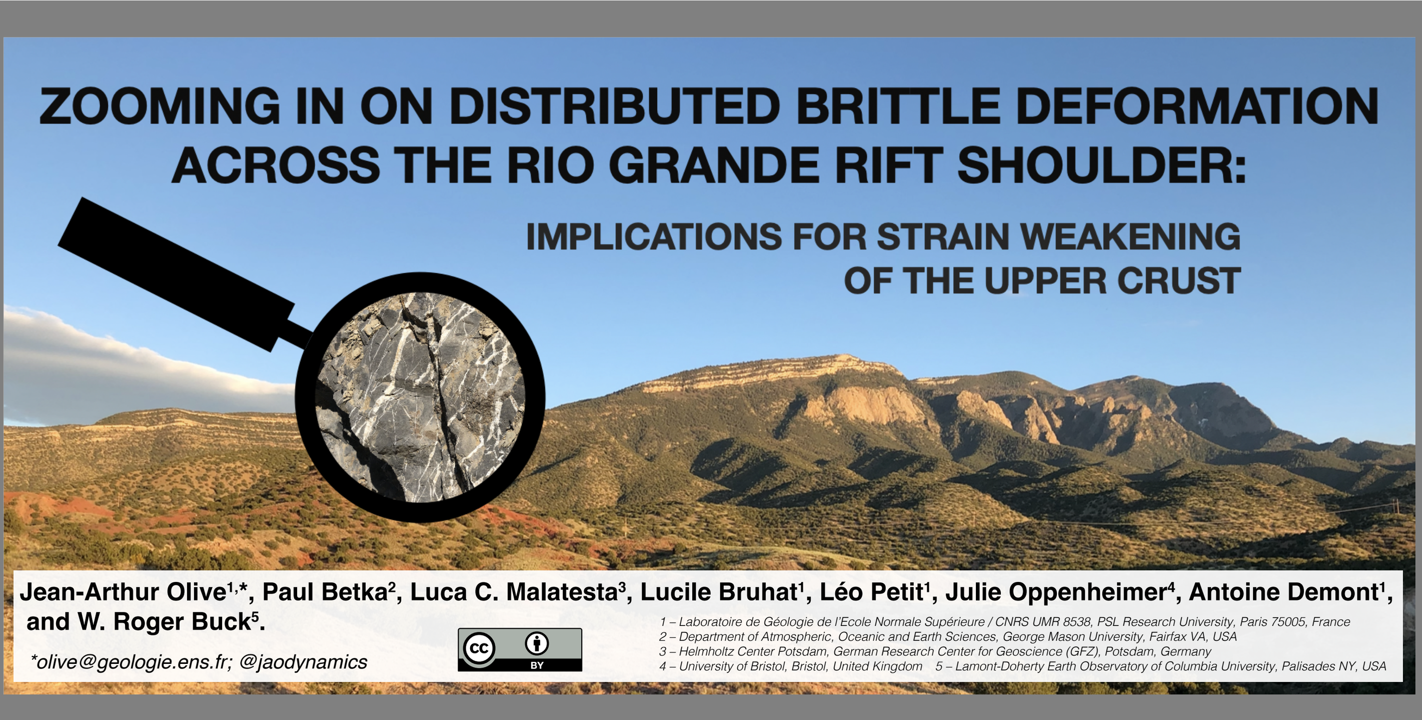

ZOOMING IN ON DISTRIBUTED BRITTLE DEFORMATION ACROSS THE RIO GRANDE RIFT SHOULDER:

IMPLICATIONS FOR STRAIN WEAKENING OF THE UPPER CRUST

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1. MOTIVATION

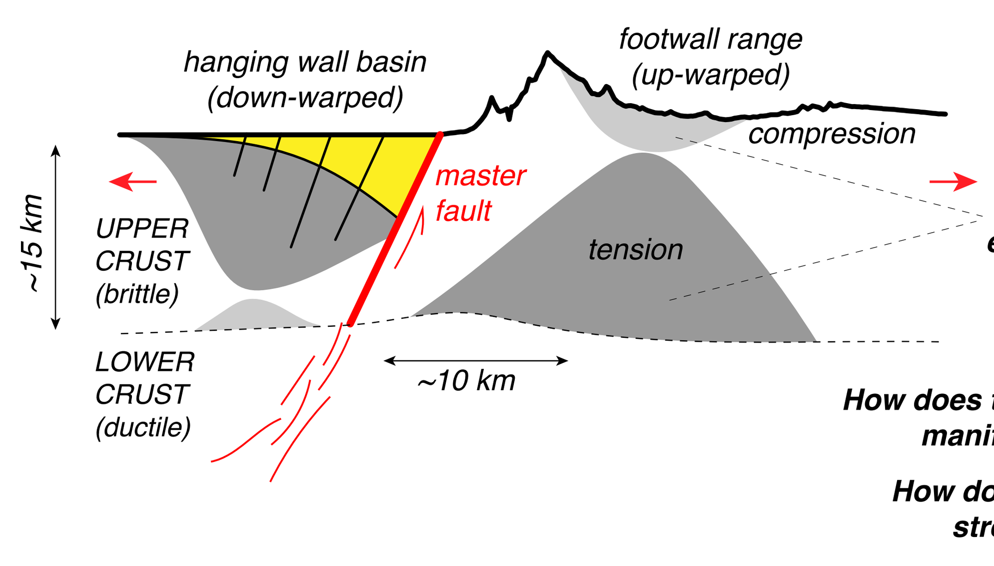
Strain localization (or lack thereof) in the **brittle upper crust** is a central question in tectonics.

