Coseismic fault-propagation folding on the Sulaiman Fold and Thrust belt

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Abstract

The continental collision at the western boundary of the Indian continent formed the tectonically complex transpressional zones of the Sulaiman Fold Thrust (SFT) and Kirthar Fold Thrust (KFT) belts. Seismic hazard around the SFT is considered elevated, but shortening across its eastern boundary is poorly understood because of the scarcity of moderate-sized earthquakes in the last few decades. Here, we use Sentinel-1A ascending and descending interferometry to analyze the coseismic crustal deformation associated with the 2015 moment magnitude (Mw) 5.7 Dajal earthquake that occurred on the boundary thrust in the SFT belt. The surface displacement was caused by slip on a blind thrust and coseismic folding in the hanging wall. We use kinematic inversions to determine the distribution of slip on the frontal ramp and flexural slip along active axial surfaces for two end-member models of fault geometry. We first consider a double fault-bend fold system involving two sub-horizontal décollements separated by a ramp. Second, we consider a fault-propagation fold system where the frontal ramp terminates below a thick sediment layer. The fault-bend fold model includes slip on the décollement-ramp-décollement and flexural slip on two active axial surfaces initiated at the fault bends. For the fault-propagation fold, the model includes slip on the décollement-ramp system and flexural slip on the lower axial surface. In a preliminary step, the geometry of the ramp is optimized using a Monte Carlo method using a single asperity model. The geometry of the décollement and active axial surfaces is inferred based on balanced cross-sections, whereby the fold axes bisect the sediment layers across a fault bend. In both end-member models, a shallow décollement branches into a shallow ramp at approximately 7 km depth. However, the undeformed sediment of the overlying floodplain indicates that a ramp is the recent geomorphic feature. We conclude that the Dajal earthquake propagated along the base of the ramp, representing coseismic ramp failure over fault-propagation folding.

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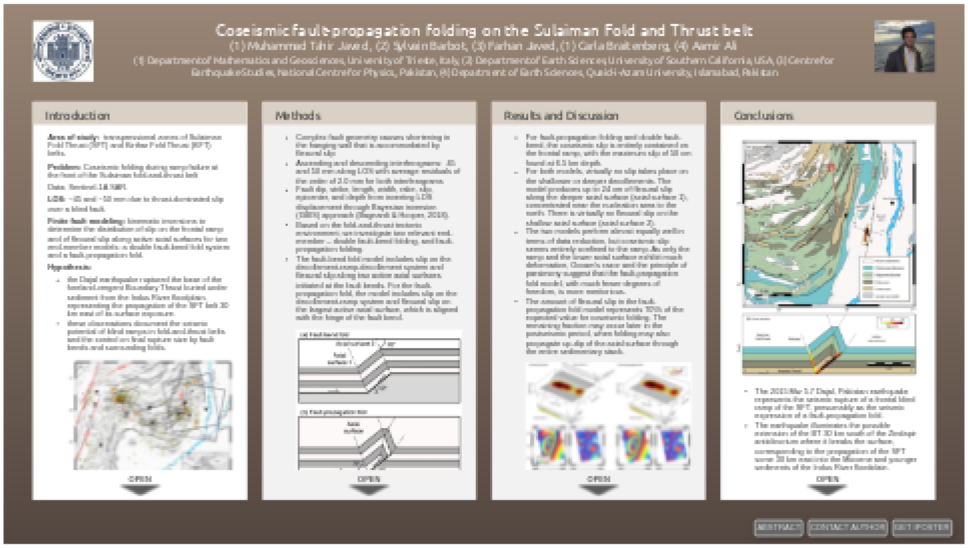

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INTRODUCTION

Area of study: transpressional zones of Sulaiman Fold Thrust (SFT) and Kirthar Fold Thrust (KFT) belts.

