PS Fault Interactions in an Experimental Model with Two Phases of Non-Coaxial Extension: Insights From Displacement Profiles*

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Abstract

This study used experimental (analog) modeling to investigate how fault geometries and interactions that developed during multiple phases of non-coaxial extension affected fault-displacement profiles. In the model, a homogeneous layer of wet clay underwent two phases of extension whose directions differed by 45°. We observed multiple types of interactions (such as nucleation, linkage, and offset) between first-phase faults and second-phase faults on the top surface of the model. These interactions influenced the displacement profiles for both first-phase faults (which commonly reactivated with oblique slip during the second phase of extension) and new second-phase normal faults. During the second phase of extension, many new normal faults nucleated at first-phase faults and propagated outward. These faults had a displacement maximum at the branch point with the first-phase faults, and their displacement decreased in the direction of fault propagation. Some new normal faults cut and offset first-phase faults as they propagated outward. The displacement profiles for these second-phase faults generally did not exhibit abrupt changes near the offset first-phase fault. The displacement profile for the offset first-phase fault, however, had an anomalously high value near the intersection of the two faults. Many second-phase faults linked with multiple first-phase faults, which produced composite faults with zig-zag geometries (with overall strikes oblique to both extension directions). For these zig-zag faults, displacement was higher along the first-phase fault segments that had linked with second-phase faults than along unlinked first-phase fault segments. In addition, the parts of the first-phase faults beyond the linked segment became inactive after linkage, creating abandoned fault segments at the ends of many first-phase faults. The fault interactions and displacement profiles in the clay model, specifically the modification of displacement on first-phase faults and variations in displacement along linked faults, are similar to those documented in basins that are inferred to have undergone multiple phases of extension (e.g., Norwegian North Sea and North Slope, Alaska).

Reference Cited

Nixon, C.W., D.J. Sanderson, S.J. Dee, J.M. Bull, R.J. Humphreys, and M.H. Swanson, 2014, Fault interaction and reactivation within a normal-fault network at Milne Point, Alaska: AAPG Bulletin, v. 98, p. 2081-2107.

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Introduction

- Many basins have undergone multiple phases of extension with differing extension directions.
- Fault patterns in these basins are complex with a variety of interactions between new and pre-existing faults.
- Complexity of interactions and limited seismic resolution make detailed interpretation of fault patterns difficult.
- Temporal evolution of fault patterns is commonly unclear.

Research Questions

- How do faults that form during one episode of extension influence length and displacement of new faults that form during subsequent episodes of extension?
- How do nucleation, growth, and linkage of new faults affect displacement and length of reactivated faults?
- How do lengths and displacements of both new faults and reactivated faults change over time?

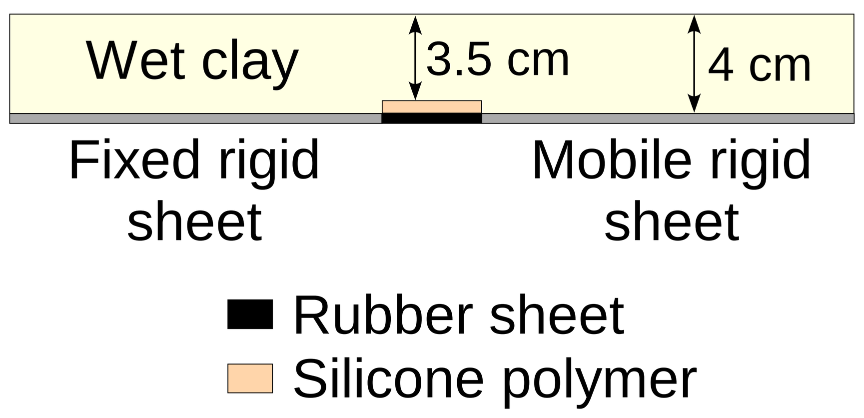
Research Approach: Scaled Experimental Modeling

Experimental modeling simulates deformation in a controlled environment and allows the observation of structures as they develop through time