An apparent paradox:
- **Faults** form when crustal stresses reach a **brittle yield stress**.
- Slip on a master fault **flexes** the adjacent crustal blocks, often **past their brittle limit**.
- Yet a master fault can accumulate large offsets without new master faults breaking in its footwall / hanging wall. → *brittle strain localization involves more than just reaching a stress threshold.*

What factors control whether brittle deformation remains distributed or localizes to form new faults? How do we best capture these processes in long-term tectonic simulations?

2. HALF-GRABENS AS "REAL SCALE DEFORMATION EXPERIMENTS"

Structurally-simple, moderately-sized settings, exhuming deep deformed units.



"plastic" regions where flexural stresses exceed brittle yield stress

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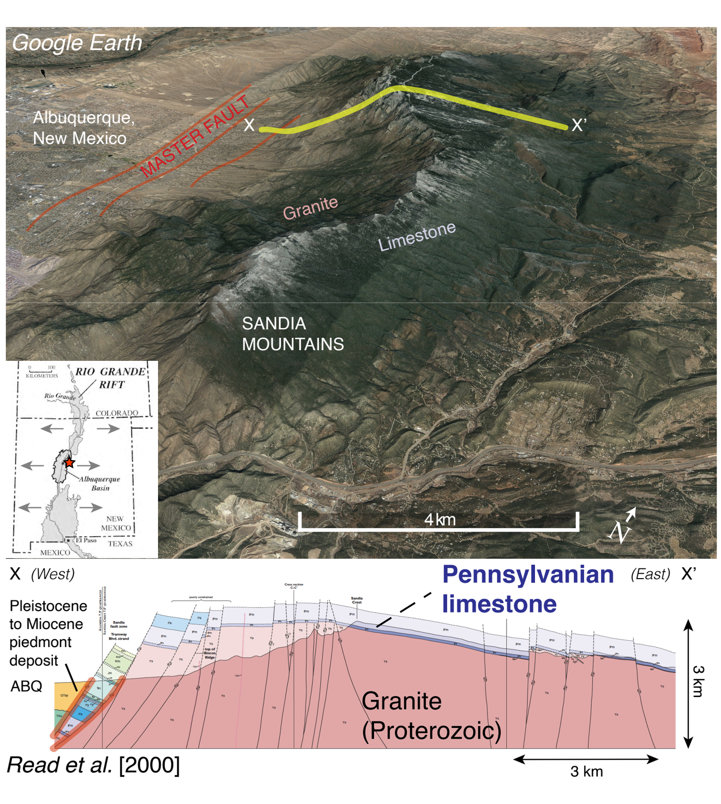
How does this inelastic brittle strain manifest at the outcrop scale?

How does it affect the integrated strength of the upper crust?

3. STUDY SITE: SANDIA HALF-GRABEN, RIO GRANDE RIFT, NEW MEXICO

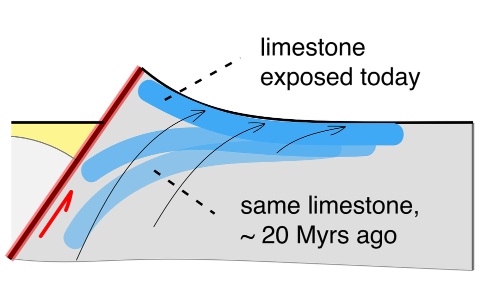


Why there?

E-W extension resulted in ~10 km of throw on W-dipping master fault system since ~20 Ma, uplift of Sandia Mountains.

Little relief and moderate deformation (e.g., Laramide compression) prior to rifting. [*Abbott et al.*, 1995; *Karlstrom et al.*, 1999]

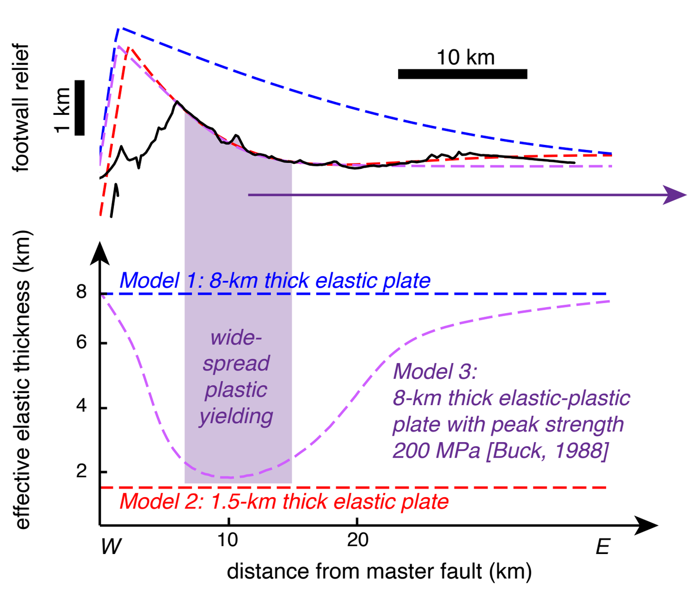
Widespread exposure of **Pennsylvanian limestone** up-warped with footwall block, initially buried at > 3 km [*House et al.*, 2003].



