 63,678 +/- 9863 a.

→ cumulated shortening vs. age describes kinematics of the fold!!!

→ Deformation started ~64 kyr ago

→ Slip rate of 15.9 +/- 1.4 mm/yr on the Changhua blind fault!

Significant contribution to crustal shortening in Taiwan.