

Investigating reverse fault paleoseismic trench observations with geomechanical models to infer earthquake source characteristics.

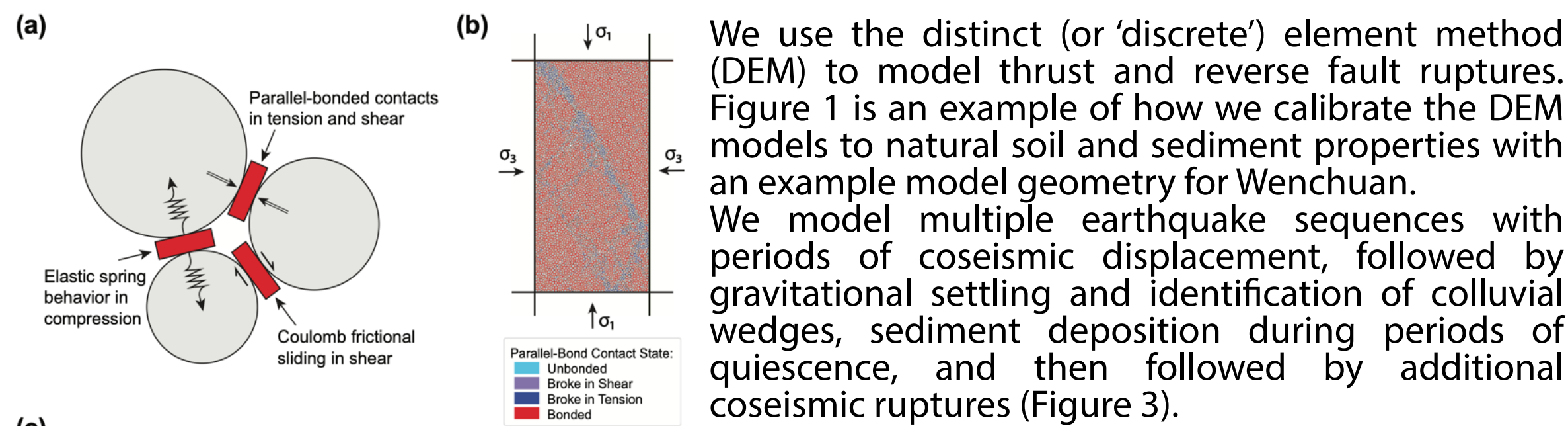
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Abstract

Paleoseismic trenches reveal critical information beyond the timing of past earthquakes, such as surface deformation patterns, fault geometries in the near-surface, and slip per event. However, the kinematics of multiple overprinted events within a trench site can be difficult to interpret and, given the limited depths of excavation, it's challenging to relate near-surface fault characteristics with earthquake source parameters at depth. In this study, we investigate three trenches that record large thrust fault earthquakes (2008 Wenchuan, Ran et al., 2019; 1999 Chi-Chi, Lee et al., 2001; and Cucamonga fault, Dolan et al., 1996) using distinct element method (DEM) models. These models incorporate sediment properties for each unit and reproduce individual earthquake events with coseismic displacements followed by periods of quiescence and sediment deposition before subsequent ruptures. They define specific slip magnitudes and fault dips that reproduce key patterns of deformation including monoclinel and pressure ridge scarps, dual forethrusts, backthrusts, folding, tensile fracturing, and colluvial wedges across multiple events. Furthermore, we developed a technique to mechanically identify colluvial wedges from particle displacement fields following each surface-rupturing event, allowing us to explore how scarps and colluvial wedges evolve through time. The results of these models show that the Wenchuan trench site experienced 3 events with ~2.8 m of dip-slip on a ~40° master fault that generated a dual fault splay towards the surface forming a monoclinel scarp (Ran et al., 2019). The models of the Chi-Chi trench consist of three events with ~2.0 m of dip-slip per event. The best models include a shallowly dipping main fault (~25°) in the trench that leads to the formation of a pressure ridge scarp with a localized, near-surface backthrust. However, this fault must steepen at depth to at least 34° to yield results consistent with the broader patterns of uplift observed in the trench (Lee et al., 2001). Finally, the Cucamonga trench site shows that there are three events of variable slip (2, 4, and 3 m of dip-slip) on a ~40° fault that produce a monoclinel scarp. This site experienced reworking of the colluvial wedges, which may have implications for dating paleoearthquakes. Our study demonstrates that DEM is well-suited to reproducing paleoseismic trench observations and can guide interpretation of trench observations to earthquake source characteristics.

Introduction & Methodology



We use the distinct (or 'discrete') element method (DEM) to model thrust and reverse fault ruptures. Figure 1 is an example of how we calibrate the DEM models to natural soil and sediment properties with an example model geometry for Wenchuan. We model multiple earthquake sequences with periods of coseismic displacement, followed by gravitational settling and identification of colluvial wedges, sediment deposition during periods of quiescence, and then followed by additional coseismic ruptures (Figure 3).

