PS Pre-existing Zones of Weakness: An Experimental Study of Their Influence on the Development of Extensional Faults*

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Abstract

We use scaled experimental (analog) models to investigate how the properties of pre-existing zones of weakness influence deformation patterns during extension. In the models, a homogeneous layer of wet clay (simulating brittle rock) undergoes two phases of extension whose directions differ by 45°. To vary the properties of the first-phase fault fabric, we vary the magnitude of the first-phase extension. Specifically, as the extension magnitude increases, the number, average length, and average displacement of the first-phase normal faults increase. Deformation during the second phase of extension depends on the properties of the first-phase fault fabric (and, thus, on the magnitude of the first-phase extension). For a poorly developed pre-existing fault fabric, new normal faults (which strike perpendicular to the second-phase extension direction) accommodate most of the extension during the second phase. For a well-developed pre-existing fault fabric, many of the first-phase normal faults are reactivated as oblique-slip faults during the second phase of extension. New normal faults also form. These second-phase normal faults are shorter and more likely to strike obliquely to the second-phase extension direction. They are also less likely to cut pre-existing faults than the second-phase normal faults that form in models with a poorly developed fabric. In all models, the pre-existing faults act as nucleation sites for the second-phase normal faults. In models with a well-developed fabric, however, the pre-existing faults also act as obstacles to the lateral and vertical propagation of the second-phase normal faults. We classify the faults patterns as first-phase dominant, second-phase dominant, or neither phase dominant, depending on which fault population (if any) controls the final deformation pattern. The relative magnitude of extension during the two phases of deformation determines the dominance of a particular fault population. Intersecting fault patterns result when first-phase faults are dominant, parallel fault patterns result when second-phase faults are dominant, and zigzag fault patterns result when neither the first-phase nor the second-phase faults are dominant. These fault patterns are common in many extensional basins (e.g., the Jeanne d'Arc Basin of eastern Canada, the Suez Rift of Egypt, the Pattani Basin of Thailand), and likely reflect the influence of a pre-existing fabric.

References

Kornsawan, A. and C.K. Morley, 2002, The origin and evolution of complex transfer zones (graben shifts) in conjugate fault systems around the Funan Field, Pattani Basin, Gulf of Thailand: Journal of Structural Geology v. 24, p. 435-449.

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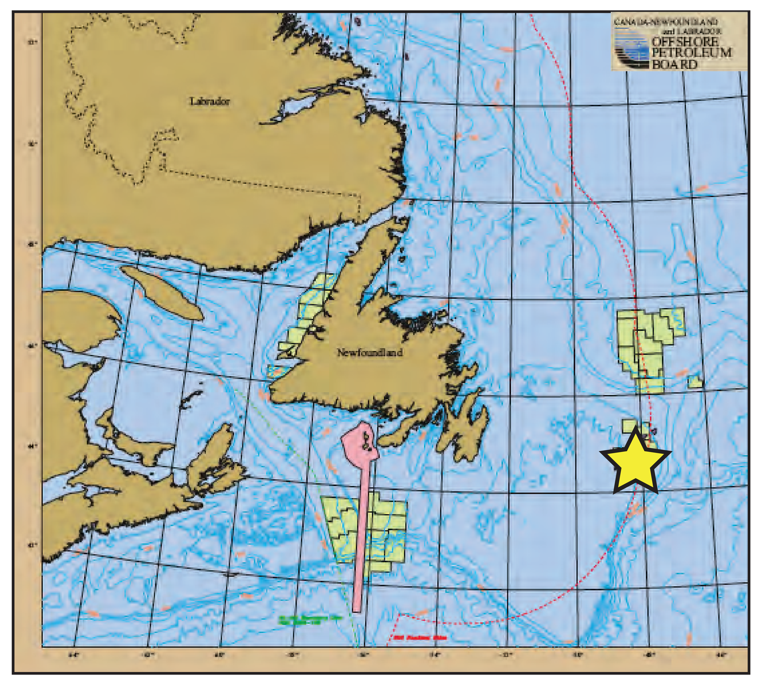
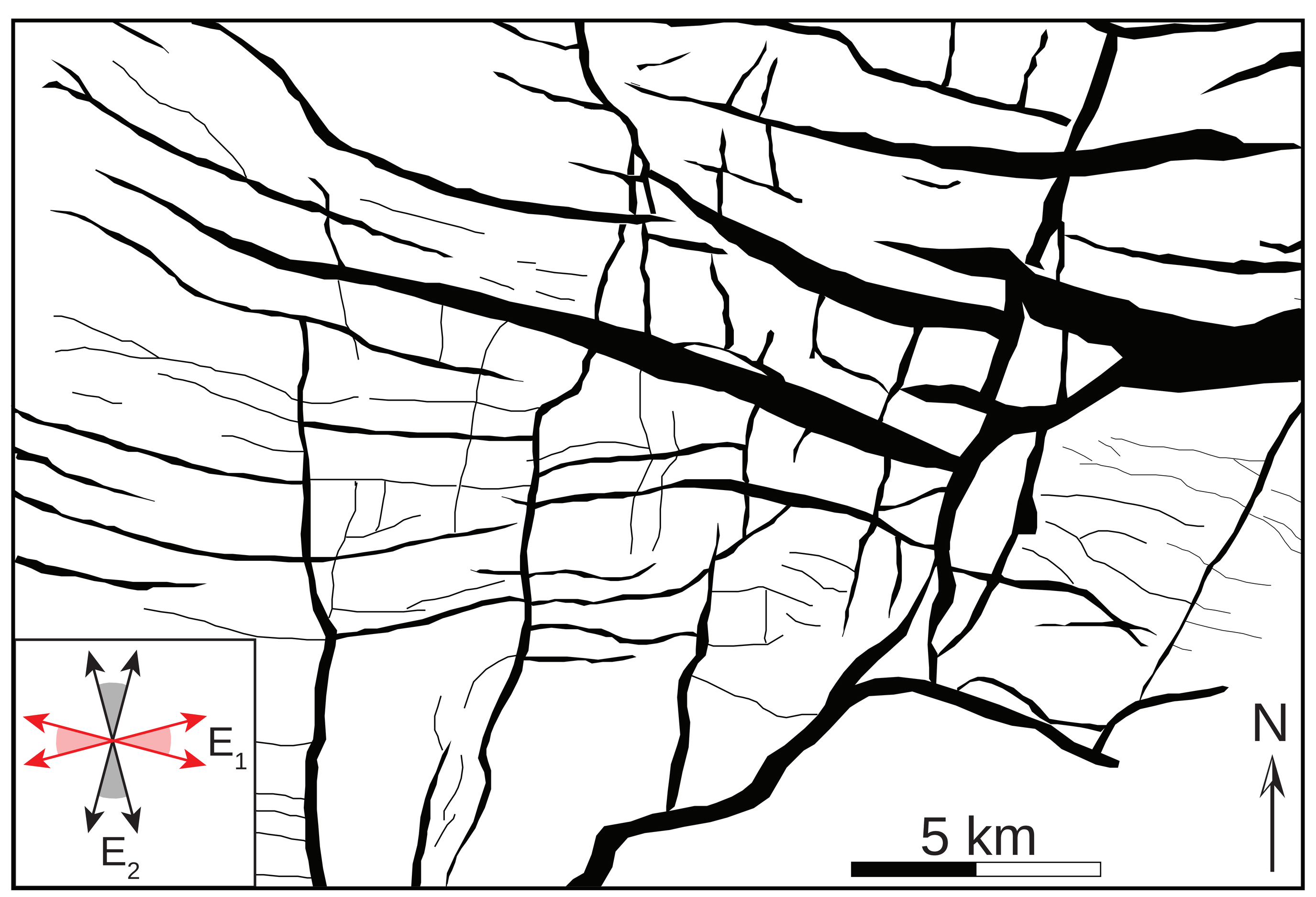
Do pre-existing faults help or hinder new fault development?