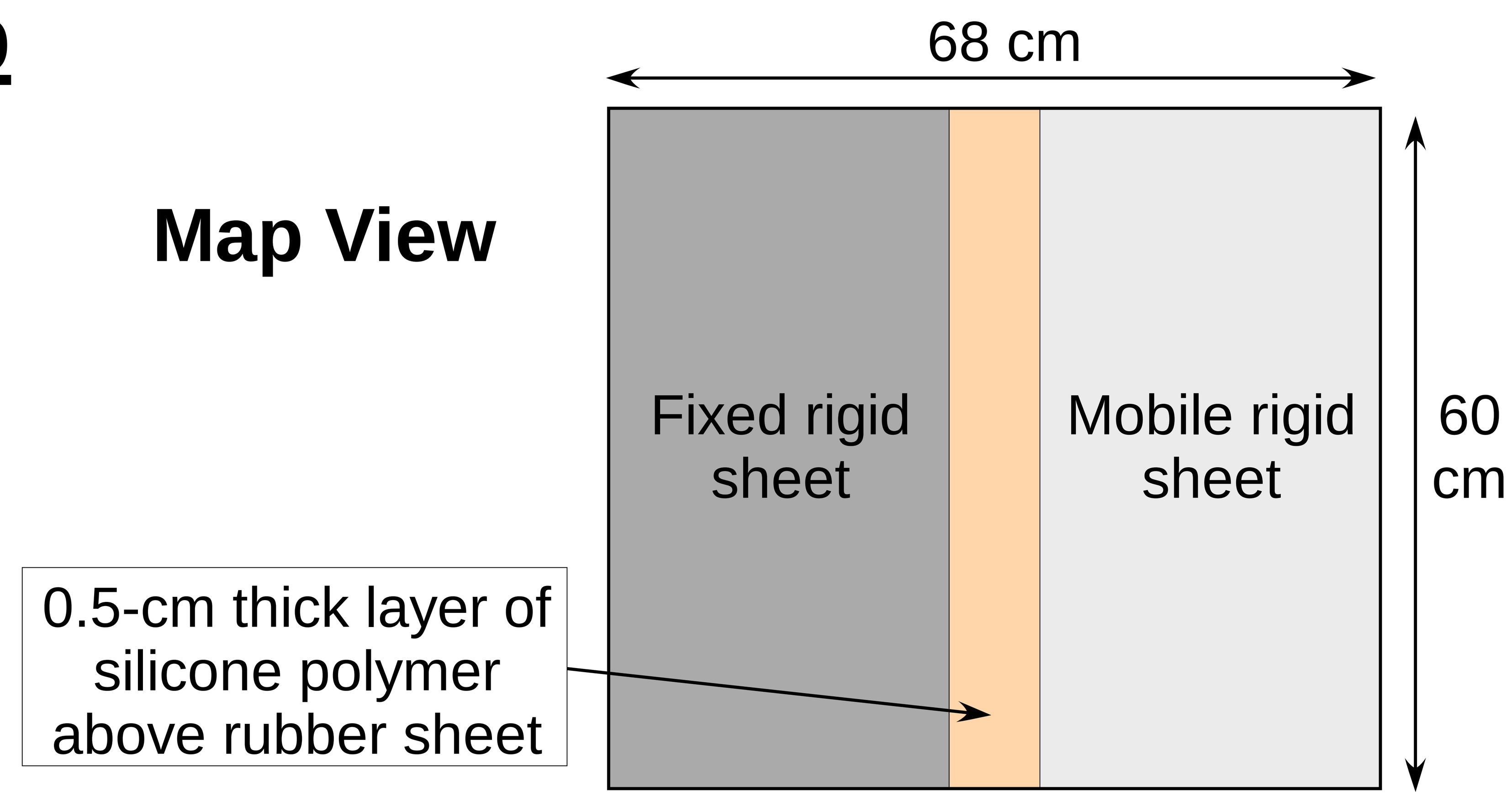
Experimental Setup

Cross-Sectional View

VE = 2

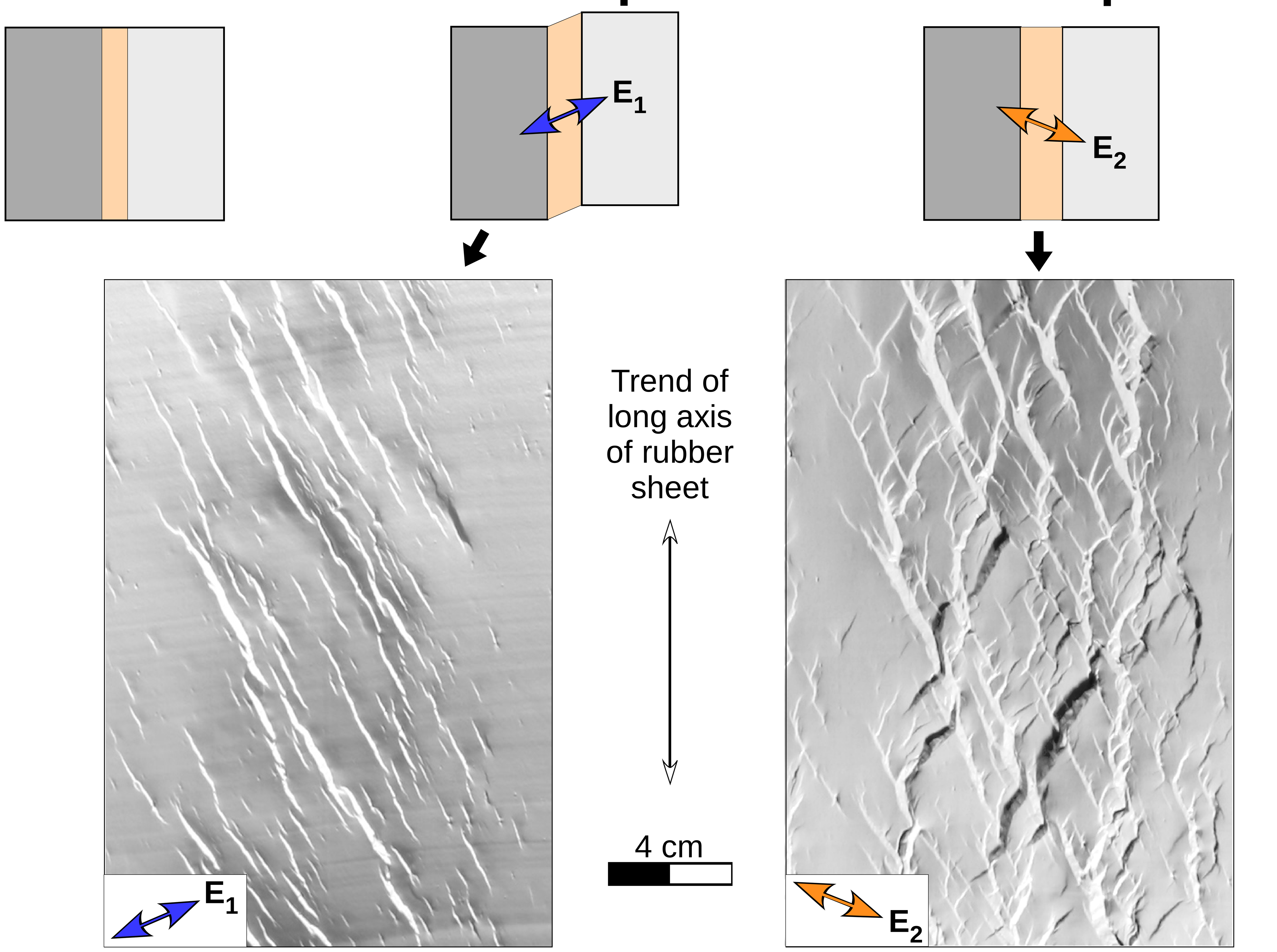


Map View



- Modeling material: wet clay with density of 1.55-1.60 g cm^{-3} and cohesive strength of ~50 Pa
- 45° between initial 1st-phase and 2nd-phase extension directions
- Rubber sheet at model base produces distributed extension
- Silicone polymer above rubber sheet decouples clay layer from rubber sheet
- Scaling factor is ~10^{-5} (1 cm in models scales to ~1 km in nature)

Initial | **End of 1st phase** | **End of 2nd phase**



Normal faults strike roughly perpendicular to extension direction

1st-phase faults reactivate with normal and strike-slip components; new faults form