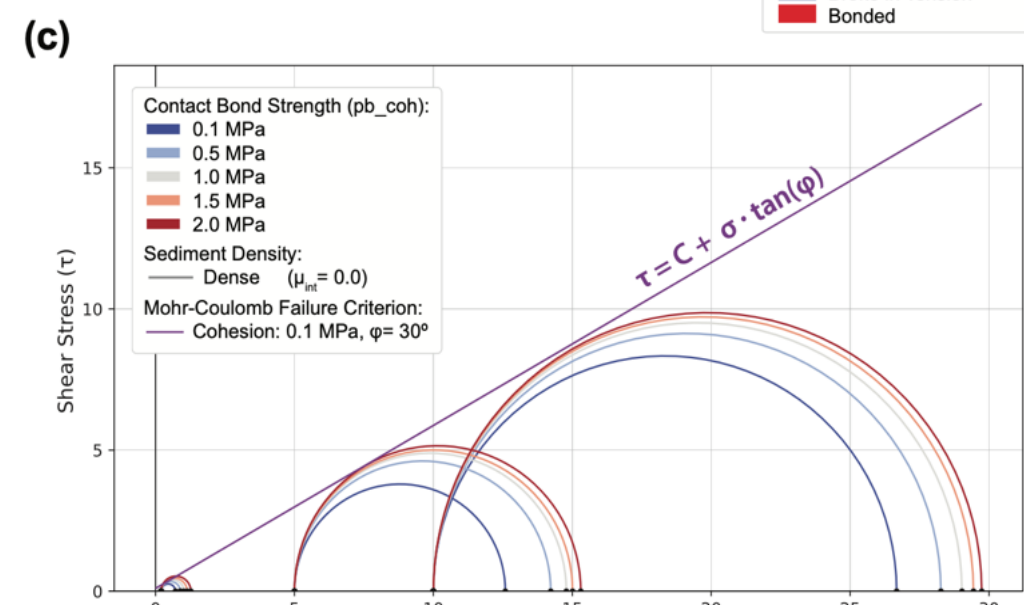


Figure 1 (left): (a) DEM Particle mechanics. (b) Biaxial stress test of stiff, cohesive material with a fracture. (c) Mohr-Coulomb failure criterion for dense sediment across a range of cohesion values and confining pressures. (d) Example model geometry for the Wenchuan trench site.