Many extensional provinces have undergone multiple phases of deformation, creating complex fault patterns

Terra Nova oilfield, Grand Banks



The Jeanne d'Arc basin likely underwent E-W extension in the late Jurassic and NE-SW extension in the Early Cretaceous (Sinclair et al., 1995; McIntyre et al., 2004).



Map of the Terra Nova region of the Jeanne d'Arc rift basin, offshore Newfoundland, showing faults offsetting the B marker (Early Cretaceous). In this region, N-striking normal faults predate E-striking normal faults. Map modified from McIntyre et al. (2004).

Pattani Basin, offshore Thailand

The rift basins of Thailand likely underwent multiple phases of deformation during the Cenozoic (Kornsawam and Morley, 2002; Morley et al., 2004)

Map of the Pattani basin showing younger (Lower Miocene to recent), NNE- to NE-striking faults overlying older (Eocene-Oligocene), NNE- to N-striking faults. Map modified from Morley et al. (2004)

References:

Kornsawan, A., Morley, C.K., 2002. The origin and evolution of complex transfer zones (graben shifts) in conjugate fault systems around the Funan Field, Pattani Basin, Gulf of Thailand. Journal of Structural Geology 24, 435-449.

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Research Questions

1) How does the fault pattern that forms during an early episode of extension affect the fault patterns that form during subsequent episodes of extension?

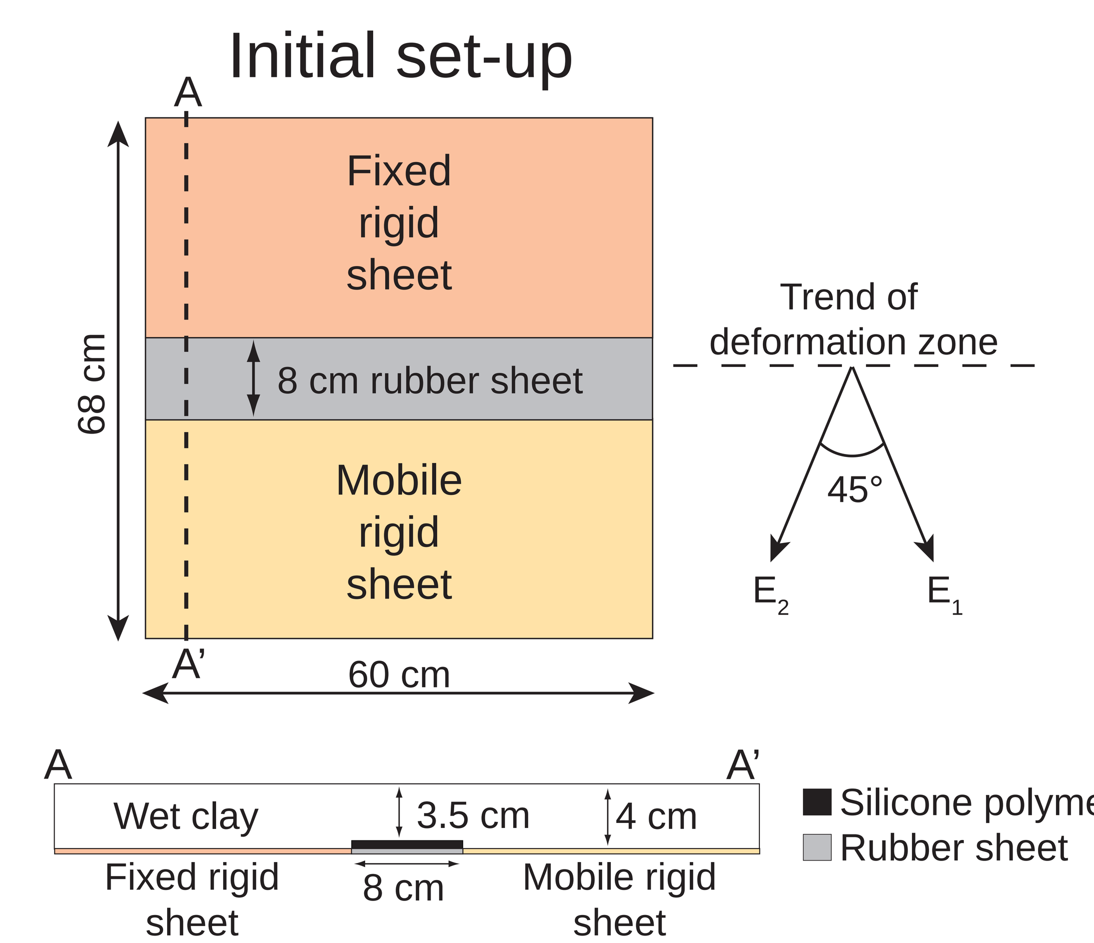
2) Does changing the properties (e.g., the number, length, displacement, and spacing) of faults within a pre-existing fault fabric affect the fault patterns that form during subsequent episodes of extension?

