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Zhenyu Peng, Fabien Graveleau, Xin Wang, Bruno Vendeville. Preexisting restraining bend and their impact on thrust propagation: insights from analogue models and the northern Tianshan foreland basin. GEOMOD 2023, Sep 2023, Paris, France. hal-04385862

HAL Id: hal-04385862

<https://hal.science/hal-04385862>

Submitted on 11 Jan 2024

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Preexisting restraining bend and their impact on thrust propagation: insights from analogue models and the northern Tianshan foreland basin

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Abstract

Fold and thrust belt growth during mountain building typically happens through the propagation of deformation toward the foreland basin. As this deformation progresses, inherited faults in the foreland basement, like normal faults, can be reactivated and can control the distribution and characteristics of structures in the cover units (Butler, 1989; Scisciani, 2009). The dynamics of this structural inheritance depends on several parameters, such as the geometry and kinematics of basement faults, the *décollement* strength in the cover units, the intensity of surface processes, etc. (Bonini et al., 2012; Ferrer et al., 2023). In some cases, the inherited basement faults can be strike-slip faults. This is the case in the northern Tianshan foreland basin, where the trend of shallow Cenozoic thin-skinned thrusts is likely controlled by the underlying deeper Mesozoic strike-slip faults (Peng et al., submitted). For example, in the Gaoquan anticline, horizontal seismic slices illustrate that the location and lateral extent of the shallow thrust-related fold are associated to an underlying restraining bend (Figure 1a and 1b). Cross section from 3D seismic cube (Figure 1c) shows that this restraining bend is superimposed by a thin-skinned thrust that roots in an upper *décollement* layer (formation E2-3a). Kinematic analysis of Gaoquan structure (Figures 1d-f) illustrates that the deep restraining bend has been reactivated prior to the occurrence of the shallow thrust ramp. While the kinematic restoration appears feasible, the dynamic relationship between the reactivation of the deep restraining bend and the initiation of the thin-skinned thrust remains uncertain under compressional stress conditions.

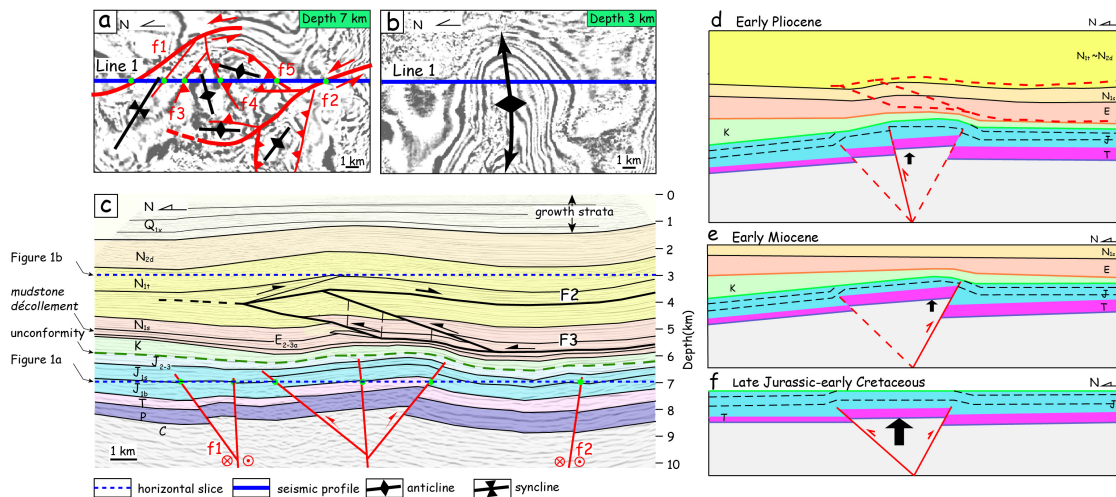


Figure 1: Structural analysis of the Gaoquan anticline, northern Tianshan foreland basin. (a-b) 2D horizontal seismic slice extracted from a 3D seismic volume. A restraining bend geometry is observed on a deep horizontal slice (at 7km), whereas an E-W-trending fold is visible on a shallow horizontal slice (at 3km). (c) Interpreted 2-D N-S seismic line (Line 1) across Gaoquan. Horizontal seismic slice levels are indicated by blue stippled lines. (d) Restoration sequence of Gaoquan structure from early Cretaceous to early Pliocene. During the middle Miocene to early Pliocene, the deep pop-up structure was active. (e) Between the Eocene and early Miocene, the deep steeply dipping fault zone was reactivated as a thick-skinned structure and then stopped. (f) The deep steeply dipping fault zone in the Jurassic is sealed with a Cretaceous unconformity (redraw after Peng et al., submitted).