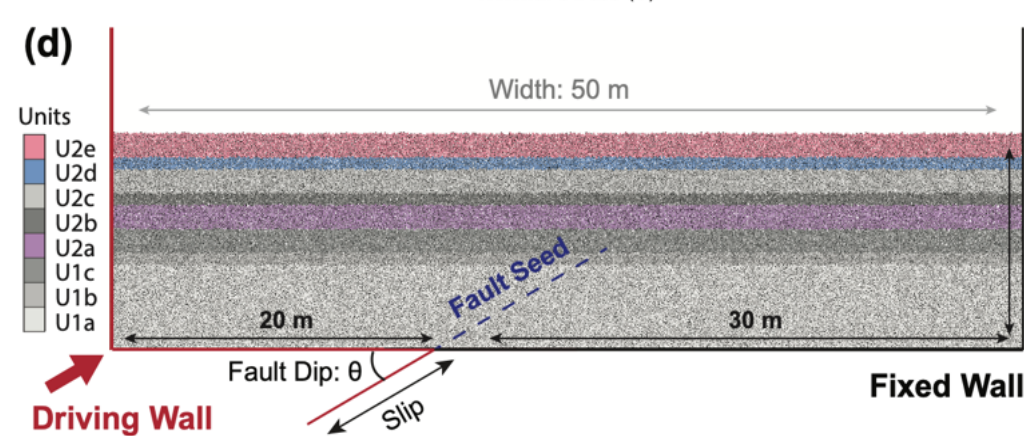
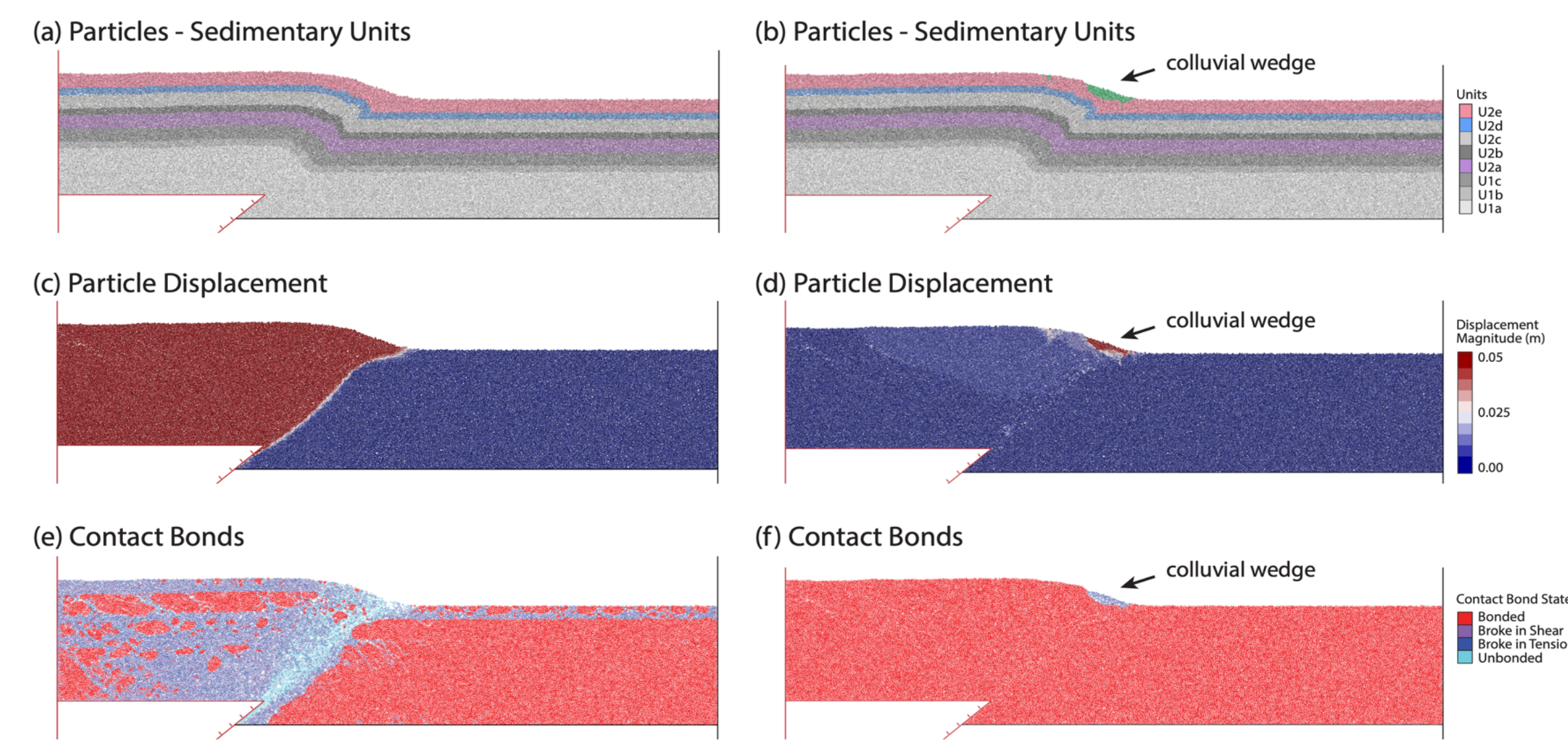
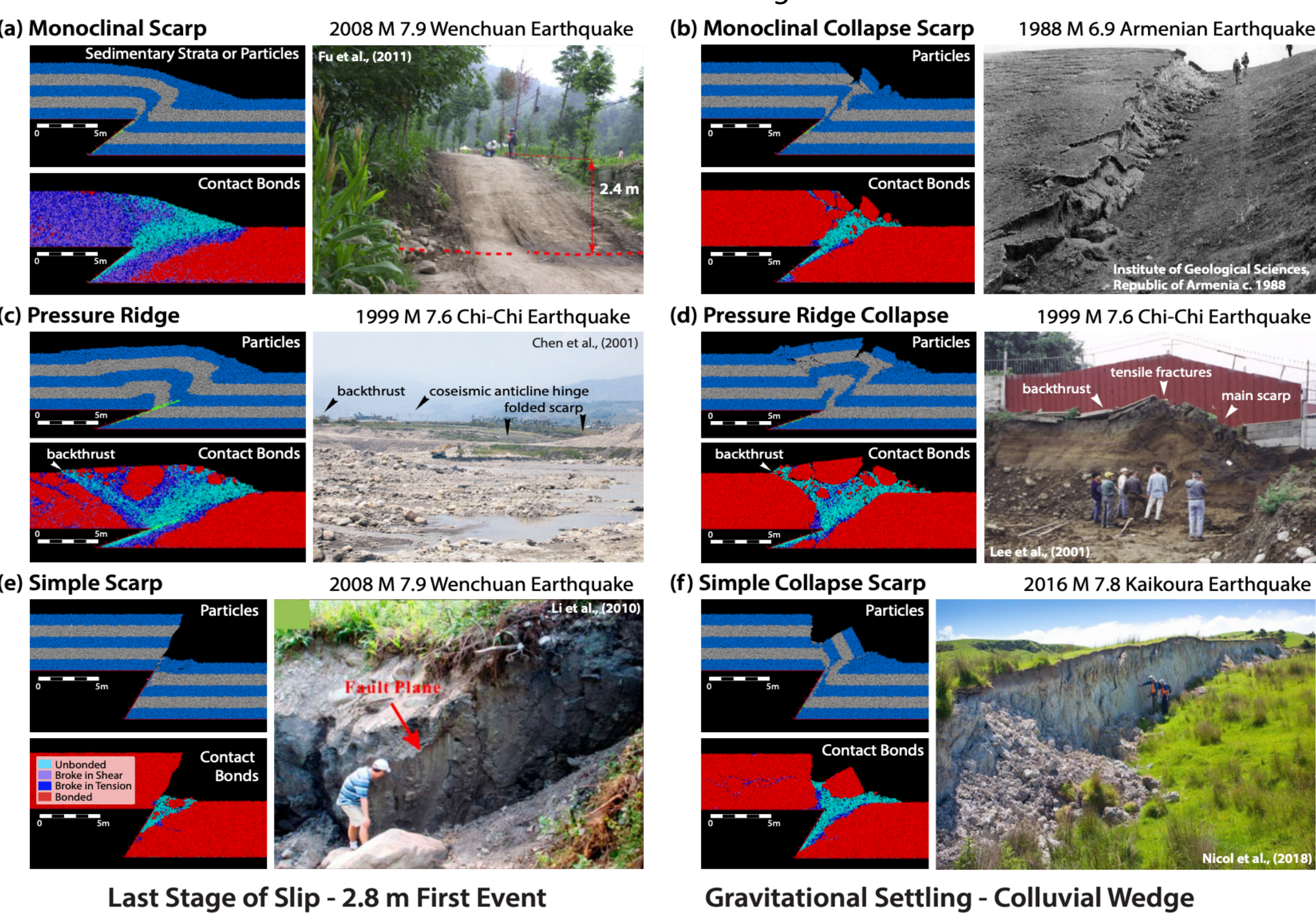


Figure 2 (middle): Previous work by Chiama et al. (2023) which identified a range of fault scarp morphologies based on different sediment strengths and fault dips.

