ON THE INTERACTION OF ACTIVE FAULTS AND BEDROCK LANDSLIDES

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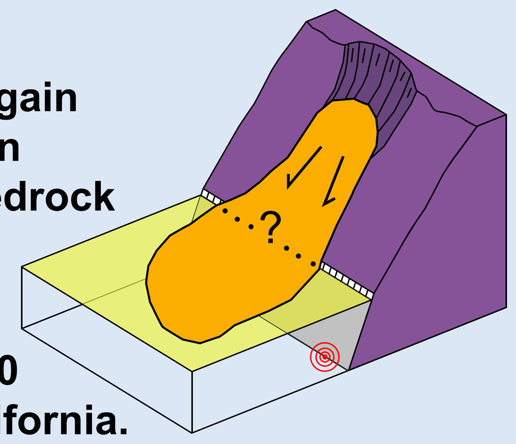
1. ABSTRACT

How do active faults regain their surface expression following burial by a bedrock landslide deposit?



This study presents 200 case studies in so. California.

A wide range of interactions are observed owing to the variations in fault properties (kinematics, geometry), deposit properties (thickness, width, rheology, type), cumulative slip since landslide event, substrate material, and preexisting fault surface expression.

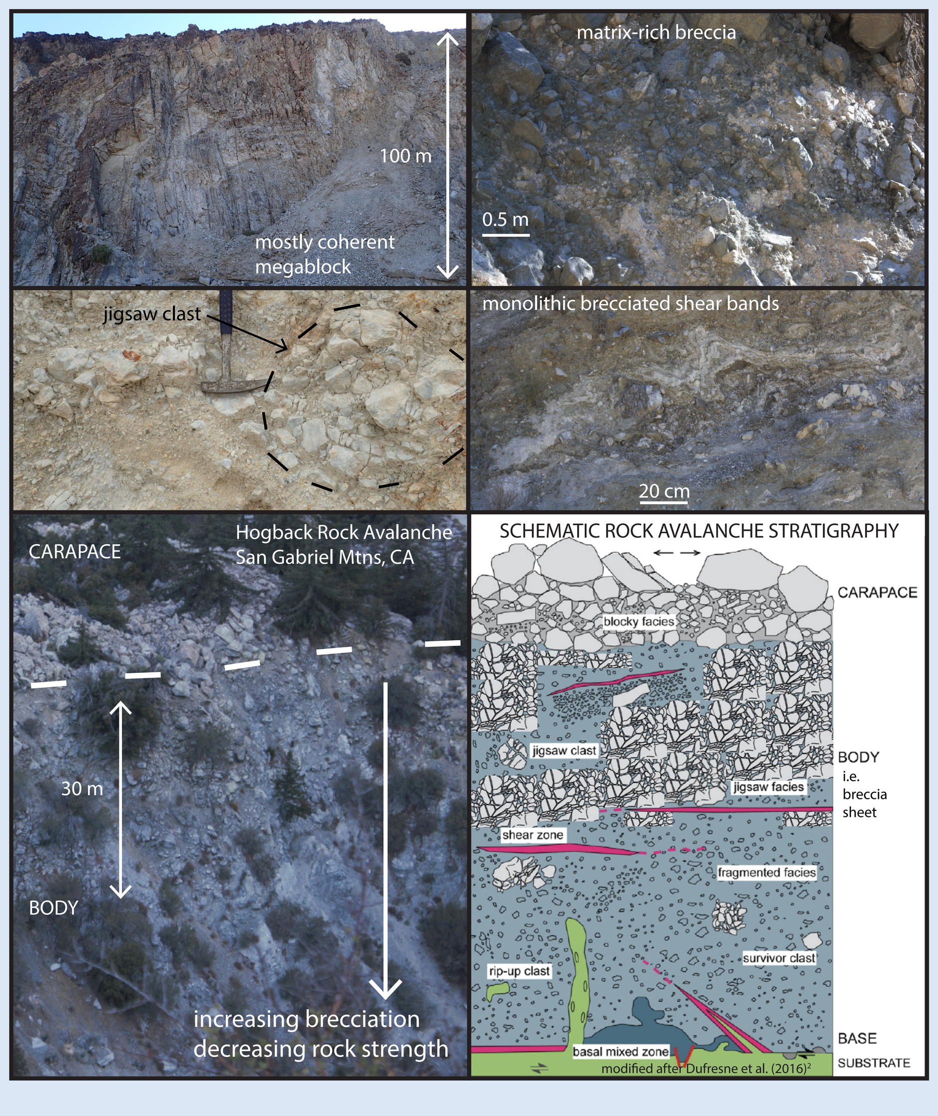
Generally, fault trace complexity is increased as earthquakes propagate upward and laterally through the landslide deposit to reestablish offset of Earth's free surface. In some cases faults remain "buried", slip apparently absorbed by the landslide deposit.