3) Is the temporal evolution of new faults affected by different degrees of initial fabric development?

Research Approach: Experimental Modeling

Complex fault interactions and limitations imposed by seismic resolution often make natural fault patterns difficult to interpret.

- Experimental modeling simulates deformation in a controlled environment
- Series of models varies displacement during first extensional phase



	Model A	Model B	Model C	Model D	Model E
1st phase	3.5 cm	3.0 cm	2.5 cm	2.0 cm	No extension
2nd phase	3.5 cm	3.5 cm	3.5 cm	3.5 cm	3.5 cm

- Modeling material is clay (density=1.55-1.60 g cm^{-3}, cohesive strength is ~50 Pa)
- 45° between extensional phases for all models
- Rubber sheet at model base simulates distributed extension
- Silicone polymer overlies rubber sheet, localizing deformation and decoupling the clay layer from the rubber sheet

Pre-Existing Zones of Weakness: An Experimental Study of their Influence on the Development of Extensional Faults

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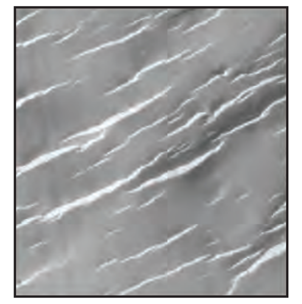
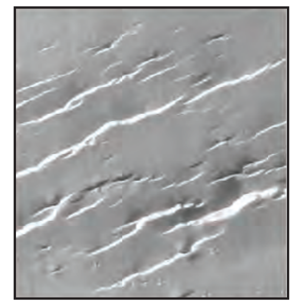
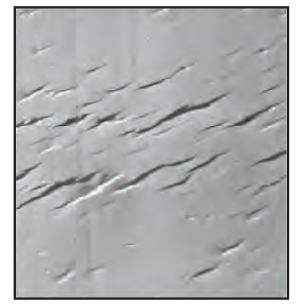
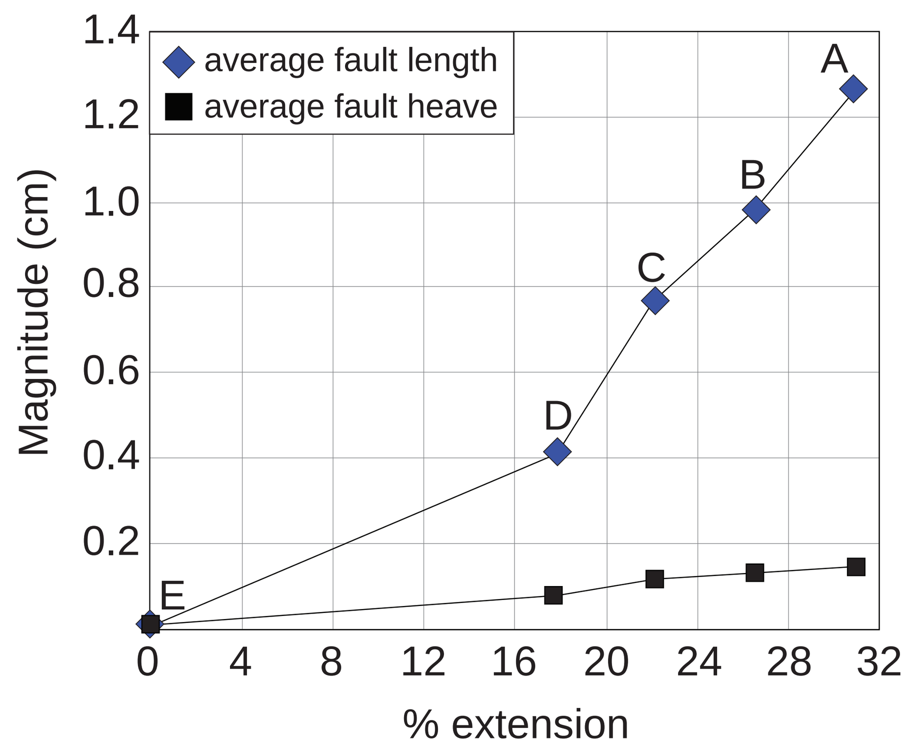
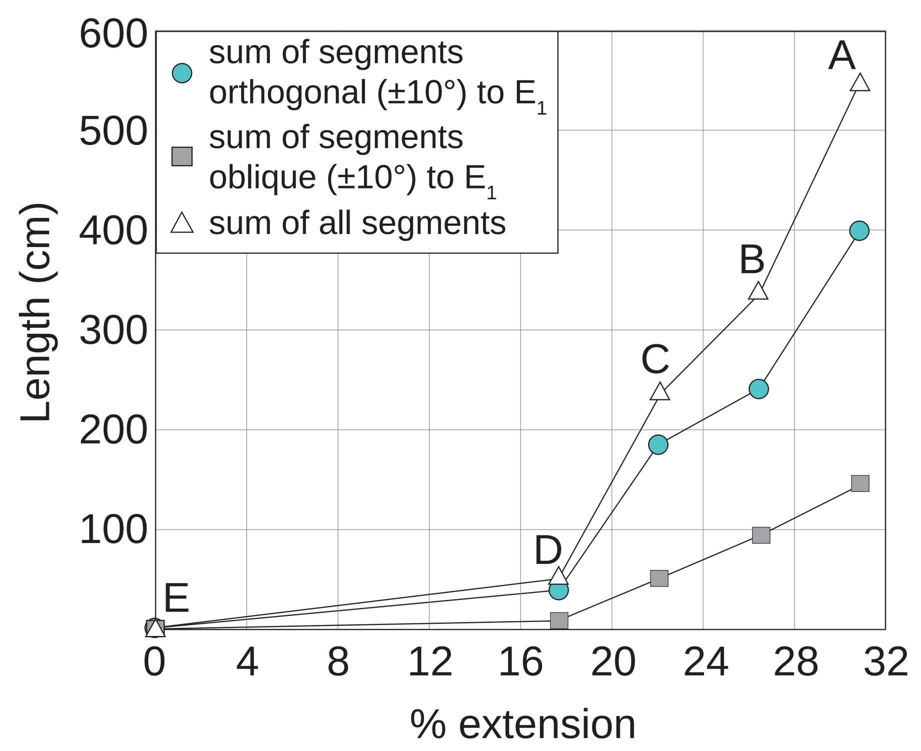
First-Phase Fabrics