Figure 3 (bottom): We can identify a colluvial wedge during gravitational settling after coseismic slip by tracking particle displacements. When the particles settle on the surface more than the smallest particle radii, they are grouped together and defined as a colluvial wedge.



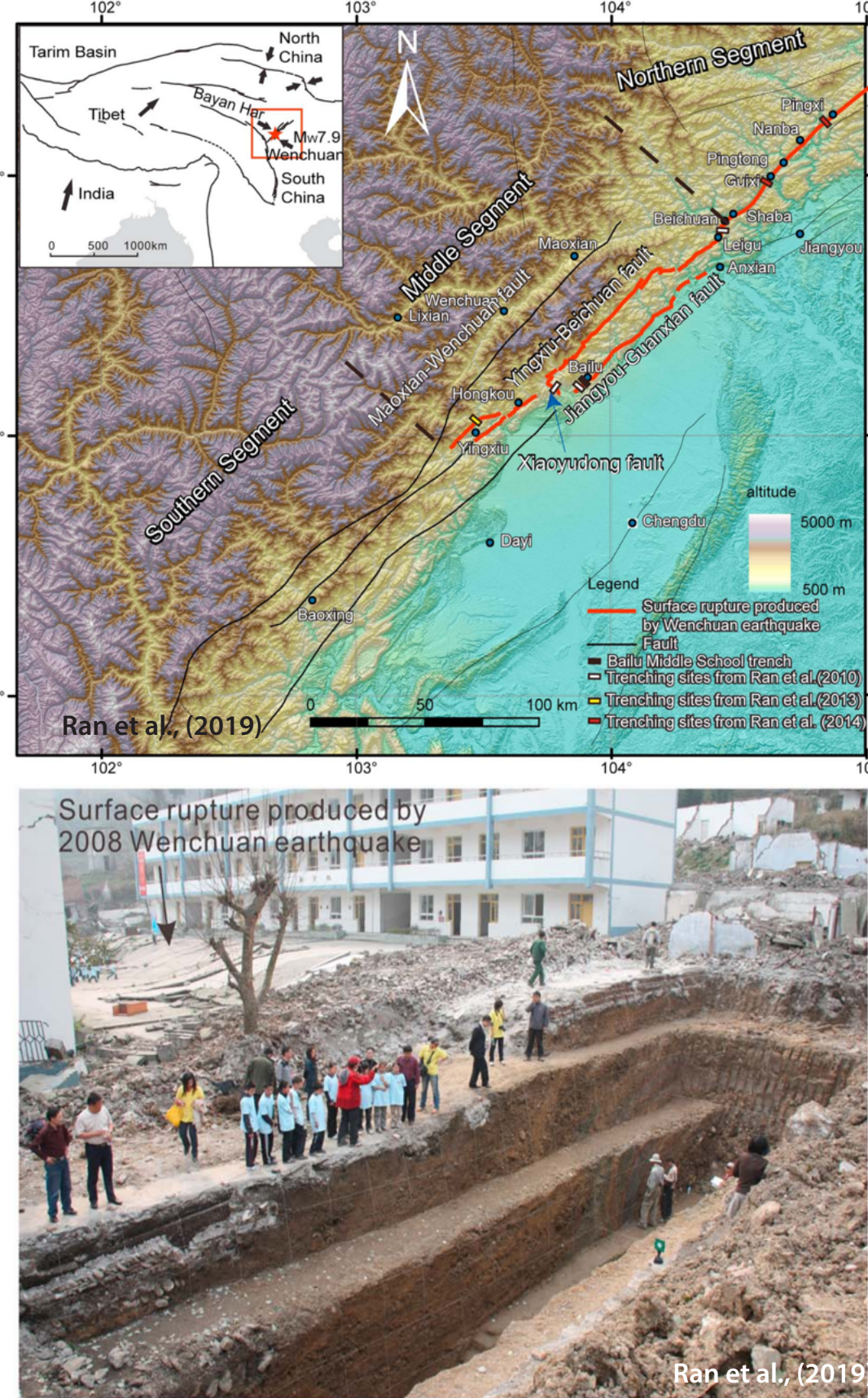
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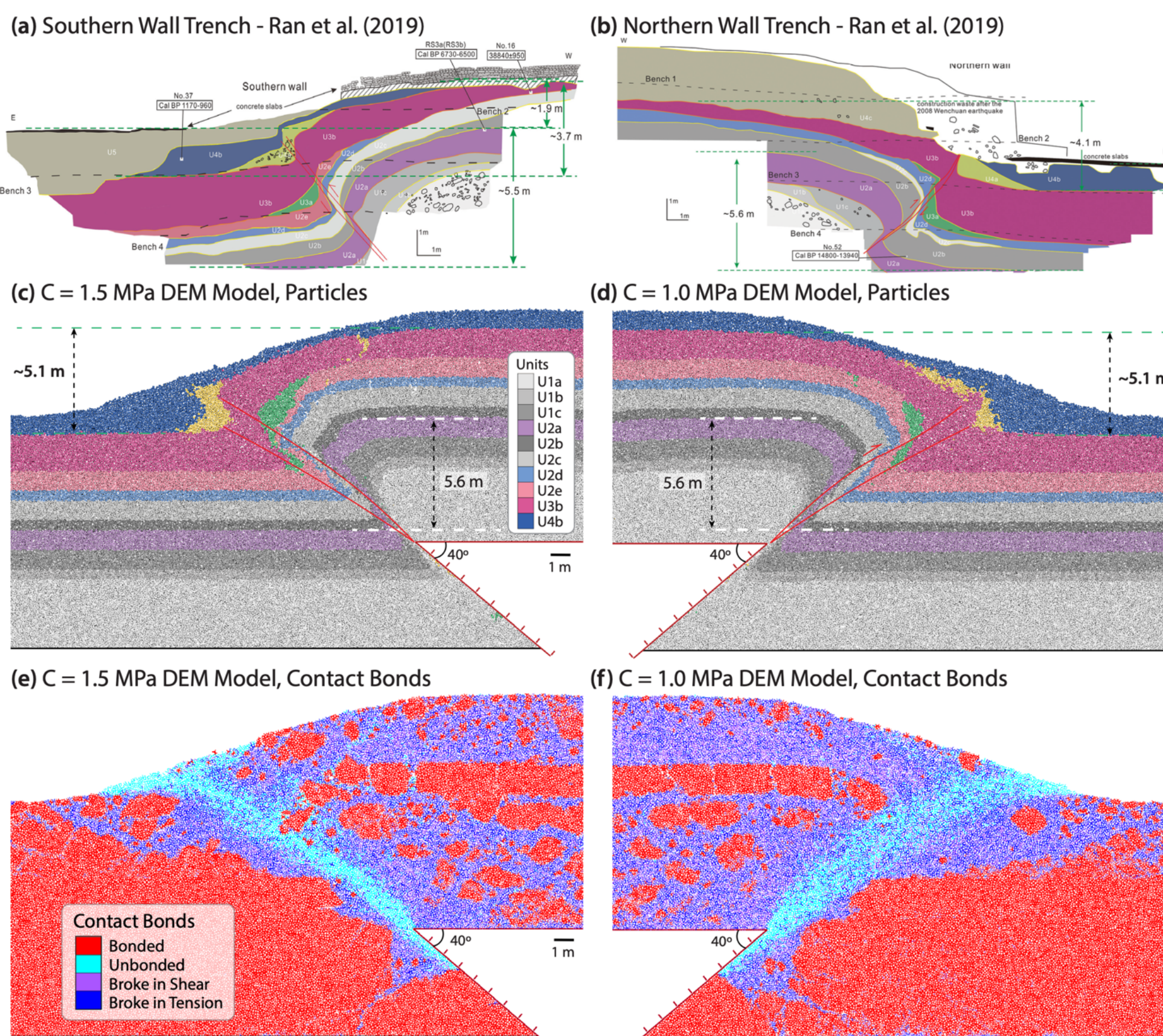
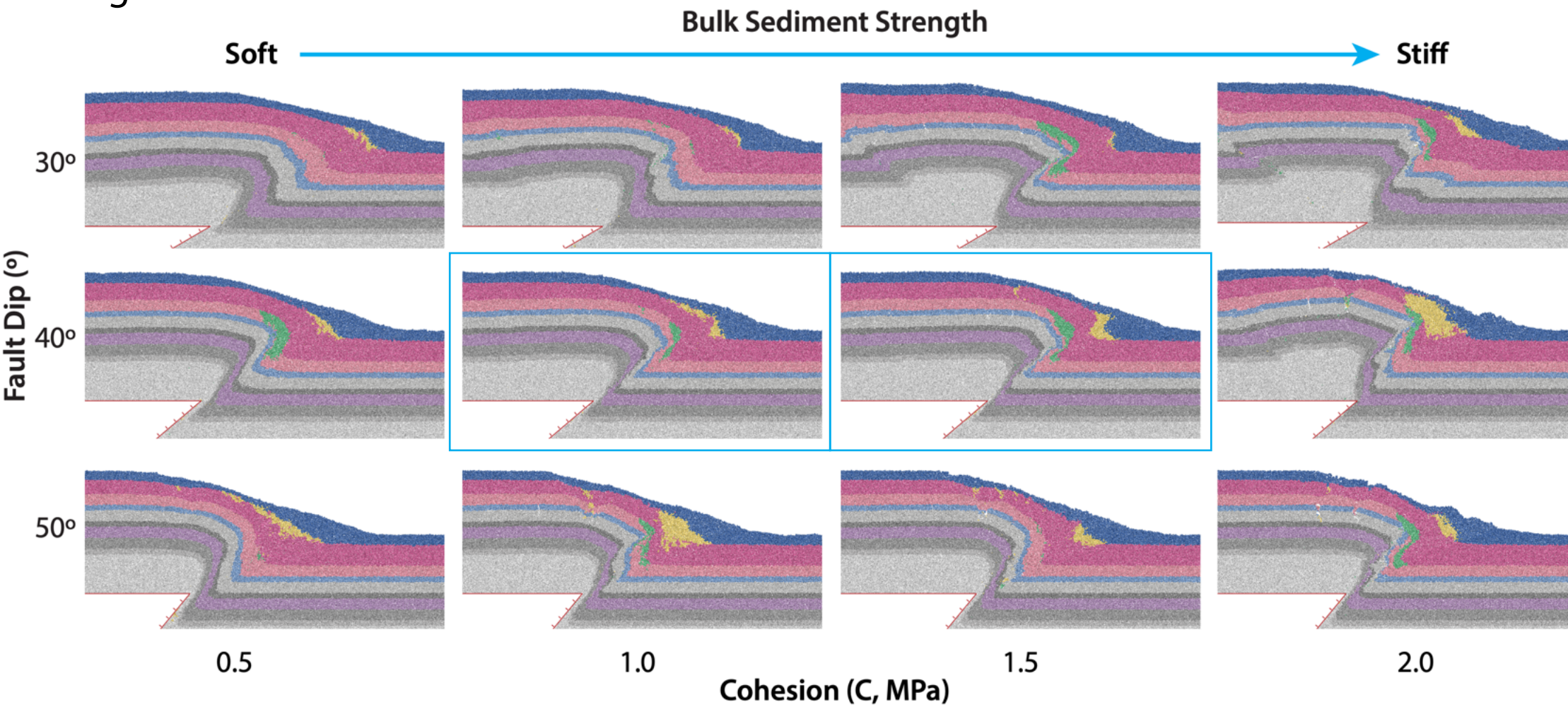
Results