A unique setting to study the mechanisms of brittle flexure across scales.

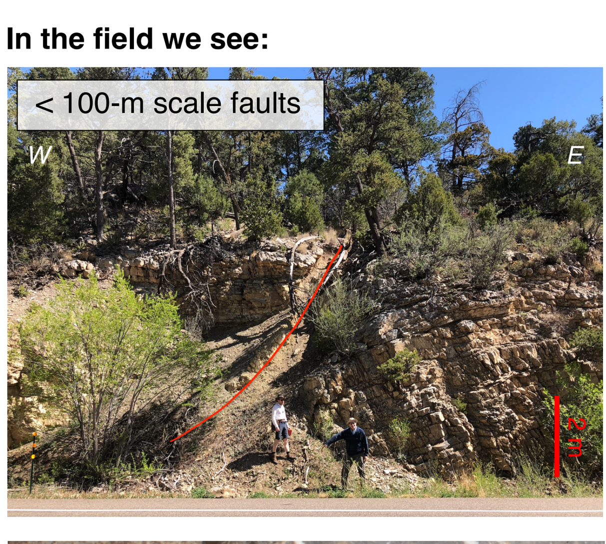
4. INELASTIC FOOTWALL FLEXURE, FROM KILOMETERS TO MILLIMETERS

10-km scale up-warping of the Sandia Mountains consistent with flexure of a low-rigidity elastic upper-crust, or better yet: an **elasto-plastic** upper crust [e.g., *Hassani & Chéry*, 1996].

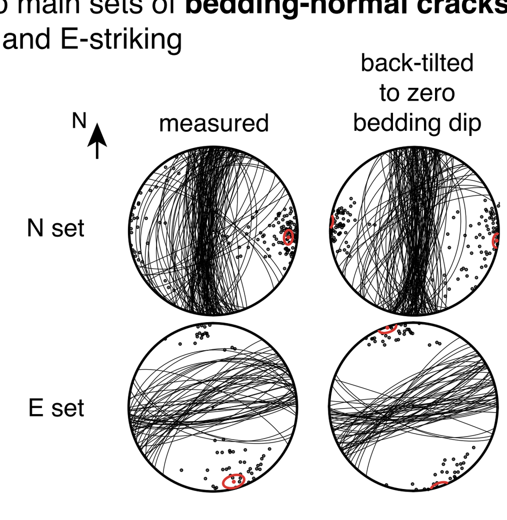


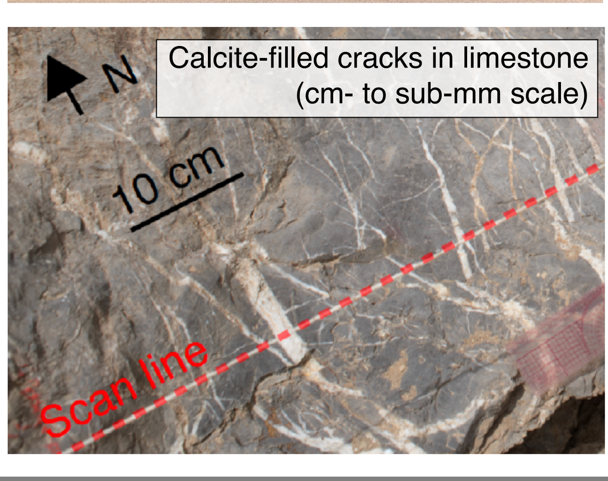
Suggests a region of distributed inelastic deformation ~10 km from master fault ("hinge" of flexure)

In the field we see:



Two main sets of **bedding-normal cracks**: N- and E-striking



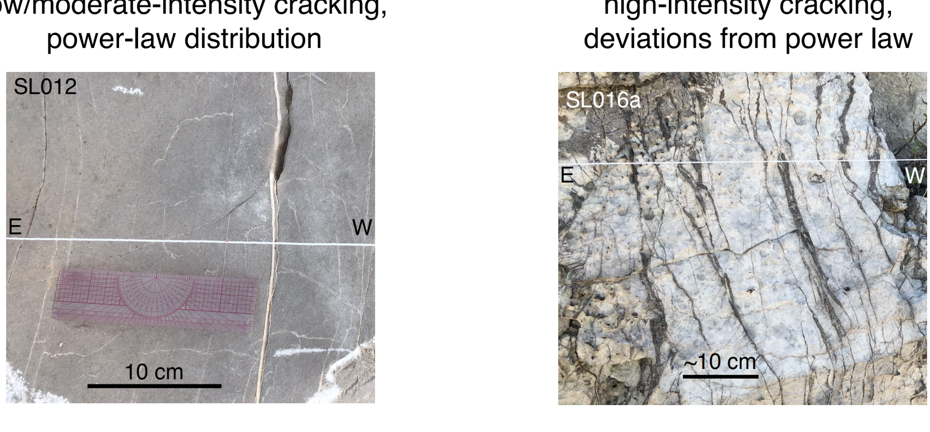


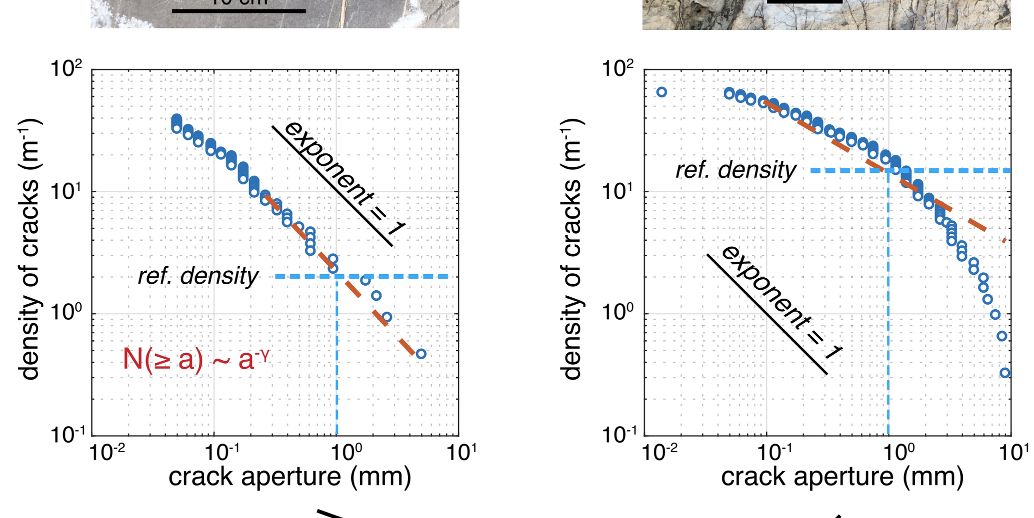
5. DISTRIBUTION OF FRACTURES ACROSS THE SANDIA FOOTWALL

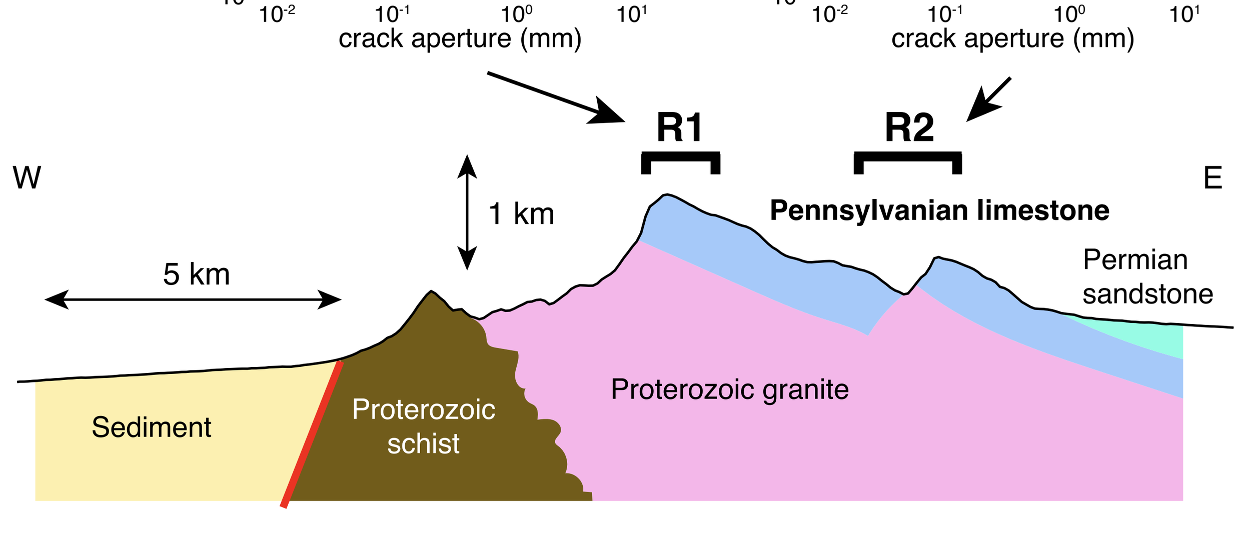
Distribution of crack apertures measured along fracture-normal scan lines following *Ortega* [2006].

Region 1 (near Sandia crest): low/moderate-intensity cracking, power-law distribution