We developed an experimental approach to unravel the kinematic and dynamic relationships between reactivated basement restraining bend and upper thrust and folds. We used a 120cm long and

80cm wide box in which we deformed a 10.5cm thick brittle-ductile upper unit (made of sand and PVC, silicone putty) that represents the upper crust, lying above a 1.5cm thick basal viscous layer (made of silicone putty) that represents a mid-lower crust level (Figure 2d). The scale between nature and model is about 1km ~ 1cm. The models underwent three tectonic phases:

- Phase 1: strike-slip deformation of a 5cm thick sand/PVC pile. No sedimentation. Relative displacement was 10cm. Relief of the restraining bend was completely erased at the end of this phase and three 5mm thick layers (one silicone and two sands) were deposited above the flattened topography.
- Phase 2: deposition of a 2cm thick sand pile without (Mod01) and with (Mod02) reactivation of restraining bend. Relative displacement was 8cm.
- Phase 3: model contraction (shortening by 9cm) with deposition of two syntectonic layers.

Boundary conditions applied to the model during strike-slip phases 1 and 2 are inspired from Boussarsar, (2022). Shear velocities during phase 1 and 2, and shortening velocity during phase 3 was fixed at 2.0cm/h.

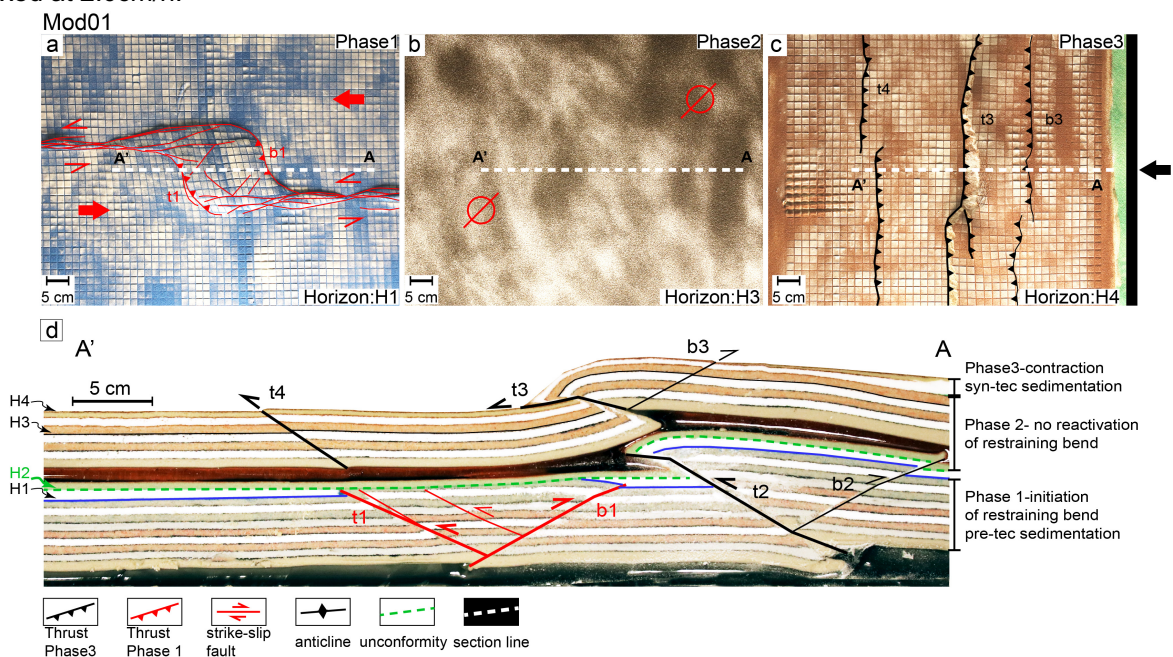


Figure 2: Mod01 results. (a) End of phase 1 with the development of the restraining bend. (b) End of phase 2 where no strike slip deformation occurred during layer deposition. (c) Final stage after contraction of the model and addition of two syntectonic layers (brown top). (d) Final cross-section across the non-reactivated inherited restraining bend. “t” is forethrust, “b” is backthrust and numbers refer to the sequence of thrusting.

Mod01 accounts for the experiment where the pre-existing restraining bend was not reactivated during phase 2 (Figure 2b). Basement pop-up was neither reactivated during phase 3 (Figure 3d) since the overlying green unconformity level (H2) is flat. Most of the phase 3 shortening has been consumed by the thick-skinned thrust (t2) and transferred upward to the upper *décollement*. This resulted in the development of a shallow pop-up (t3-b3) and a long and fairly cylindrical thrust sheet (t4) detaching in the upper silicone level.