2008 M 7.9 Wenchuan, China - Paleoseismic trench from Ran et al. (2019)

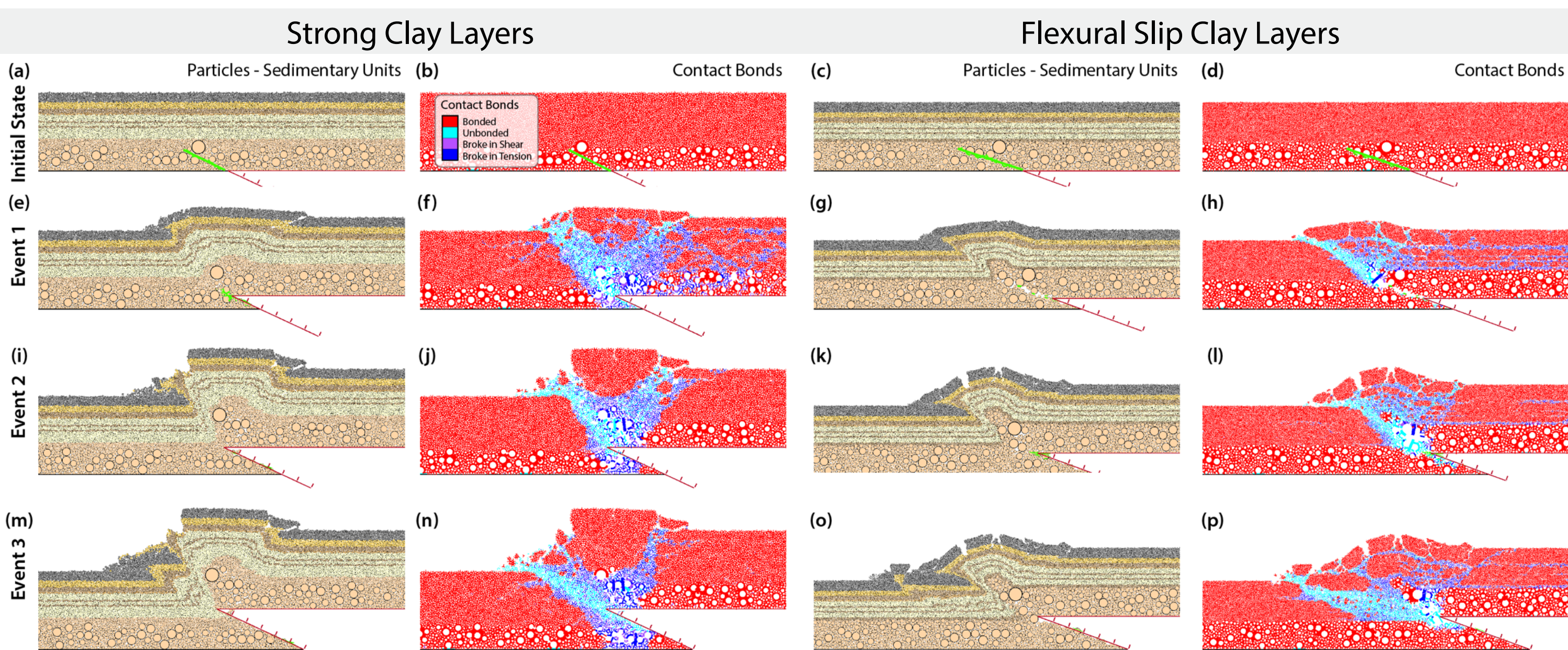


We modeled the paleoseismic trench from Ran et al., (2019) excavated after the 2008 M 7.9 earthquake in Wenchuan, China. We ran a series of experiments testing a range of fault dips and sediment strengths (below) and identified two key models that best reproduced the deformation geometries and colluvial wedge development between successive events shown on the right.