A simplified model is proposed in which fault dip and kinematics play a central role in expected behavior:
(1) Normal fault zones widen when they propagate through landslide deposits.
(2) Thrust fault zones may exploit the low-angle interface between sediment and overlying deposit to daylight at the landslide deposit's toe.
(3) Strike-slip fault zones can manifest as en echelon traces or surficial step-overs.

Thus, an improved understanding of the interactions between active faults and landslide deposits may require reinterpretation of fault traces, surface rupture hazard widths, recency of fault activity, and expected earthquake rupture lengths.

2. BACKGROUND

Active faults often create topography, reduce rock strength, and generate ground shaking that contribute to an abundance of co-located bedrock landslides. Landslides, particularly bedrock slumps and rock avalanches, can bury the surface expression of an active fault beneath a thick (often 50 m, up to 1 km) and laterally-extensive (often 1 km, sometimes >10km) deposit. Landslide transport reworks the existing bedrock mass containing organized planes of weakness (joints, foliations, faults, etc.) into a landslide deposit with new textures and rheology that may be resistant to fault rupture. Diagnostic textures include jigsaw breccia, matrix-rich breccia, monolithic brecciated shear bands, and mostly coherent "megablocks" in excess of 100 m across[1]. Deposits are commonly misinterpreted as bedrock, fault zone, or sediment depending on the quality of the exposure and facies.