In contrast, Mod02 accounts for the experiment where the pre-existing restraining bend was reactivated during phase 2 (Figure 3b). This folded the upper silicone level and influences the localization of deformation during phase 3. Indeed, two thin-skinned thrusts t4 and b4 nucleated right above the restraining bend zone (Figure 3d), and their lateral extent was consistent with the width of the underlying restraining bend (Figure 3c).

Sequential restoration of the Mod02 final cross-section illustrates the reactivation of restraining bend during phase 2, which folded the upper *décollement* layer and the overlying units (Figures 3e and 3f), as evidenced by the fanning growth strata. During phase 2, about 1.0cm of shortening has been consumed by the pop-up. During phase 3, the contractional deformation was consumed by the thick-

skinned thrust (t2, b2) and transferred into the shallow pop-up (t3, b3) and localized on thrusts t4 and b4. This consumed about 6cm shortening.

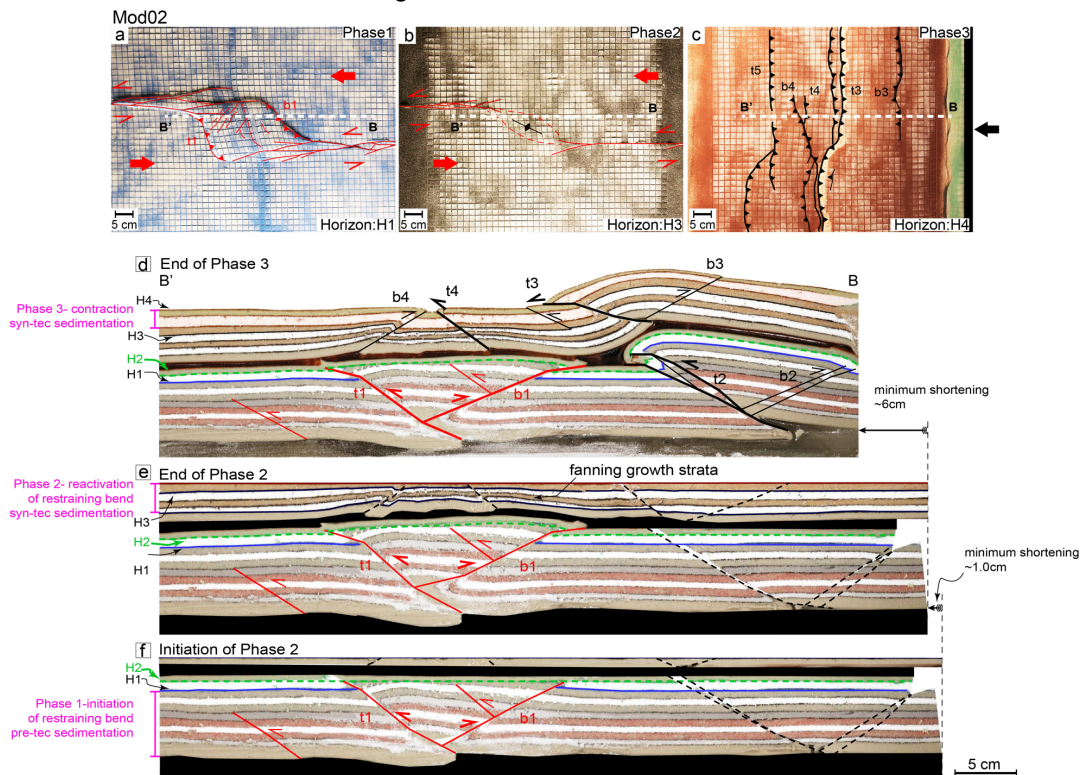


Figure 3. Mod02 results. (a) End of phase 1 with the development of the restraining bend. (b) End of phase 2 with syntectonic sedimentation coeval with strike-slip motion. (c) Final stage after contraction of the model and addition of two syntectonic layer (in brown). (d) Final cross-section across the reactivated inherited restraining bend. (e) Restoration at the end of phase 2 and (f) at initiation of phase 2.

In conclusion, our work illustrates how the reactivation of a pre-existing restraining bend inherited from an early strike-slip phase can influence the distribution of deformation during a latter fold-and-thrust belt development. In section view, the reactivation of a deep inherited restraining bend can fold an upper *décollement* layer which influences deformation localization during deformation propagation. In map view, the reactivated restraining bend zone would limit the lateral extent of the overlying thrust and related folds. In this way, our results provide explanations why the shallow Gaoquan anticline within the northern Tianshan foreland basin is localized right above the basement restraining bend. Additionally, this explains the constancy of the lateral extent of the shallow Gaoquan anticline and the underlying restraining bend zone. This kinematic and dynamic relationship between the basement restraining bend and upper thin-skinned thrust can be insightful for understanding the structural evolution of foreland basin that present wrench-thrust tectonic interaction.

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