These models accumulate ~2.8 m of dip-slip on a 40° fault in moderate (1.0, 1.5 MPa cohesion contact bonds) strength sediment for a total of 3 events and produce two colluvial wedges by tracking particle displacements during gravitational settling after a coseismic slip event. Additionally, we deposited unit U3b and U4b after each successive event to replicate the trench site. These models show a dual fault splay originating from a master 40° fault at the base of the trench and generate similar vertical displacements and patterns of folding.

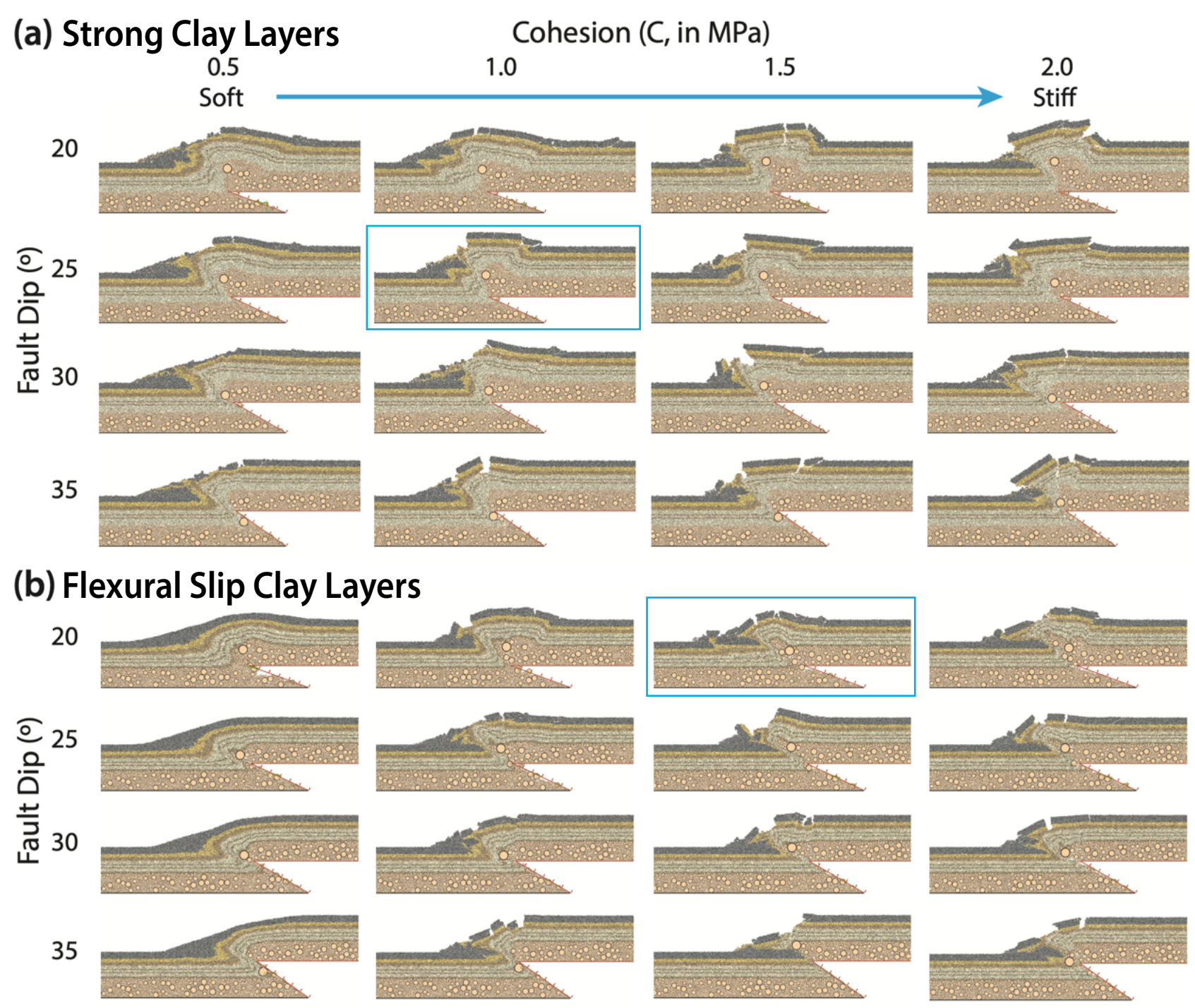


1999 M 7.6 Chi-Chi, Taiwan - Paleoseismic trench from Lee et al. (2001)



This trench site was excavated by Lee et al. (2001) after the 1999 M 7.6 Chi-Chi event formed a prominent backthrust and pressure ridge fault scarp (top left). This site expresses a 34° main fault that has a dual forethrust and a backthrust pinned to a large grain that yields folding and uplift. There are up to three events represented in this site with ~2.0 m of dip-slip in each event. Lee et al. (2001) postulated that the large grain in the center of the trench could be responsible for localizing the backthrust but were unsure of timing for the kinematic formation of features within the trench. We approached this model with two possible sediment types: (a) where the clay layers are strong and (b), where the clay layers are weak and provide flexural slip surfaces.