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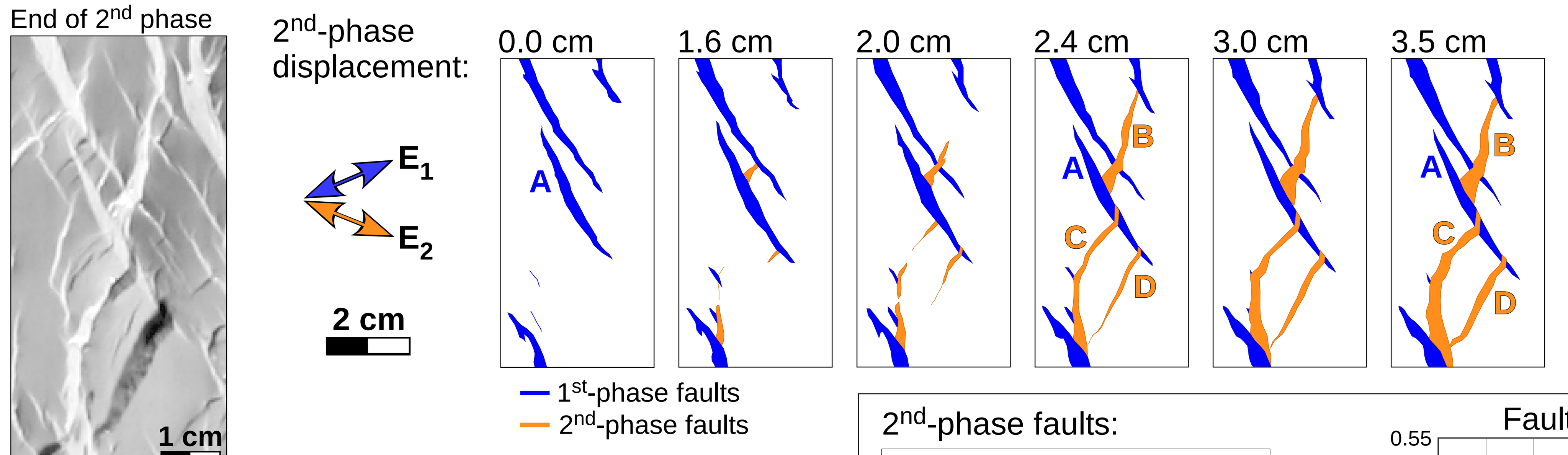
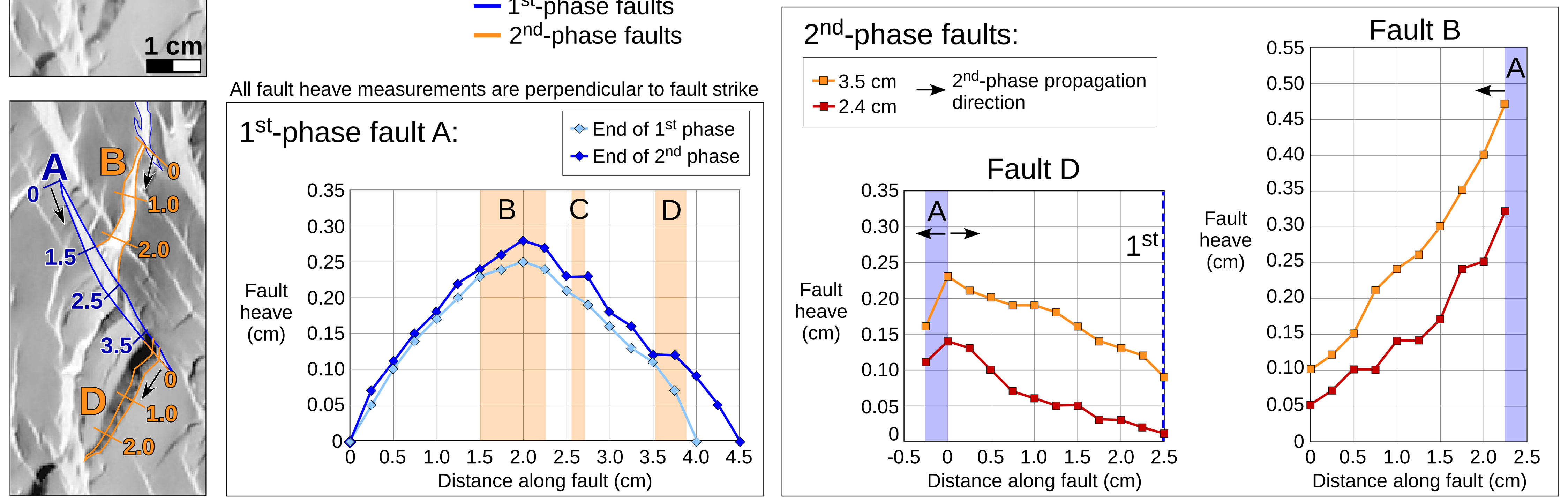
Fault nucleation, linkage, and abandonment