Characteristics of fault populations after the first phase of extension depend on the magnitude of displacement of the mobile sheet

	Model A	Model B	Model C	Model D	Model E
1st phase displacement (cm)	3.5	3.0	2.5	2.0	0
1st phase strain (%)*	30.9	26.5	22.1	17.7	0
Fault patterns (4 cm)					No first-phase extension
Fault properties	More — Number of first-phase faults — Less More — First-phase fault length — Less				N/A
Fault-growth processes	Nucleation and Propagation Linkage				N/A

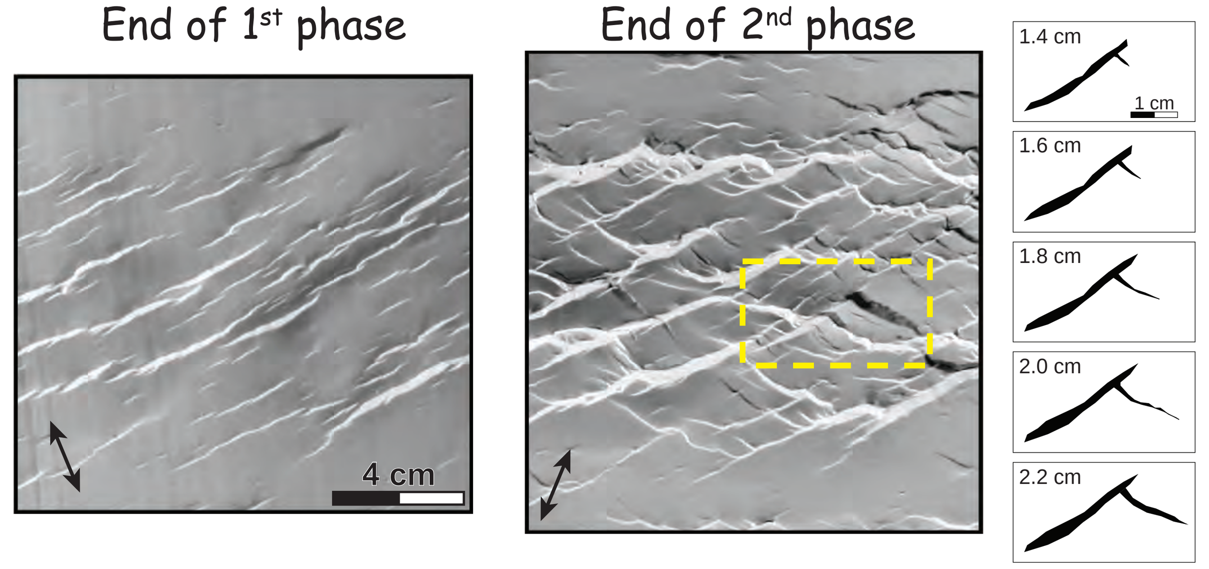
* Measured orthogonal to the trend of the deformation zone



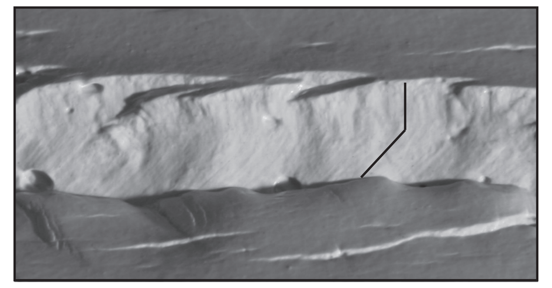


Second-Phase Deformation

For Model A:

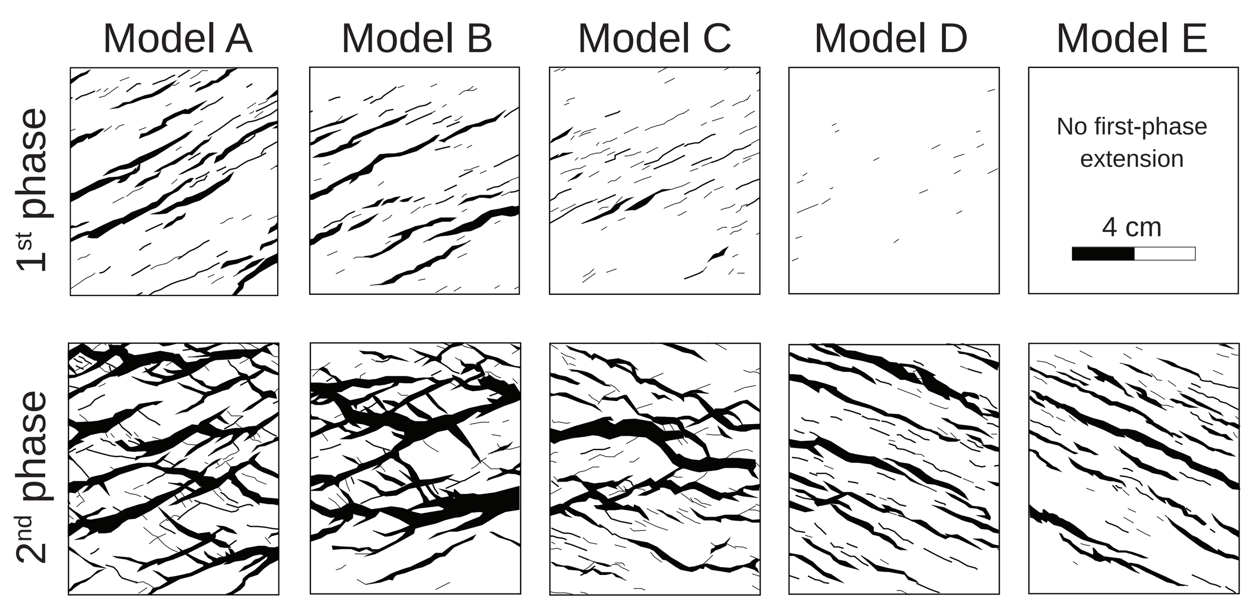


- Many first-phase faults reactivate with both normal and strike-slip components
- New faults commonly initiate at pre-existing faults and propagate away from them
- Displacement on new faults is greatest next to pre-existing faults



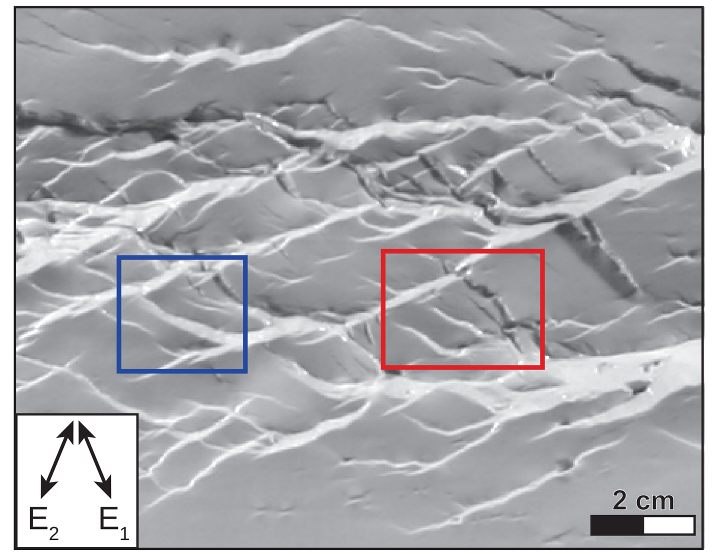
Corrugations (grooves) on the fault surface parallel the two slip directions on reactivated faults

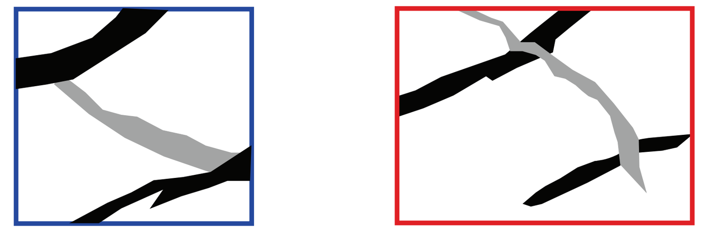
Decreasing the magnitude of first-phase displacement:



- New faults are present on the model surface at lower displacements in Models A-D than in Model E (with no first-phase displacement)
- New faults are generally shorter in Models A and B than in Models D and E (with little to no first-phase displacement)