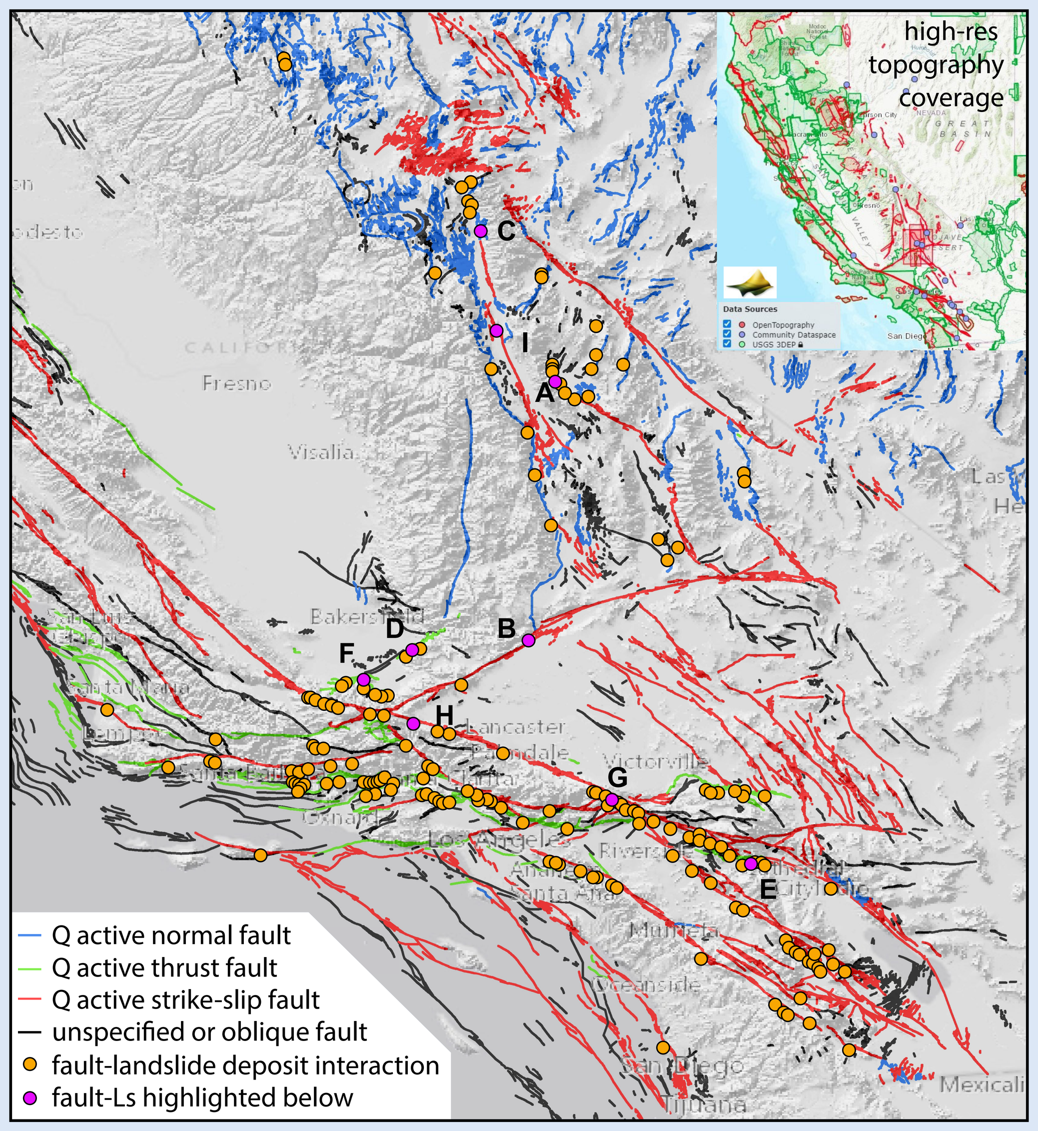
3. CASE STUDIES

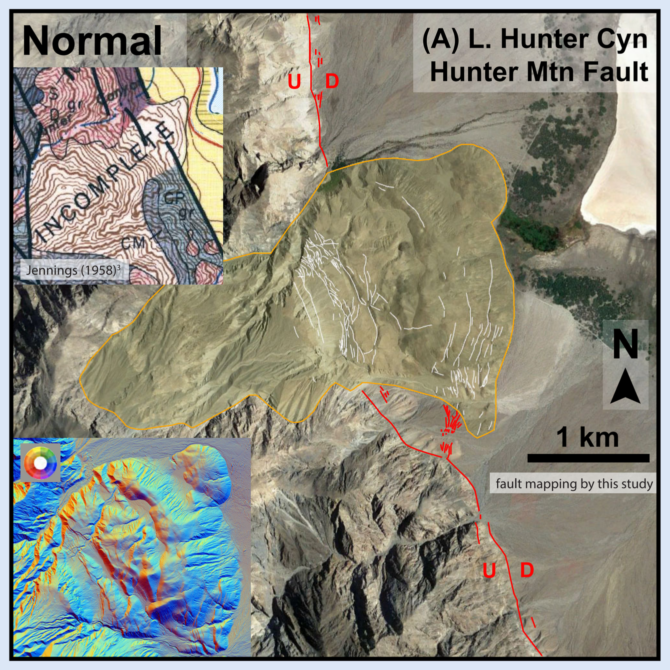
Southern California was chosen for study due to the range of active fault kinematics represented, abundance of existing data (maps, publications, slip rates, etc.), availability of high-resolution topographic data along active faults, and legal importance in classifying surficial fault zone complexity and activity.

The database was compiled from existing geologic maps (112), publications (25), and those introduced by this study (63). There can be considerable ambiguity in the geomorphic and geologic mapping of landslides and active faults, particularly since both can produce similar geomorphology (i.e. scarps) and rock textures (sheared and brecciated rock). Care was taken in providing a confidence rating system (high, moderate, low, speculative) for interpretations of individual case studies, with high confidence examples factoring more strongly into the simplified models presented.