Problem: Coseismic folding during ramp failure at the front of the Sulaiman fold-and-thrust belt

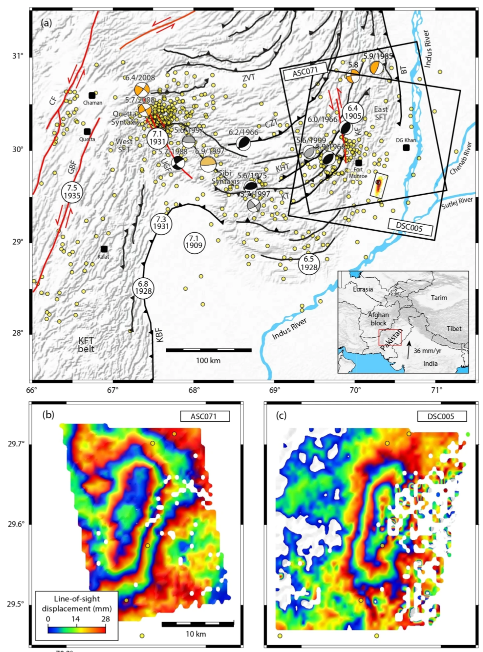
Data: Sentinel-1A SAR.

LOS: ~45 and ~50 mm due to thrust-dominated slip over a blind fault.

Finite fault modeling: kinematic inversions to determine the distribution of slip on the frontal ramp and of flexural slip along active axial surfaces for two end-member models: a double fault-bend fold system and a fault-propagation fold.

Hypothesis:

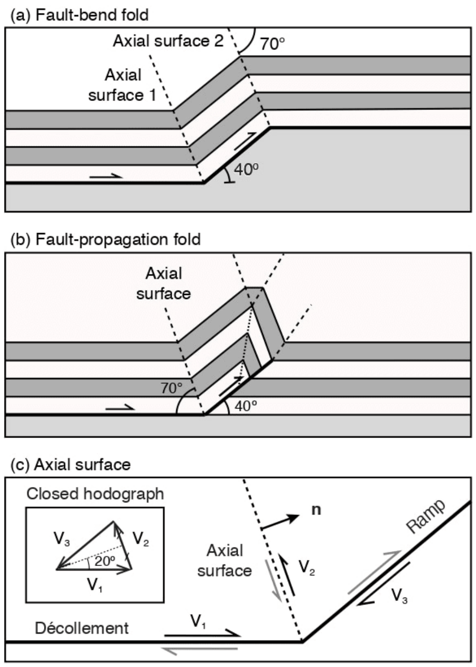
- the Dajal earthquake ruptured the base of the foreland-vergent Boundary Thrust buried under sediment from the Indus River floodplain, representing the propagation of the SFT belt 30 km east of its surface exposure.
- these observations document the seismic potential of blind ramps in fold-and-thrust belts and the control on final rupture size by fault bends and surrounding folds.



Mw 5.6, 23 October 2015 at 00:27:39 (Coordinated Universal Time, UTC) 10 km NNW of Dajal and 55 km SSW of Dera Ghazi Khan.

