Investigating the kinematics of the Changhua thrust and related Pakuashan Anticline, West Central Taiwan

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Location of our study area

* Deformation front of west central Taiwan
* Changhua fault: blind thrust - Pakuashan and Tatushan anticlines: fault-propagation folds.
*Slip rate and age of deformation initiation unknown

however... evidence that fault locked!
Need to understand kinematics of fold growth:
→ insights into shortening across whole range
→ seismic hazard assessment.

Purpose of this study

Constrain kinematics of deformation of a fault-propagation fold

* Finite deformation: Seismic profiles, well logs
* Incremental deformation:
DEM mapping of lateritic surface
Geometry of deformed 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

Modeling approach

Previous models for fault-propagation folds cannot reconcile finite and incremental shortening.

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

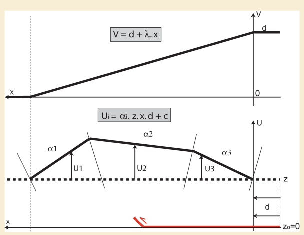

Figure: Sketch illustrating the parameters used within our analytical approach [Bernard et al (in prep.)]. After an incremental shortening d, a layer originally at an altitude z above the decollement, gets to be deformed. The pattern of vertical displacements U can be described in terms of different 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; is characteristic of each domain, and c 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!

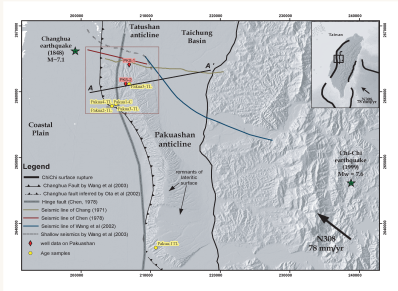

Figure: Map of the Pakuashan anticline, showing the blind Changhua fault as inferred by [Wang et al., 2003] and by [Ota et al., 2002] to the south. This thrust would have been responsible for the 1848 Changhua (M~7.1) earthquake [Tsai, 1985]; no clear evidence for surface ruptures have been reported nor observed. The trend of the fault shows a strong obliquity with the general convergence direction in Taiwan (thick arrow) [Seno et al., 1993; Yu et al., 1997]. Also reported is the former normal hinge fault as proposed by [Chen, 1978]. PKS-1 and PKS-2 wells, along with the seismic lines of [Chang, 1971; Chen, 1978; Wang et al., 2003; Wang et al., 2002] were indicated. Most of our age samples are located in the northern area of Pakuashan, except for Pakua1-TL, which is located to the south, ~30m below the lateritic terraces. All the data were projected on a N78 direction indicated by line A-A'. Inset locates more precisely our field area. Coordinates are given in the Taiwanese system TW67.

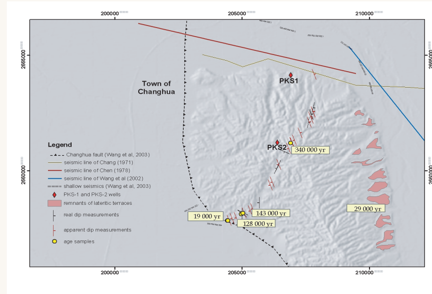

Figure: Map of our field area in the northern portion of the Pakuashan anticline (TW67 coordinate system). Field measurements were performed along highway 74. When enough 3D data could be retrieved, real strike and dip measurements were calculated; otherwise, apparent dips were converted to "virtual" real dips by assuming a N168 strike. Ages samples could only be collected in the forelimb of the anticline. From the 40m-resolution DEM, remnants of lateritic terraces were mapped and their geometry could be compared with our measurements and the fold geometry deduced from seismic profiles. All these measurements were projected on a N78 direction indicated by line A-A'.

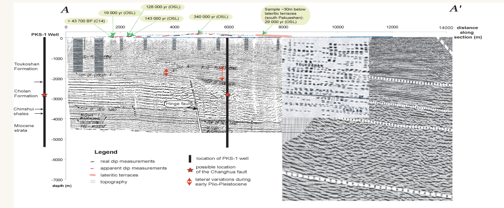

Figure: Cross-section in a N78 direction along line A-A'. Field measurements (real and apparent dips of surveyed strata) were combined with the fold topography and the geometry of the lateritic surfaces retrieved from the 40m-resolution DEM. The deeper structure of the Pakuashan anticline is documented by seismic profiles [Chang, 1971; Chen, 1978; Wang et al., 2003; Wang et al., 2002] and by the data from the PKS-1 and PKS-2 wells [Chang, 1971] (only data from PKS-1 was reported for simplicity). The possible position of the Changhua thrust along the PKS-1 well is indicated (red star) and corresponds to a reported repetition of 380-420m of the Cholan Formation [Chen, 1978]. 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. Only shallower levels will be considered to assess the kinematics of the Pakuashan anticline.