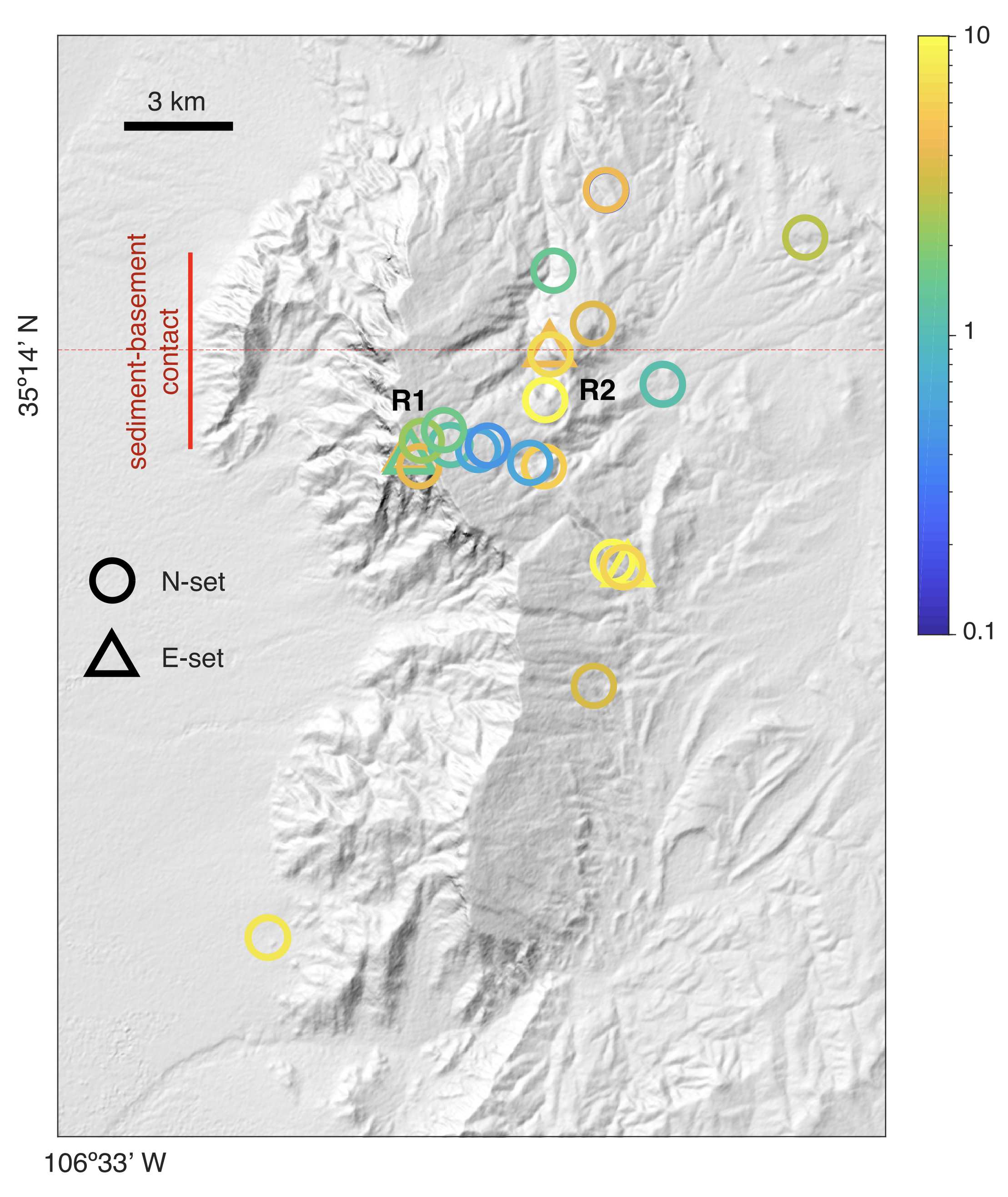
Region 2: high-intensity cracking, deviations from power law



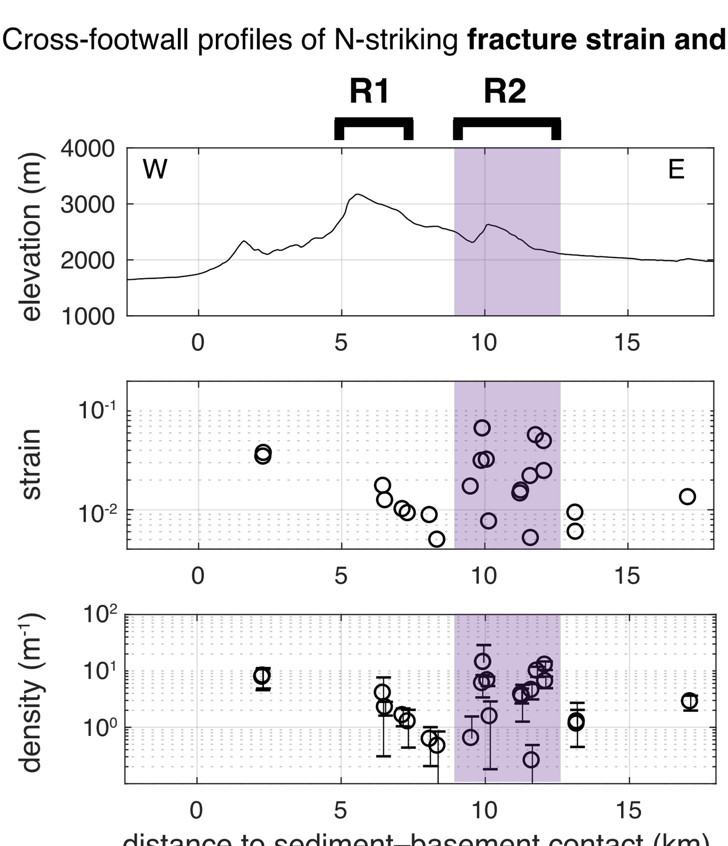




Map of measured N-striking **crack density** (in m^{-1}, for reference aperture of 1 mm):



Cross-footwall profiles of N-striking **fracture strain and density**:



"**Plastic hinge**" of footwall flexure (region 2) characterized by:

- high density of N-striking fractures with deviations from power law distribution, acommodating strains > 3%.
- < 100-m scale normal faults.
- structures mostly consistent with E-W extension, little evidence for E-W compression expected in shallow parts of up-warped footwall.

What does this pattern of distributed cracking tell us about brittle flexure and the effective strength of the upper crust?