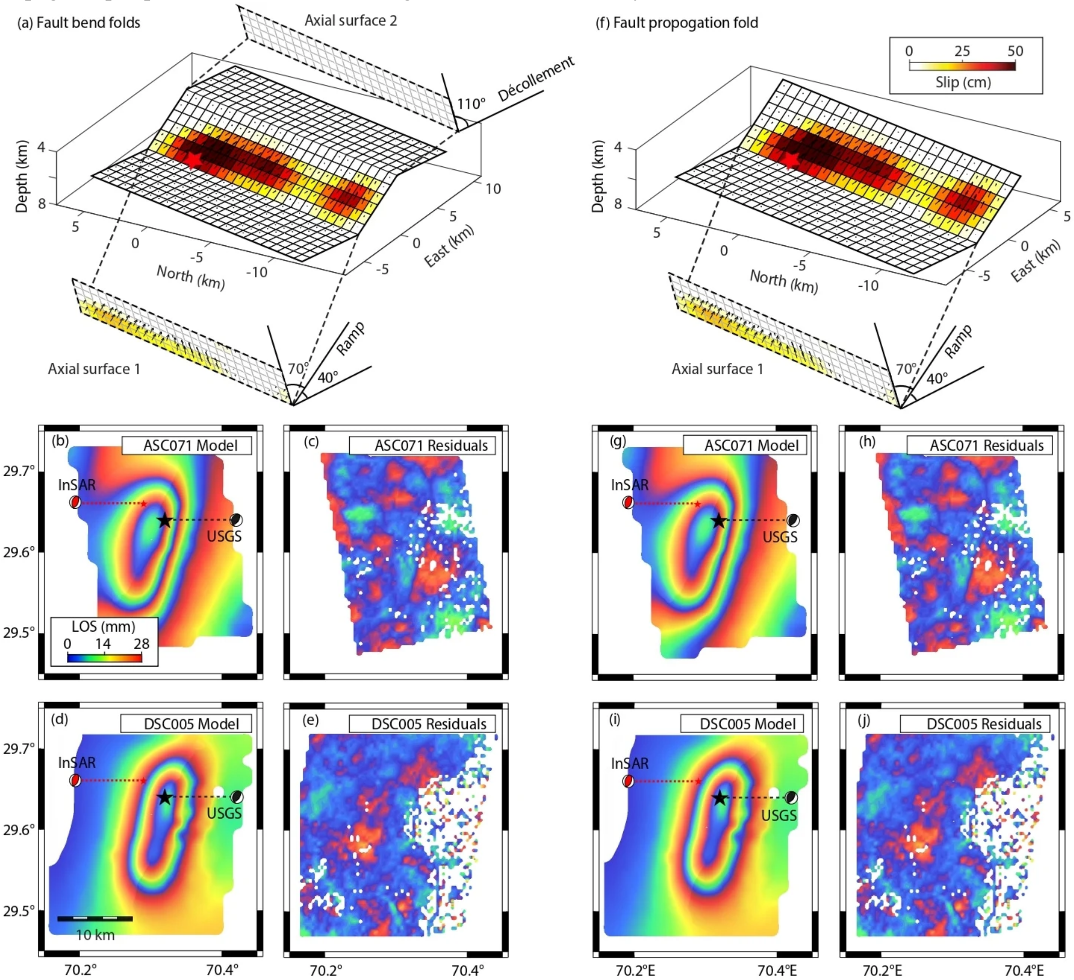
METHODS

- Complex fault geometry causes shortening in the hanging wall that is accommodated by flexural slip
- Ascending and descending interferograms: 45 and 50 mm along LOS with average residuals of the order of 2.0 mm for both interferograms
- Fault dip, strike, length, width, rake, slip, epicenter, and depth from inverting LOS displacement through Bayesian inversion (GBIS) approach (Bagnardi & Hooper, 2018).
- Based on the fold-and-thrust tectonic environment, we investigate two relevant end-member – double fault-bend folding, and fault-propagation folding.
- The fault-bend fold model includes slip on the decollement-ramp-decollement system and flexural slip along two active axial surfaces initiated at the fault bends. For the fault-propagation fold, the model includes slip on the decollement-ramp system and flexural slip on the largest active axial surface, which is aligned with the hinge of the fault bend.