Fault nucleation

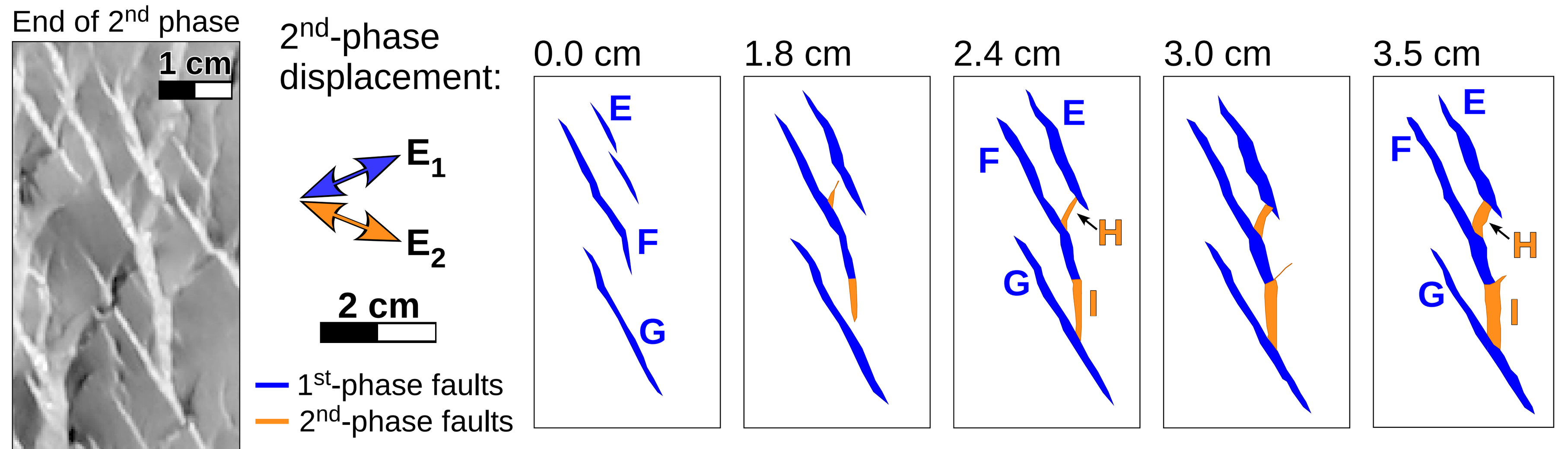


- 2nd-phase faults B, C, and D nucleate at 1st-phase fault A and propagate outward
- 2nd-phase faults C and D, which nucleate on the footwall of fault A, later cut 1st-phase fault A

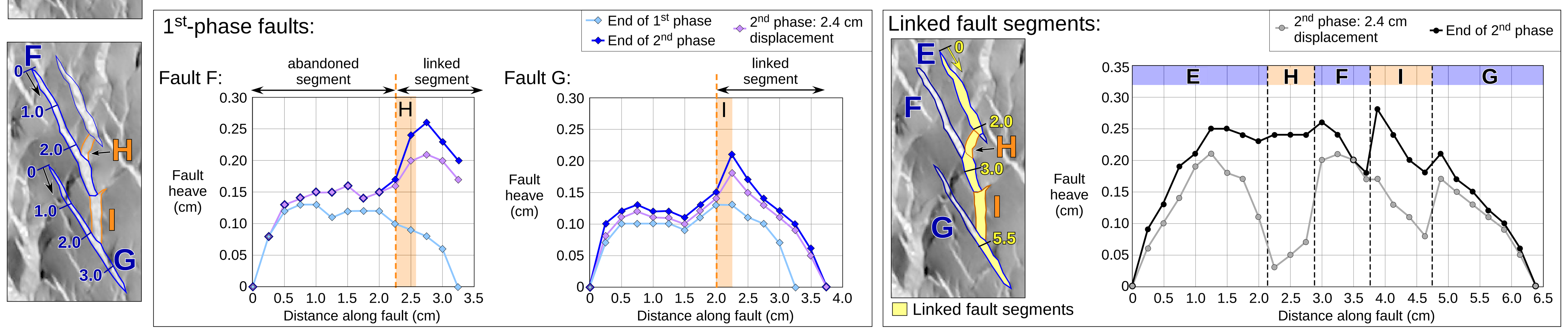


- Maximum heave on 2nd-phase faults B and D occurs at branch point with 1st-phase fault A
- Fault-heave profiles for 2nd-phase faults B and D, once established, are preserved throughout the 2nd phase of extension