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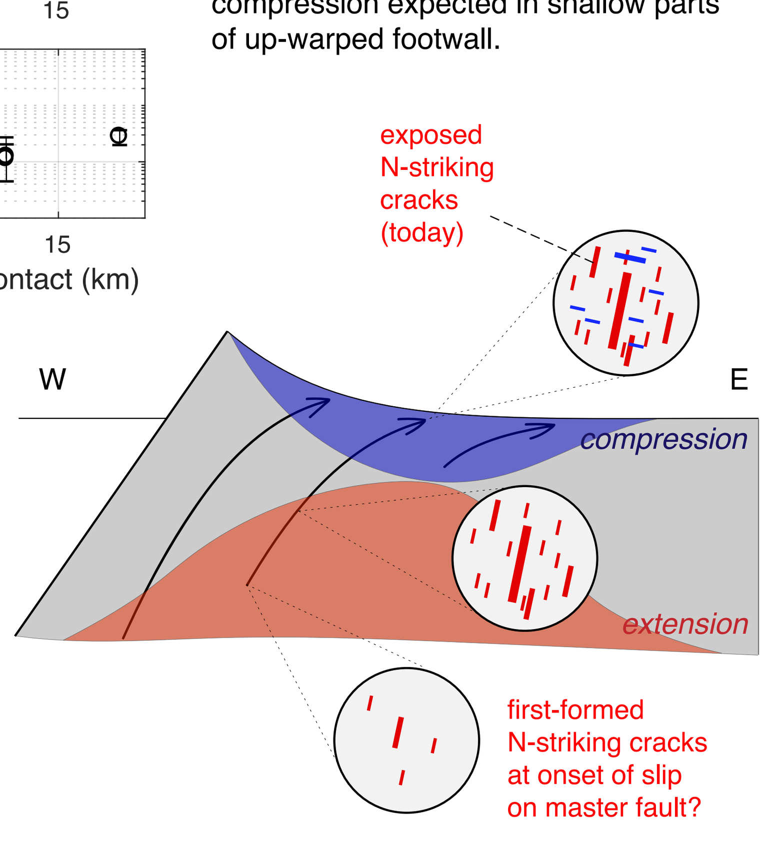
Comparison with numerical models of visco-elasto-plastic deformation in normal fault footwalls.



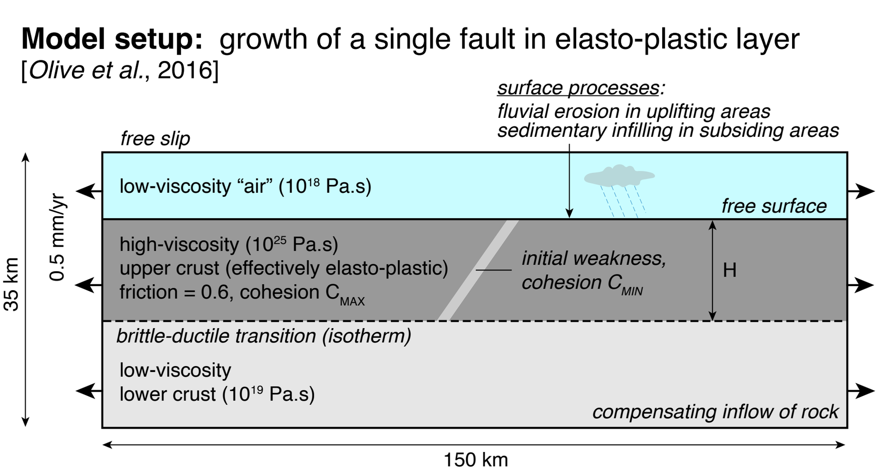
6. CONSTRAINING TECTONIC MODELS WITH OUTCROP-SCALE MEASUREMENTS

Standard visco-elasto-plastic geodynamic models keep track of **plastic strain** accumulated in brittle regions, wherever stresses have reached a Drucker-Prager yield stress.

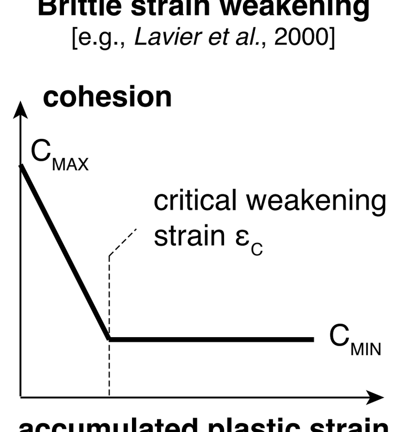
Focus is usually on plastic strain localized within **shear bands**, representing faults in a continuum.

Here we investigate **non-localized plastic strain and what it can tell us about crustal strength**.

Model setup: growth of a single fault in elasto-plastic layer [*Olive et al.*, 2016]

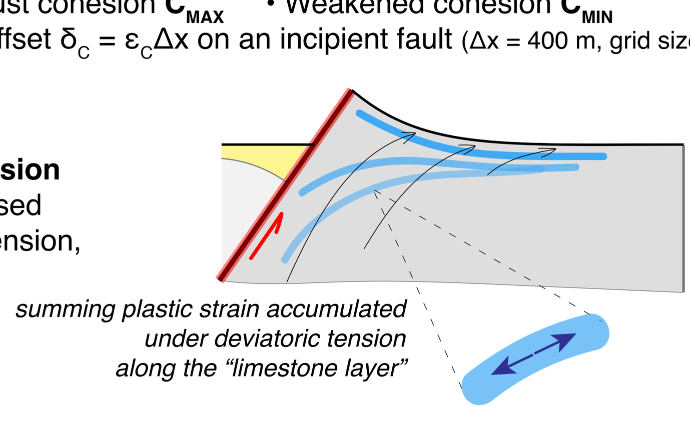


Brittle strain weakening [e.g., *Lavier et al.*, 2000]