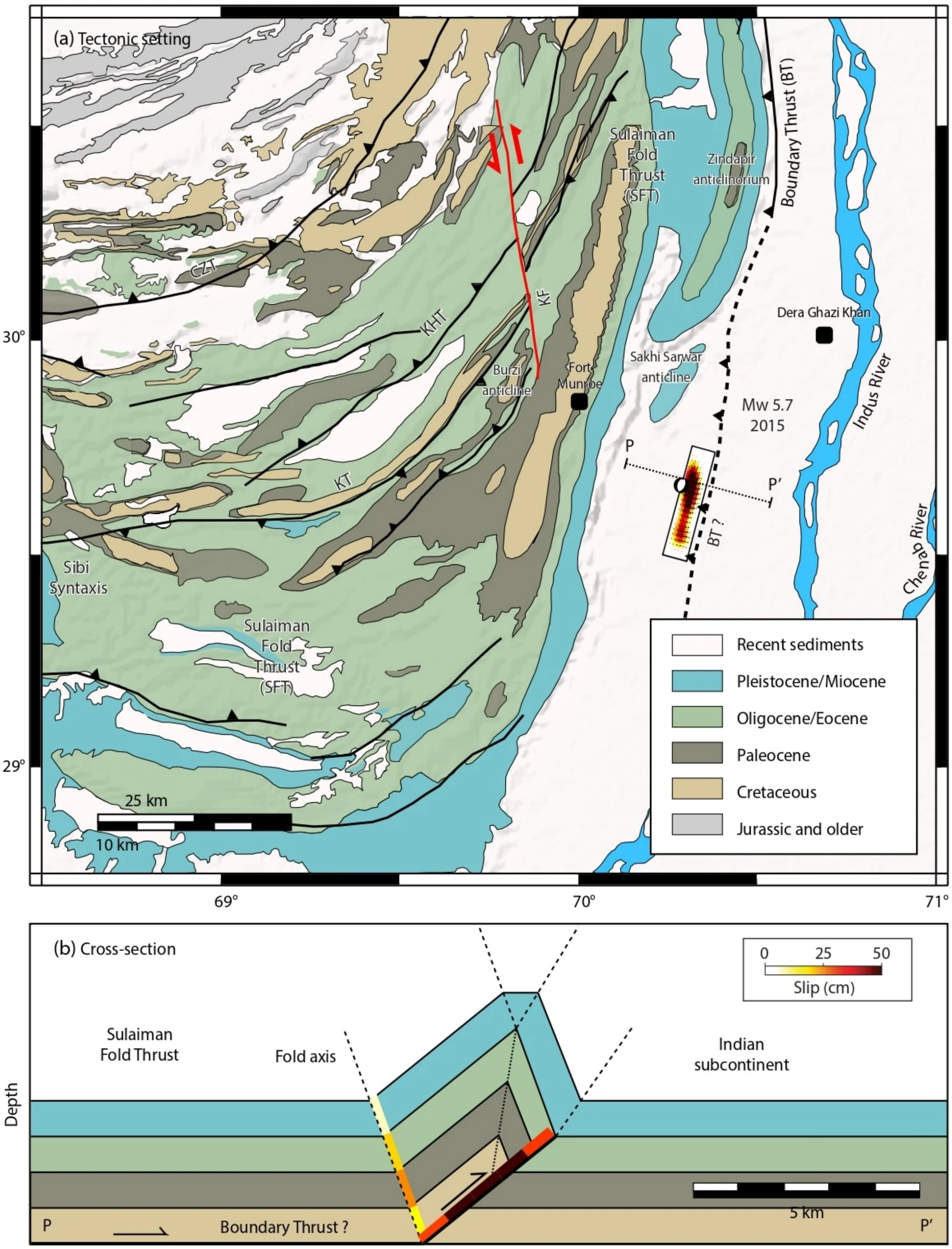


RESULTS AND DISCUSSION

- For fault-propagation folding and double fault-bend, the coseismic slip is entirely contained on the frontal ramp, with the maximum slip of 50 cm found at 6.5 km depth.
- For both models, virtually no slip takes place on the shallower or deeper decollements. The model produces up to 24 cm of flexural slip along the deeper axial surface (axial surface 1), concentrated near the nucleation area to the north. There is virtually no flexural slip on the shallow axial surface (axial surface 2).
- The two models perform almost equally well in terms of data reduction, but coseismic slip seems entirely confined to the ramp. As only the ramp and the lower axial surface exhibit much deformation, Occam's razor and the principle of parsimony suggest that the fault-propagation fold model, with much fewer degrees of freedom, is more meritorious.
- The amount of flexural slip in the fault-propagation fold model represents 70\% of the expected value for coseismic folding. The remaining fraction may occur later in the postseismic period, when folding may also propagate up-dip of the axial surface through the entire sedimentary stack.



CONCLUSIONS



- The 2015 Mw 5.7 Dajal, Pakistan earthquake represents the seismic rupture of a frontal blind ramp of the SFT, presumably as the seismic expression of a fault-propagation fold.
- The earthquake illuminates the possible extension of the BT 30 km south of the Zindapir anticlinorium where it breaks the surface, corresponding to the propagation of the SFT some 30 km east into the Miocene and younger sediments of the Indus River floodplain.
- Despite this short period of observation, flexural slip is tantamount to 70% of the expected value for coseismic folding, indicating strong mechanical coupling and synchronicity between faulting and folding at the time scales of the seismic cycle.