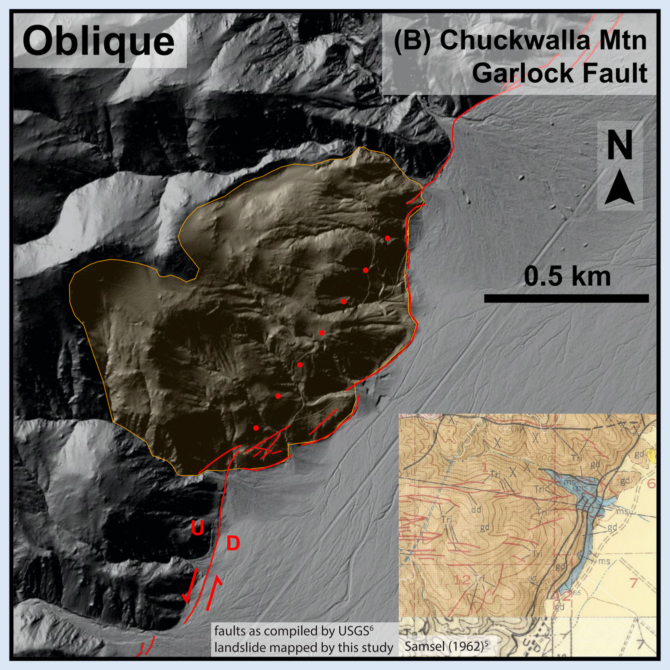
Many additional speculative landslides were identified in areas of high structural complexity, but not included in this compilation. More detailed fieldwork is warranted.

Surface rupture-landslide deposit interactions are found to be quite variable, but the examples below provide a good overview of typical behaviors.

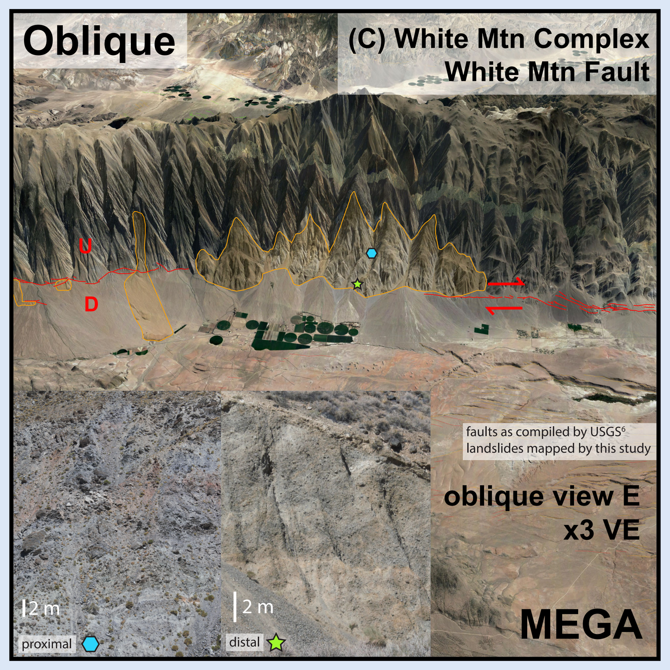




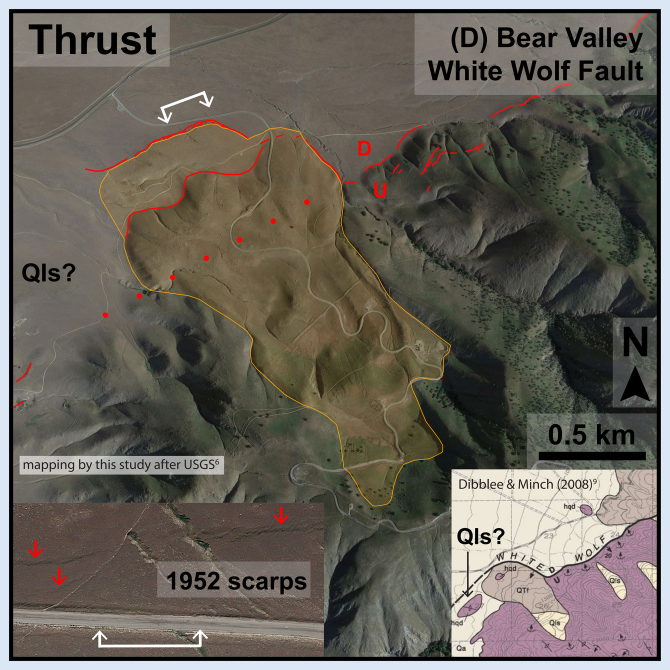
Many long runout rock avalanches occur along the steep rangefront of the Inyo Mtns facing Saline Valley. The deposit at Little Hunter Cyn is the most conspicuous and noted in multiple fault studies[4]. Fault traces are localized to the rangefront north and south; a complex >1 km-wide horst-and-graben system develops as the Hunter Mtn Fault propagates through the >200 m-thick deposit.