Fault Interactions

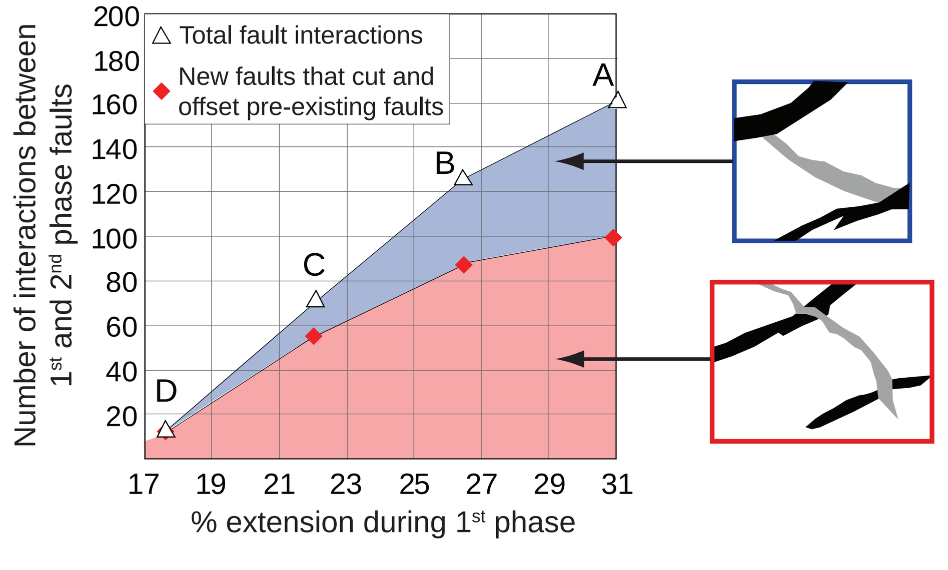


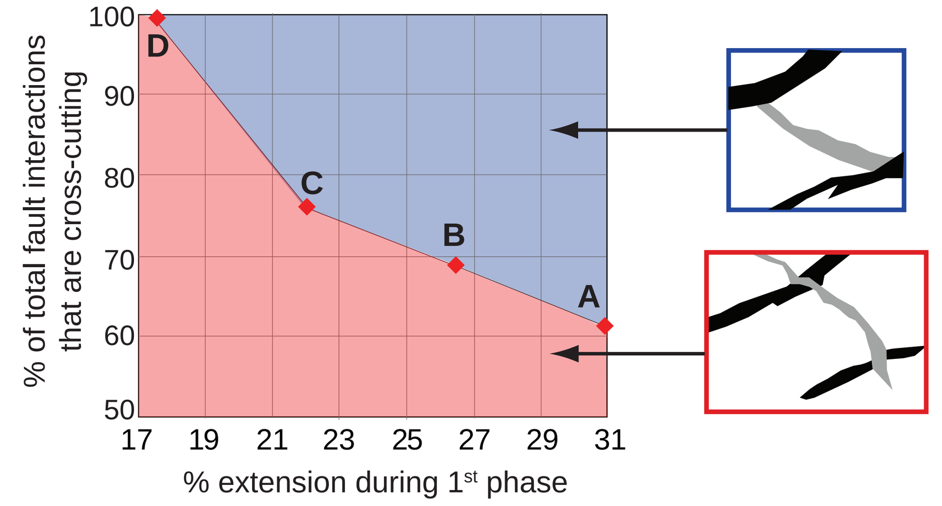


New fault terminates against pre-existing fault

New fault cross-cuts pre-existing fault

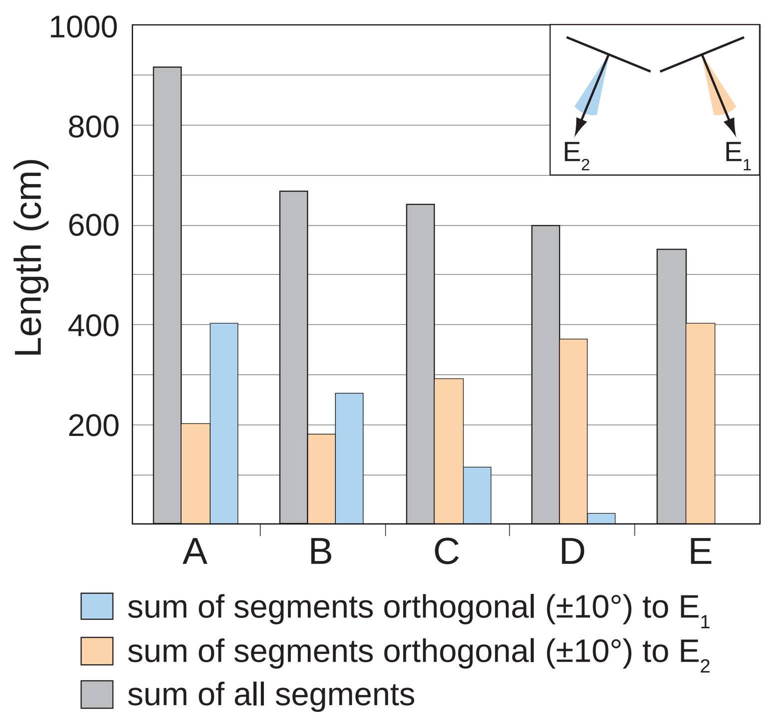
Pre-existing fault
New fault

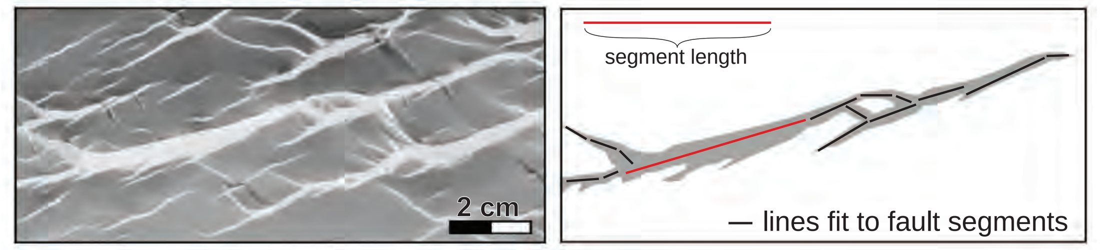




- Both total number of fault interactions and number of cross-cutting interactions increase with increasing magnitude of first-phase extension
- Percentage of the total fault interactions that are cross-cutting decreases with increasing magnitude of first-phase extension