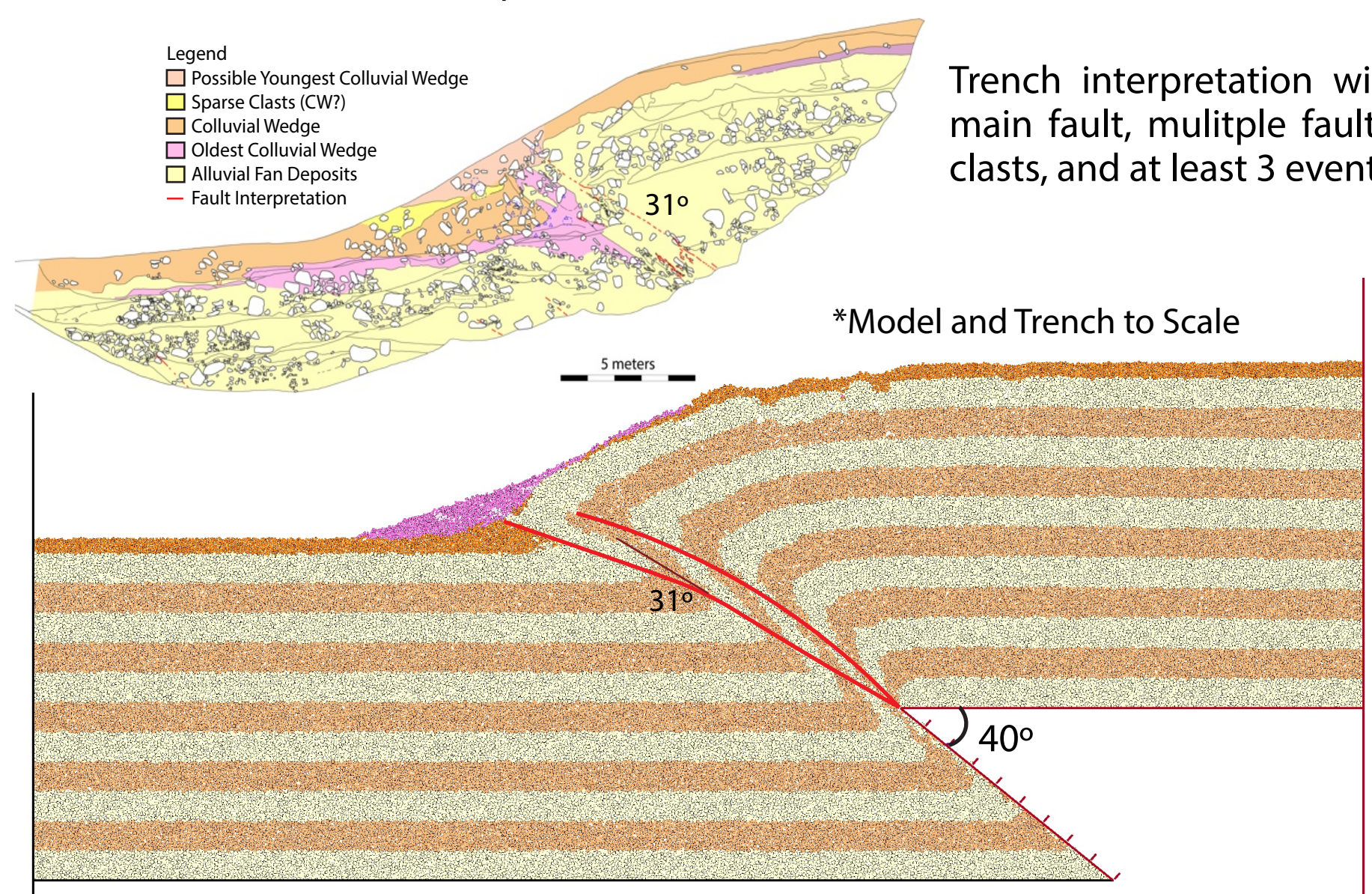
We evaluated a range of sediment strengths and heterogeneous grain sizes (including the one large grain) and fault dips for three events of 2.0 m of dip-slip per event (right) to identify two models that have similar geometric features from the Chi-Chi trench site (bottom left with event sequence). We find that both of these models reproduce the dual forethrust, backthrust, uplift and folding with slightly shallower fault dips.



Cucamonga Fault - Paleoseismic trench from Dolan et al. (1996) and Weigandt et al. (in prep.)



Fig. 9: (a) Map of Southern California, CFM 6.0 fault traces in white and Cucamonga fault in red. Yellow pin shows the trench site. (b) Field photo of the trench site from Dolan et al., (1996).



This model shows one, maybe two, potential colluvial wedges forming with three events representing 2 m, 4 m, and 3 m of slip for a total of 9 m of displacement above a 40° fault. We can represent multiple stacking colluvial wedges over a series of surface rupturing events when enough vertical displacement is accumulated in each event. This trench site is still a work in progress.

Discussion & Conclusions

- DEM models can effectively reproduce the fault geometry and patterns of deformation observed in paleoseismic trenches, including folding, uplift, multiple fault splays, backthrusts, and sequences of colluvial wedges.
- We developed a method of tracking particle displacements during gravitational settling between periods of coseismic slip to identify sequences of colluvial wedges.
- We can invert for precise displacements and dips of the fault zone at shallow depths to reproduce trench-scale observations.
- We can quantitatively relate these models to seismic sources and slip distributions at depth.
- Furthermore, we propose that insights from these models of trench-scale observations at these sites can inform forward modeling of ground surface rupture hazards in future earthquakes.