Composite faults: linkage and abandoned segments

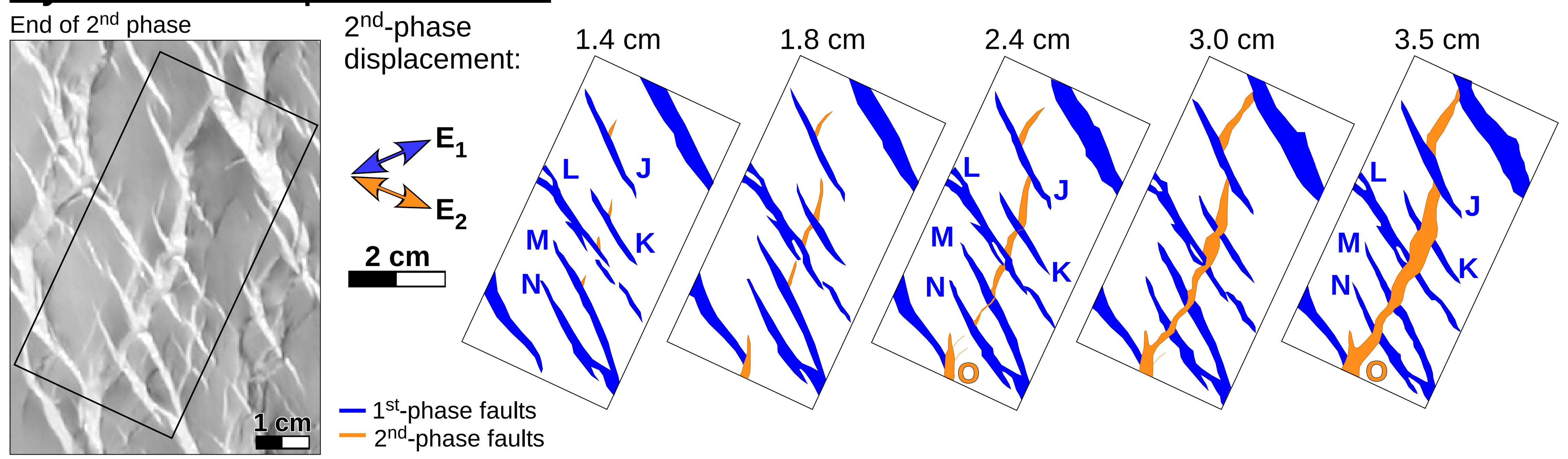


- Composite faults are created by linkage of 1st-phase and 2nd- phase fault segments; linked segments accommodate most deformation
- Some 1st-phase fault segments become inactive after linkage, creating abandoned segments
- Fault growth rates vary along linked segments