Fault-Segment Lengths

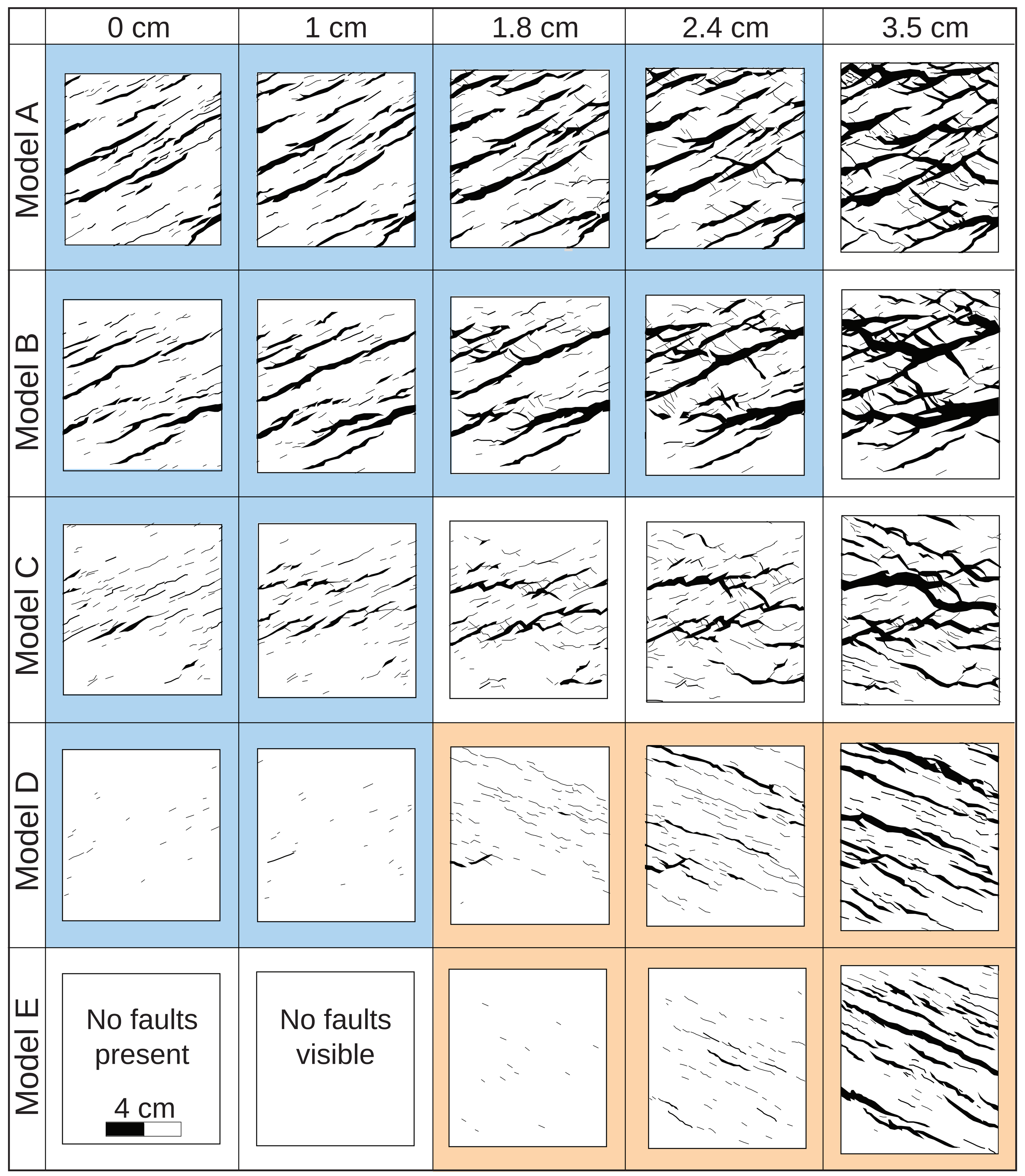




- Sum of fault segments orthogonal to the second-phase extension direction is lowest for Models A and B
- Sum of fault segments orthogonal to the second-phase extension increases with decreasing initial fabric development (first-phase displacement)

Summary and Implications

Categorizing Second-Phase Geometries



Evolution of fault patterns during second-phase extension falls into three categories:

First-phase dominant: reactivated first-phase faults are longer and have more displacement than second-phase faults; intersecting fault pattern

Second-phase dominant: new second-phase faults are longer and have more displacement than first-phase faults; parallel fault pattern

Neither phase dominant: first-phase and second- phase faults have similar lengths, displacements, and accommodate similar amounts of deformation; zig-zag fault pattern

Conclusions

- Pre-existing faults serve as nucleation sites for new faults
- If pre-existing faults are sufficiently developed, they serve as lateral obstacles to fault propagation and growth
- The dominance of first-phase or second-phase faults is controlled by the strain magnitude during both the first and second phases of extension

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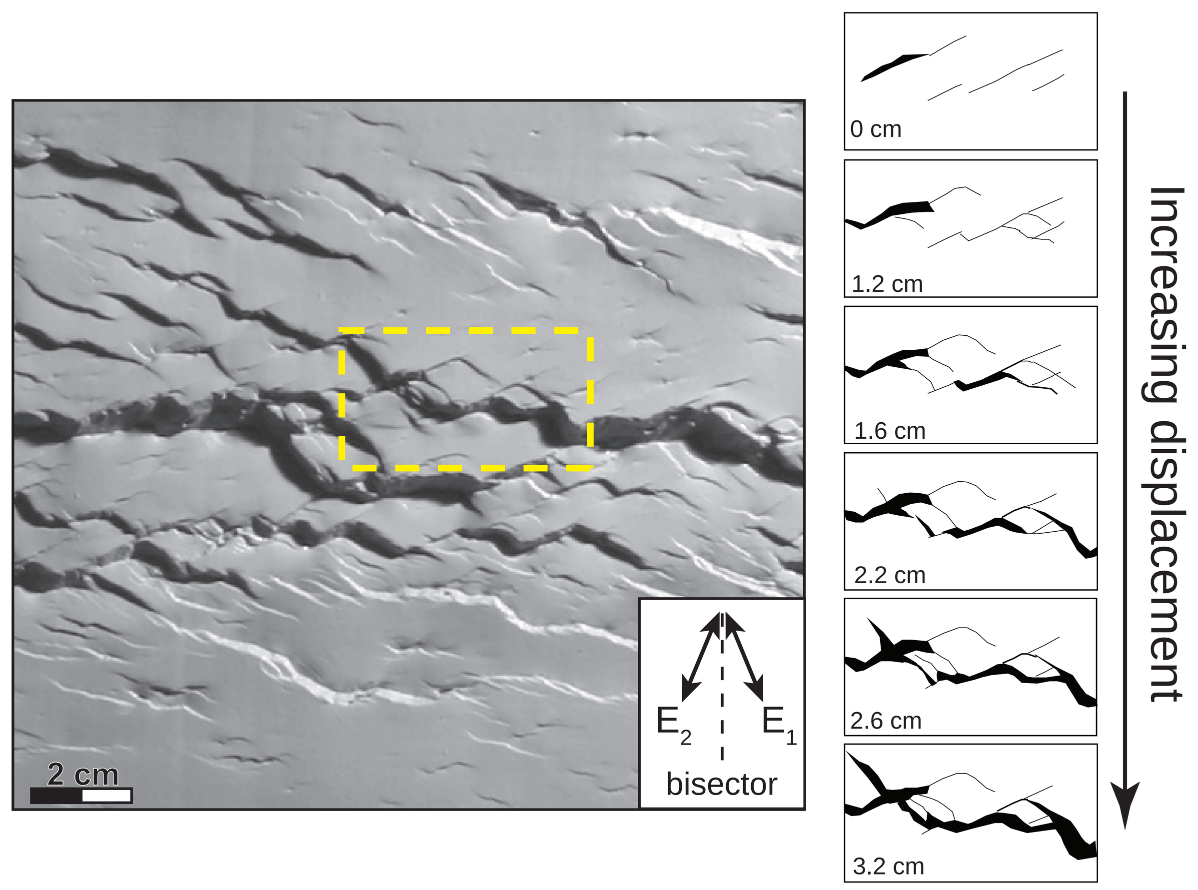
Formation of zig-zag faults