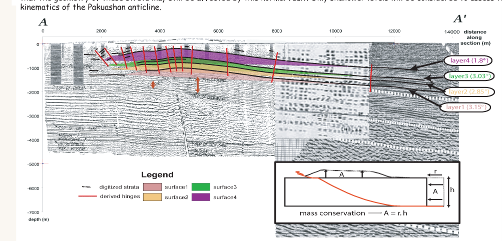

Figure: Analysis performed on the seismic profiles projected along line A-A'. Only the best reflectors above the early Plio-Pleistocene were digitized: indeed the base of the Toukoshan Formation might still be affected by the hinge fault (thick red arrow) so that its geometry may not be used simply to 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 (inset); 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 t he 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 flexure of the layers to the east is attributed to the Chelungpu fault and is thus not considered in our modeling.

Analysis of Pakuashan

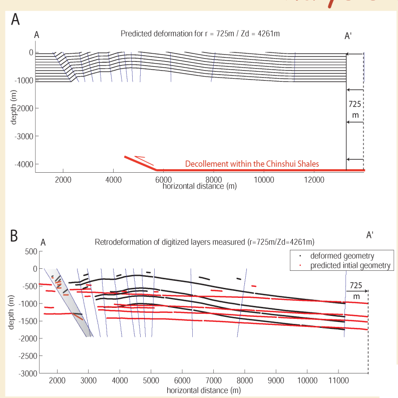

Figure: Application of the analytical approach proposed by Bernard et al (in prep) to the Pakuashan anticline along line A-A', for a total shortening of 725m, corresponding to a decollement located within the Chinshui Shales. (A) Predicted deformation for initially horizontal levels. (B) Retrodeformation 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 2.2 to 1.8° given the uncertainties on the model; this is in good agreement with the analysis performed on the seismic profiles. However, 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 too steep predicted initial dip: this is an artifact of the model since the observation of the seismic profiles suggests that the two last hinges do not apply to this stratum.

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

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725 m of finite shortening across the Pakuashan anticline and decollement within the Chinshui Shales

Predicts well the deformation pattern observed for the Pakuashan anticline

Misfit: standard deviation of ~3 degrees

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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

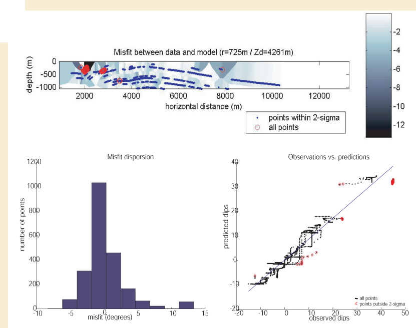
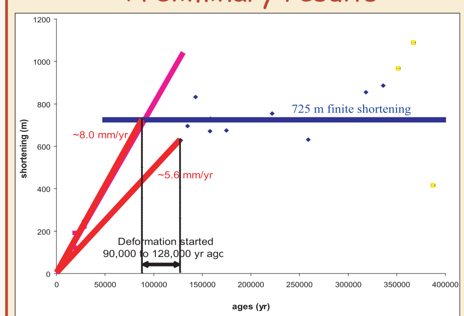


Figure: Computed misfits between dips observed and predicted by the model, taking in account the initial geometry inferred by the analysis of the seismic profiles. The cumulated shortening and the corresponding depth of the decollement considered are respectively 725m and 4261m.
(A) Residuals between 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 dips 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- 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°, with a standard deviation of 3.09° 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 good correlation is expressed by the high coefficient of correlation of 0.9769 and by the ~1:1 plot of observations and predictions. Here also, points inside and outside the 2- distribution of the residuals have been distinguished. Negative dips plunge to the east (A') while positive values correspond to dips to the west (A). The dispersion of the points around the best-fitting line increases with increasing dips: indeed, data, and thus model, are better defined within the backlimb of the fold whereas the poorer resolution of the seismic profiles in the forelimb results in a higher misfit.

Preliminary results



Model used to determine cumulated shortening needed for present tilt of strata surveyed and dated in the field
→ incremental shortening vs. age describes kinematics of the fold!!!

→ Deformation started ~90,000 to 128,000 years ago

→ Slip rate of 5.6 to 8 mm/yr on the Changhua fault!