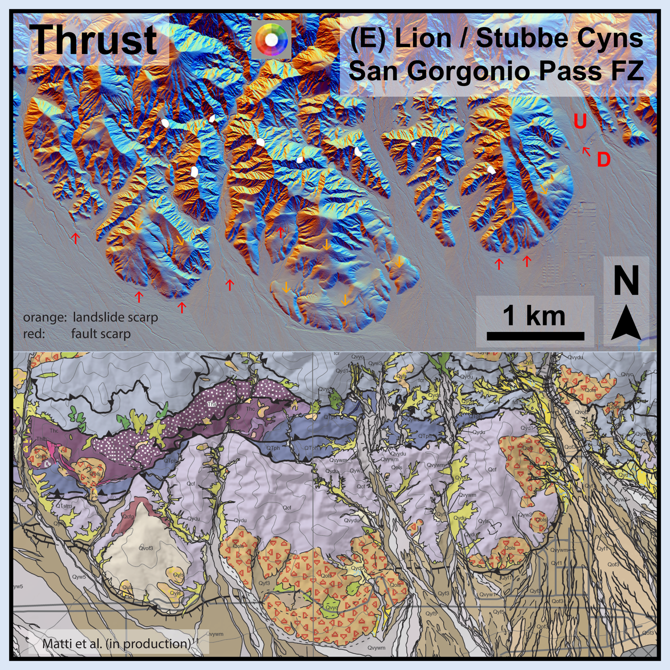
The left-lateral Garlock Fault deviates to a more northerly strike where it steps over from its western and central sections, seemingly accomodating a greater component of normal slip. Here a deep-seated bedrock slump appears to either force the fault expression basinward[6] or bury it. Rangefront sinuosity is increased.



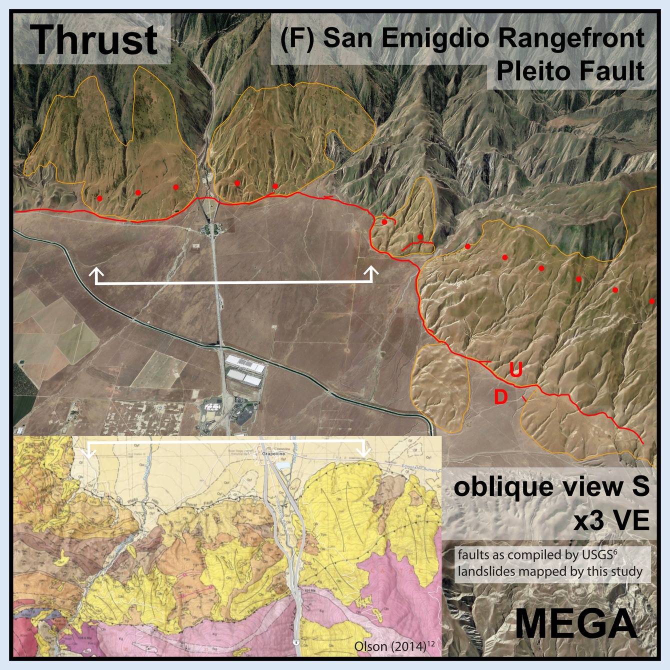
The White Mountain Fault is predicted by some to transfer 2-3 mm/yr of slip northward into the Mina deflection[7], yet there is a 15 km-long section of the rangefront that lacks evidence for latest Quaternary offset. "Normal faults" are instead mapped up the slope of the range[6] with a wide zone of "sheared rocks"[8]. This study suggests deep-seated collapse of the rangefront, which is supported by observed rock textures thoughout Jeffrey Mine Canyon.



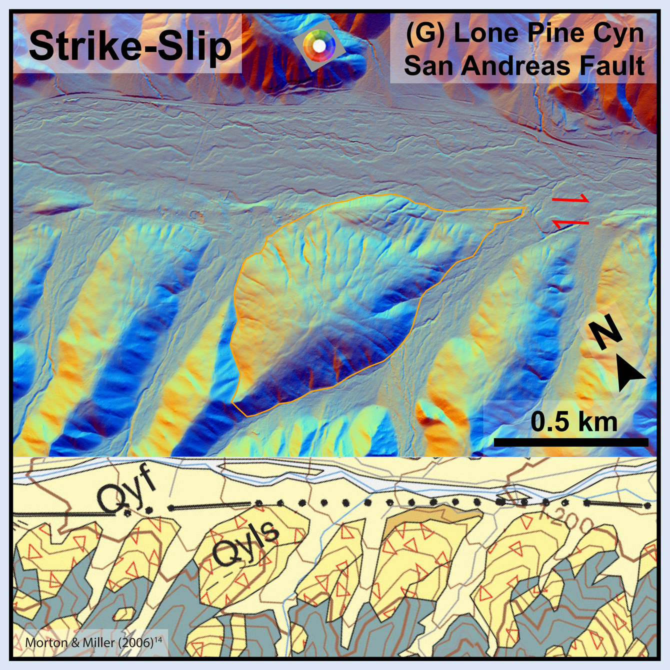
The 1952 Kern County Earthquake on the White Wolf Fault[10] provides a historic example of thrust rupture along the base of a rangefront that extends basin-ward following the toe of a ~50 m-thick landslide deposit. No rupture was observed within the deposit at the buried position of the fault, only near the toe.