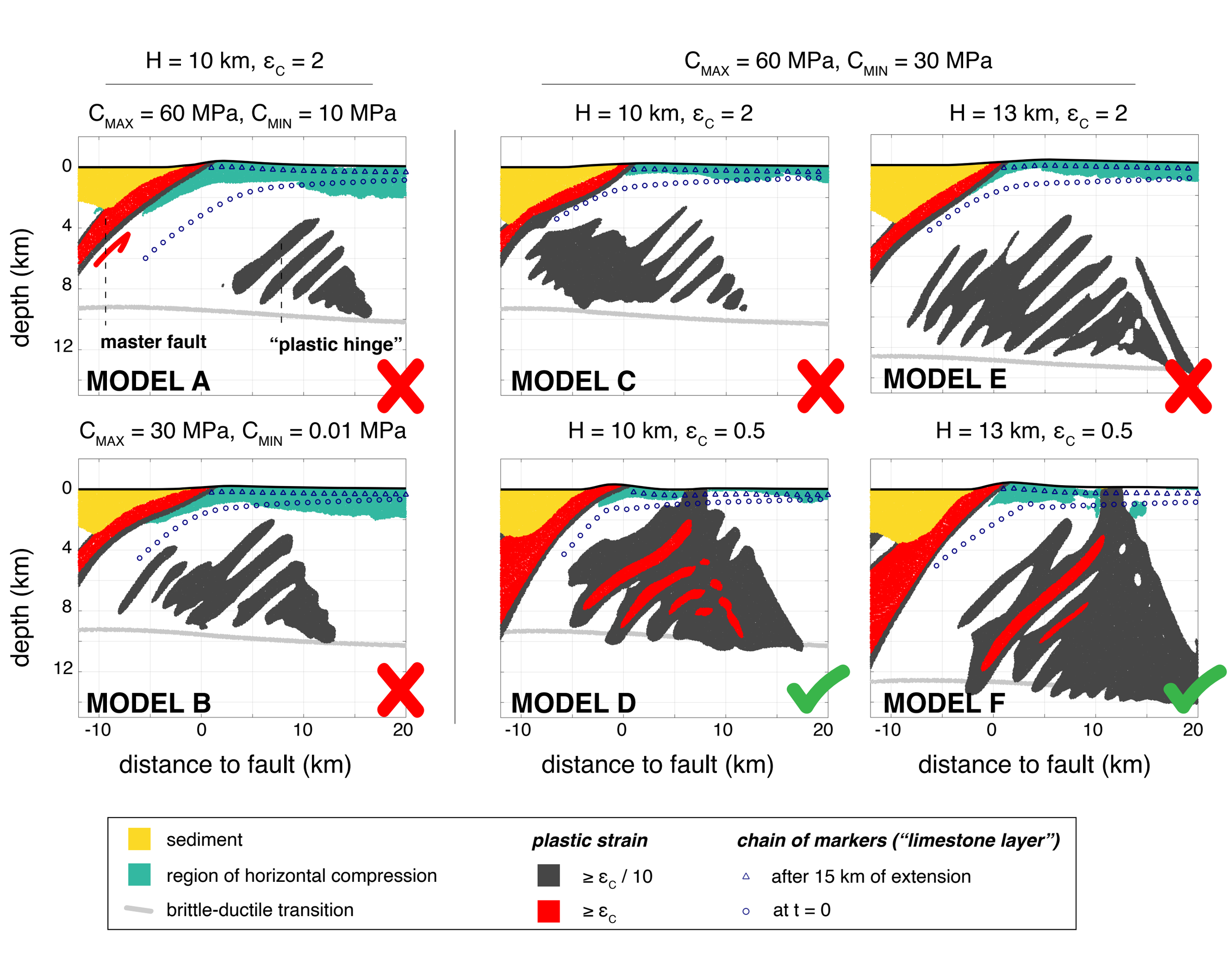


Parameters varied:
- Thickness of brittle upper crust **H** • Intact crust cohesion $\mathbf{C_{MAX}}$ • Weakened cohesion $\mathbf{C_{MIN}}$
- **Critical weakening strain ε_c**, equivalent to offset $\delta_C = \varepsilon_C \Delta x$ on an incipient fault (Δx = 400 m, grid size)

Outputs of interest:
- Topography
- **Non-recoverable strain accumulated in tension** along a string of markers which ends up exposed along the free surface after 15 km of total extension, representing the Sandia limestone.