- As second-phase extension increases, new segments link with pre-existing faults creating composite faults
- New composite faults strike perpendicular to the bisector of the angle between the first-phase and second-phase extension directions

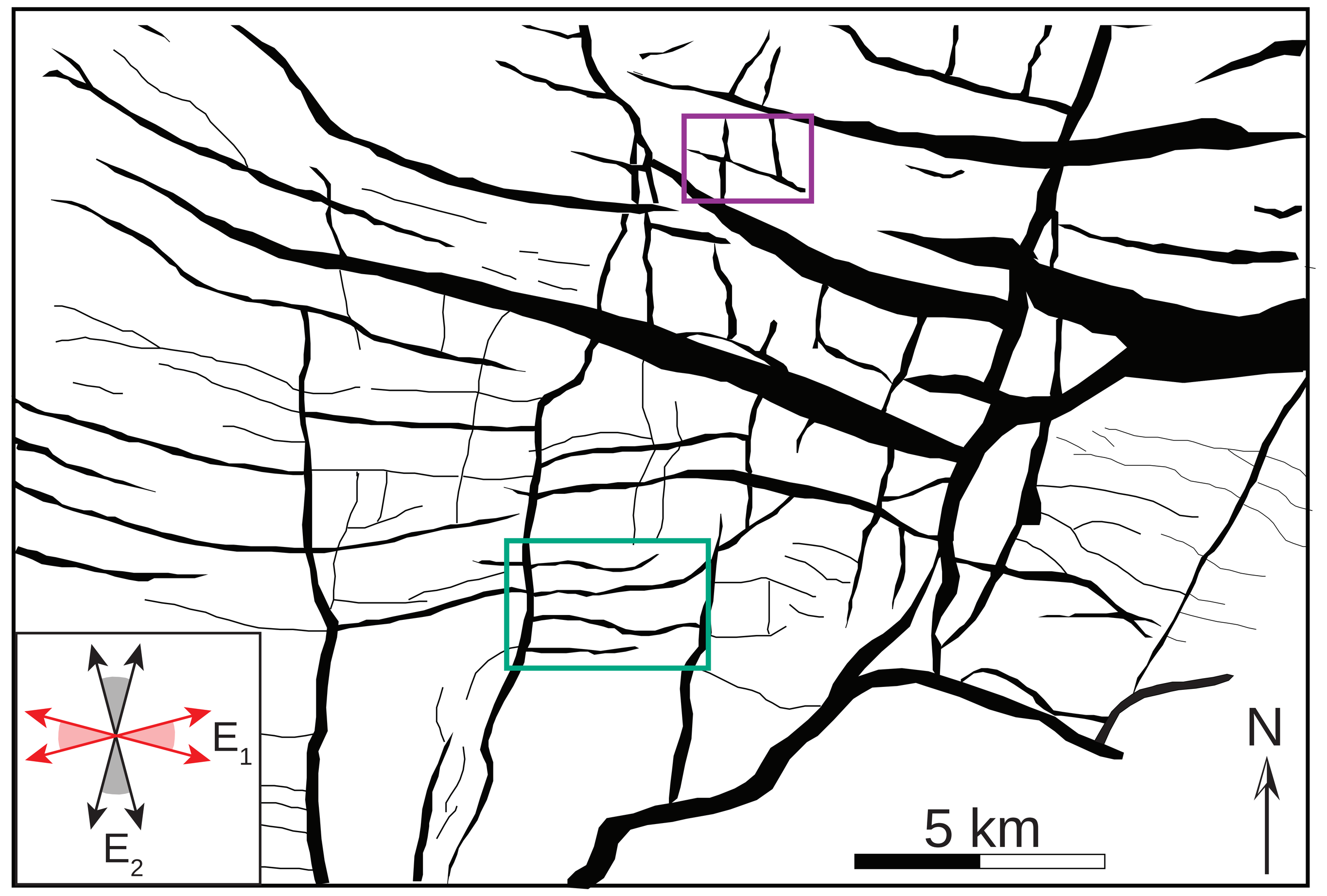


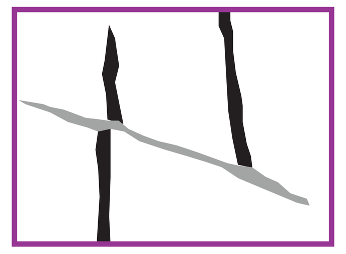
Implications for Reservoir Connectivity

If an initial fault fabric is poorly developed, a reservoir may be highly connected with only one oil-water contact.

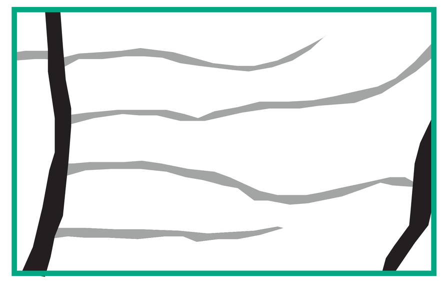
If an initial fabric is well developed, a reservoir may be compartmentalized with many oil-water contacts.

Interpreting Natural Fault Patterns: Terra Nova Oilfield





Second phase faults terminate against first phase faults



Second phase faults cut and offset first phase faults

Pre-existing faults

New faults

- Both types of fault interaction observed in the models are present at Terra Nova
- Younger, E-striking normal faults likely initiated at and propagated outward from older, N-striking faults