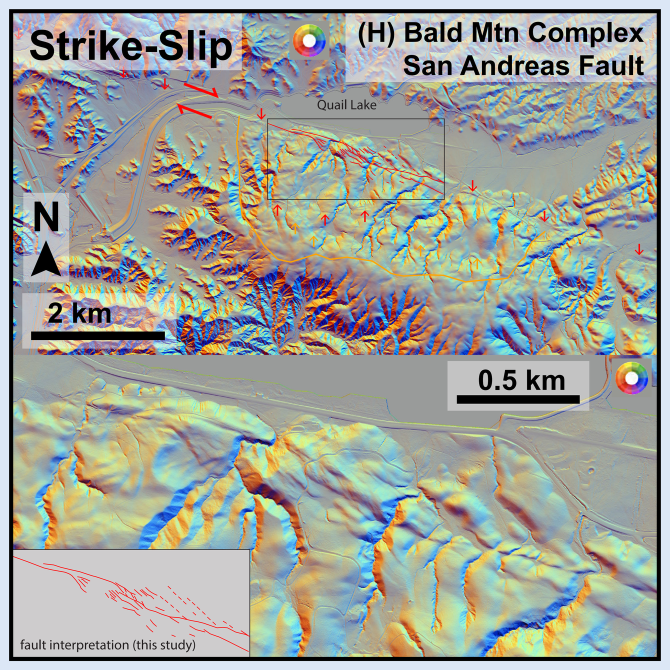
The sinuous rangefront trace of the eastern San Gorgonio Pass Fault Zone is partially a result of the fault propagating out of the toe of several landslide deposits. The geomorphically youngest landslide deposit (at lower center above) does not have an obvious fault scarp at its front, suggesting the fault is still buried beneath.



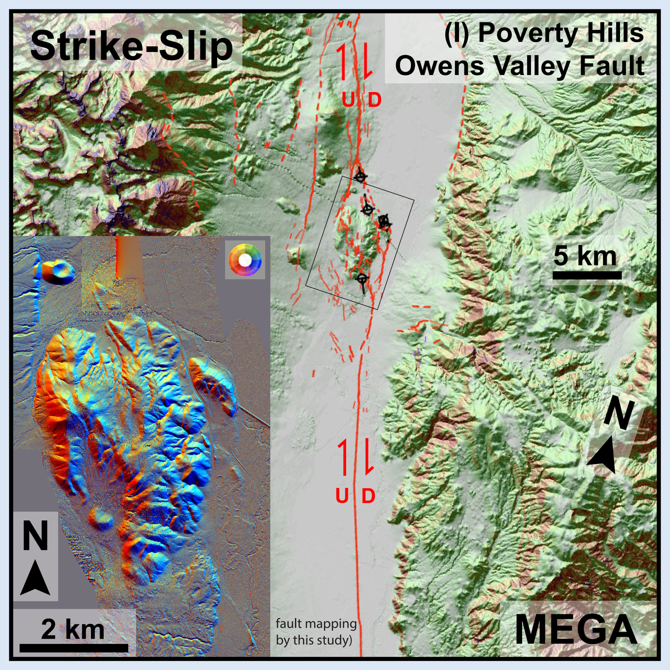
The Pleito and Wheeler Ridge fault systems both have highly sinuous traces at the base of the steep San Emigdio rangefront. Drainages and hummocky topography indicate a complex region of multi-generational landslides interspersed with bedrock outcrops. A "relic intermontane rangefront"[13] is present at the position of the Grapevine Fault that is co-located with many landslide headscarps.