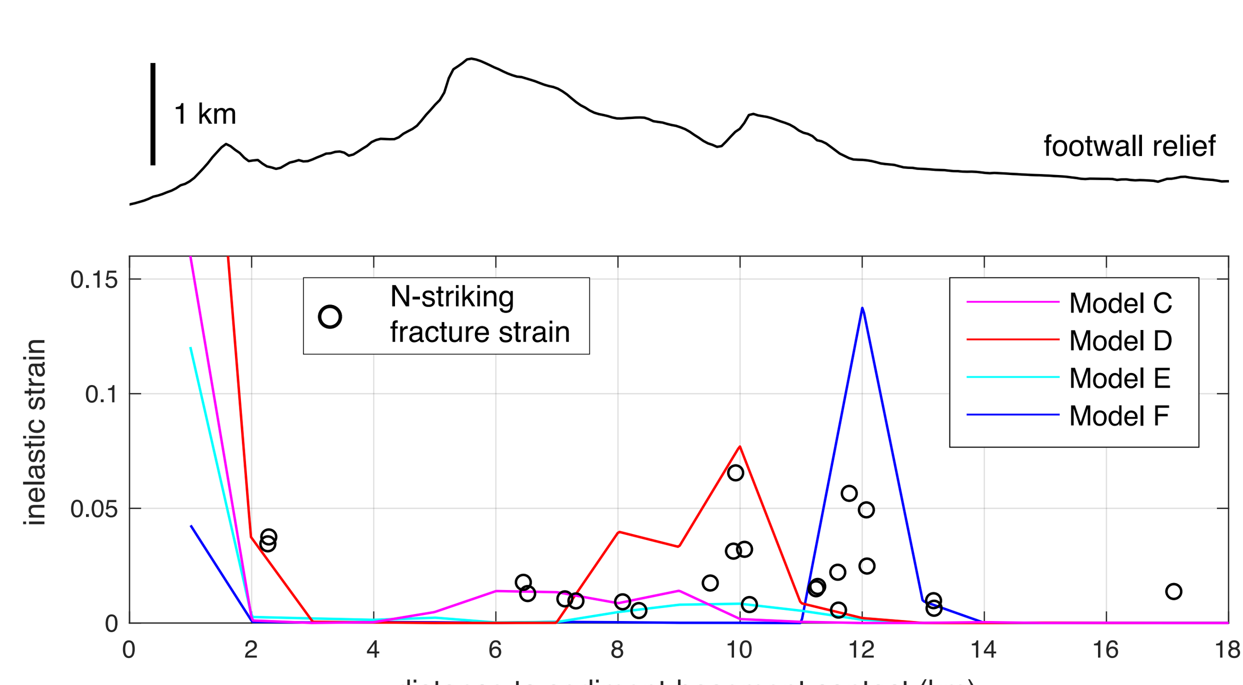
Footwall cross-sections after 15 km of total applied extension:



Discarded models:
- C_{MIN} too low (models A & B) leads to little deviatoric extension in footwall block = strong shallow compression, no resolvable plastic extension in "limestone".
- ε_C too high (models C & E) fails to build up enough extensional plastic strain in limestone layer.

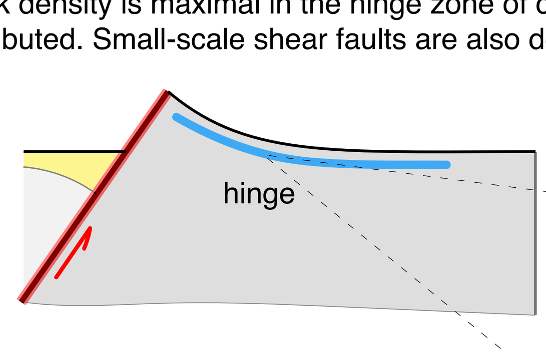
Valid models (D & F)**:** ε_C = 0.5, high residual strength on master fault (C_{MIN} = 30 MPa), true thickness of brittle upper crust between 10 and 13 km.

Successful models predict location and magnitude of high brittle strain in flexural hinge:

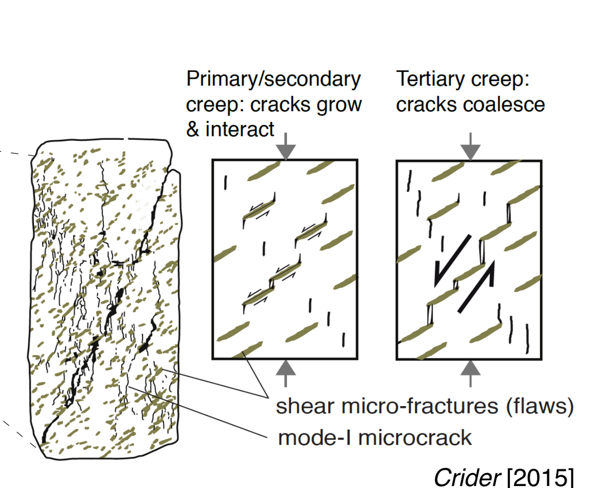


7. WHAT DID WE LEARN ?

- **Low effective rigidity** of normal fault footwalls [e.g., *Armijo et al.*, 1996; *Anders et al.*, 1993] directly stems from the build-up of compressional and tensile **inelastic brittle strain** during warping [e.g., *Buck*, 1988; *Hassani & Chéry*, 1996].
- Non-recoverable, distributed brittle strain manifests as **pervasive tensile cracking** (sub-mm to cm-scale) following a power law distribution of exponent ~1.
- Crack density is maximal in the hinge zone of crustal flexure, where fractures are no longer power-law distributed. Small-scale shear faults are also documented in this area.



- This can be interpreted as **tensile cracks growing and coalescing** into new shear faults, as is routinely observed in deformation experiments.



Crider [2015]

- The standard modeling approach of **weakening the brittle yield strength with accumulated plastic strain** can be viewed as a parameterization of this process, where the **weakening strain contains information on the rate of tensile crack growth**.
- **Outcrop-scale measurements of inelastic strain can be used to calibrate** parameterizations of brittle strain weakening.
- Adequate description of brittle yielding must account for dilatancy, and allow straightforward micromechanical interpretation**.**

ACKNOWLEDGEMENTS

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