In Lone Pine Canyon near Wrightwood, the Pelona Schist forms "flat blunt-nosed sagging ridges" due to radially spreading landslides[15] that bury the San Andreas Fault. En echelon fault traces develop within the landslide deposit to reestablish the fault position (example at center above) and the surface rupture zone widens. With progressive slip it is expected that a localized trace will develop (such as the shudder ridge at left above).



Bald Mountain has a complex series of multi-generational bedrock slump landslides that extend northward over the position of the San Andreas Fault[16]. In the off-landslide vicinty the surface rupture zone is typically <100 m wide. Within the landslide deposit multiple traces form a classic extensional duplex releasing bend as the fault dissects the landslide deposit's toe.



The Poverty Hills (PH) are well-studied and contain unambiguous rock avalanche textures throughout (though debate continues)[17]. The trace of the OV Fault is straight except within 12 km of PH. The 1872 OV Earthquake ruptured through this 4 km-wide stepover[18]. The interpretation presented here is that the OV Fault is straight and throughgoing beneath the PH and the observed dextral-normal flower structure is due to the OV Fault propagating through a very coherent >300 m-thick mass.

4. MODELS

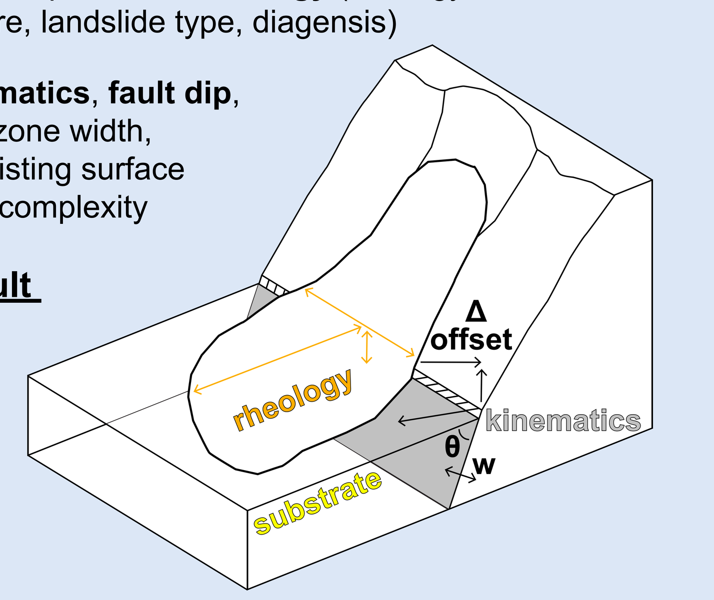
FACTORS AFFECTING INTERACTION

<u>Deposit</u> **thickness above fault**, distance along fault, distance past fault, **rheology** (lithology, texture, landslide type, diagensis)

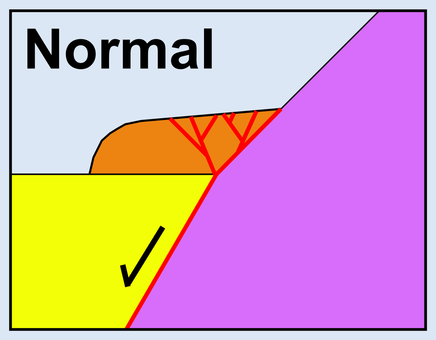
<u>Fault</u> **kinematics**, **fault dip**, fault zone width, preexisting surface trace complexity

<u>Cumulative Fault Slip Since Landslide Event</u>

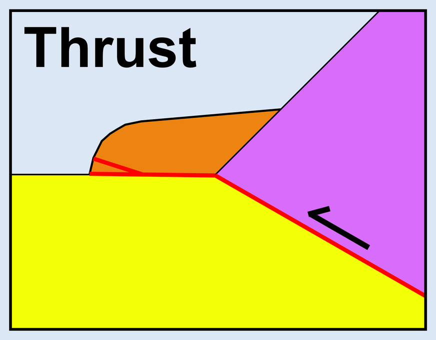
<u>Substrate</u>



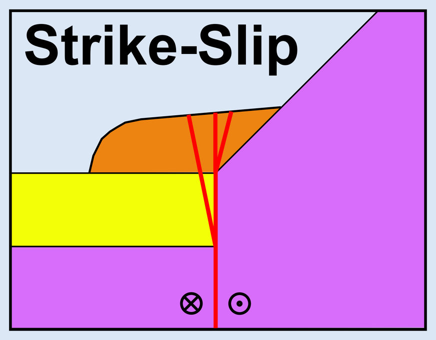
sediment: low strength, low cohesion
landslide deposit: moderate strength, moderate cohesion (closer to bedrock)
bedrock: high strength, high cohesion



Normal fault zones become a wider horst-and-graben surface rupture zone. Thick bedrock slumps appear to absorb slip completely or redistribute it through ambiguous deformation within the deposit.



Thrust fault zones exploit the low-angle strength contrast between sediment and overlying landslide deposit to daylight at the deposit's toe. Thick slides may lead to relic intermontane rangefronts or out-of-sequence thrusts.



Strike-slip fault zones manifest as en echelon traces, bend duplexes, or flower structures. Large deposits may lead to flower structures and/or multi-kilometer step-overs in the surficial fault trace.

5. DISCUSSION

Except in instances where fault traces appear buried, surface rupture complexity is generally increased when faults propagate through an overlying landslide deposit. Effects scale with the size of the landslide deposits. Areas of abnormal complexity along active faults may thus be worthwhile targets for reexamination, especially with the increasing availability of high-resolution topographic data.

Recognition of fault-landslide interactions may require reinterpretation of the recency of fault activity, fault position at depth, surface rupture hazard widths, and expected earthquake rupture lengths. Landslide deposits may have a rheology capable of absorbing or redistributing fault slip, warranting caution when using them for fault slip rate studies.

Mismapped landslides lead to incorrect assumptions of basin depth and total vertical offset across a rangefront. Landslide deposits buried in basin sediments may partially explain the abundance of rangeward-facing normal fault scarps observed in the Basin & Range. Some landslide basal planes are misinterpreted as low-angle normal faults. Some intermontane rangefronts may be driven by landslides, not tectonics. Some strike-slip shudder ridges are likely composed of landslide deposits, not fault rocks as commonly mapped.

More detailed study of landslide deposit rheology and modeling of surface rupture (e.g. using discrete element simulations) may inform observed behavior and how instances are likely to evolve.

The general observations presented are likely applicable to active faults worldwide with adjacent topography suitable to produce bedrock landslides. Go find the landslides!

1 Yarnold & Lombard (1989) archives.datapages.com/data/pac_sepm/079/079001/pdfs/9.htm
2 Dufresne et al. (2016) https://doi.org/10.1016/j.earscirev.2016.10.002
3 Jennings (1958) CDMG Geologic Map of California: Death Valley sheet
4 Oswald & Wesnousky (2002) https://doi.org/10.1016/S0169-555X(01)00089-7
5 Samsel (1962) CDMG Geology of the SE quarter of the Cross Mtn quad
6 USGS Q Fault & Fold Database (accessed 2022) usgs.gov/programs/earthquake-hazards/faults
7 DeLano et al. (2019) https://doi.org/10.1130/GES01636.1
8 Crowder & Sheridan (1972) USGS Geologic map of the White Mtn Peak quad
9 Dibblee & Minch (2008) DGF Geologic map of the Cummings Mtn & Tehachapi 12' quads
10 Buwalda & St Amand (1955) CA Div Mines Geological effects of the Arvin-Tehachapi EQ
11 Matti, Cox, Morton, Powell, Dudash, Kendrick, Mahan, Tinsley, Fuis, Rymer (in prod.) Geologic map of the San Gorgonio Pass region, Riverside and San Bernardino Counties, southern California: Advancing the legacy of Clarence R. Allen. USGS Sci Investigations Map, 2019 draft circulated among coauthors of Kendrick et al. (2022)
12 Olson (2014) CGS Prelim geologic map of the Grapevine 7.5' quad
13 Keller et al. (2000) https://doi.org/10.1130/0016-7606(2000)112<86:TGOAFO>2.0.CO;2
14 Morton & Miller (2006) https://pubs.usgs.gov/of/2006/1217/
15 Morton & Sadler (1989) IGS The failings of the Pelona Schist pg301-322
16 Olson & Swanson (2019) CGS Prelim geologic map of the La Liebre 7.5' quad
17 Bishop & Clements (2006) https://doi.org/10.2113/gseegeosci.12.4.301
18 Haddon et al. (2016) https://doi.org/10.1002/2015GC006033

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