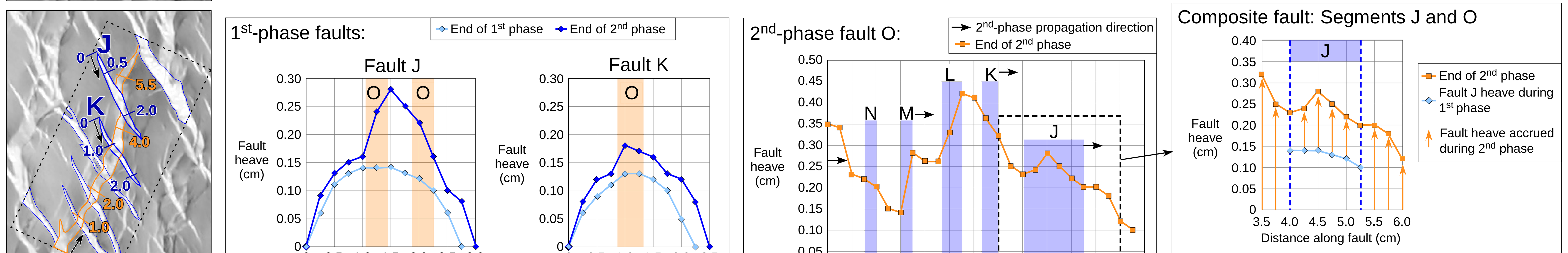


2nd-phase faults that cut and offset 1st-phase faults

Synthetic 2nd-phase fault

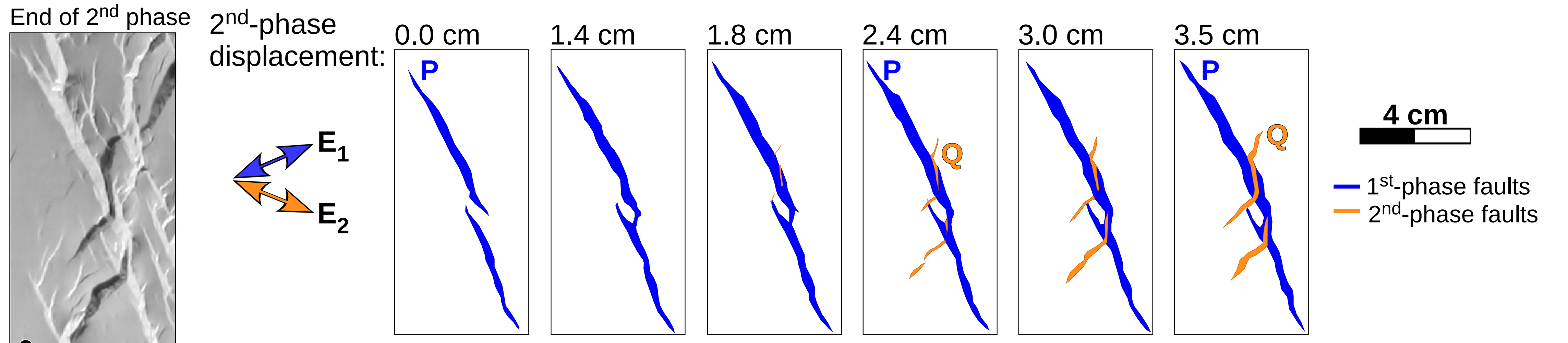


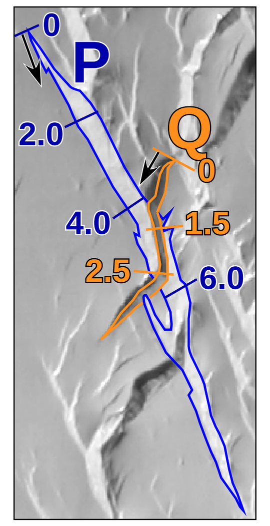
- 1st-phase faults have anomalously large heave where cut by synthetic 2nd-phase faults
- Linked 2nd-phase fault segments have significant variations in heave along strike
- Variations in heave along linked 2nd-phase faults correspond with nucleation and propagation direction of 2nd-phase fault segments



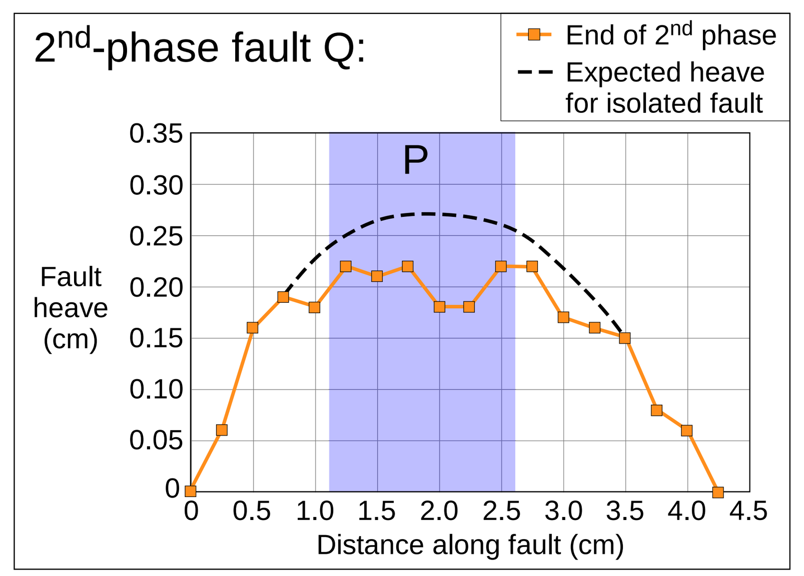
1st-phase segment J has smaller accrual of heave during 2nd phase compared to nearby segments of 2nd-phase fault O

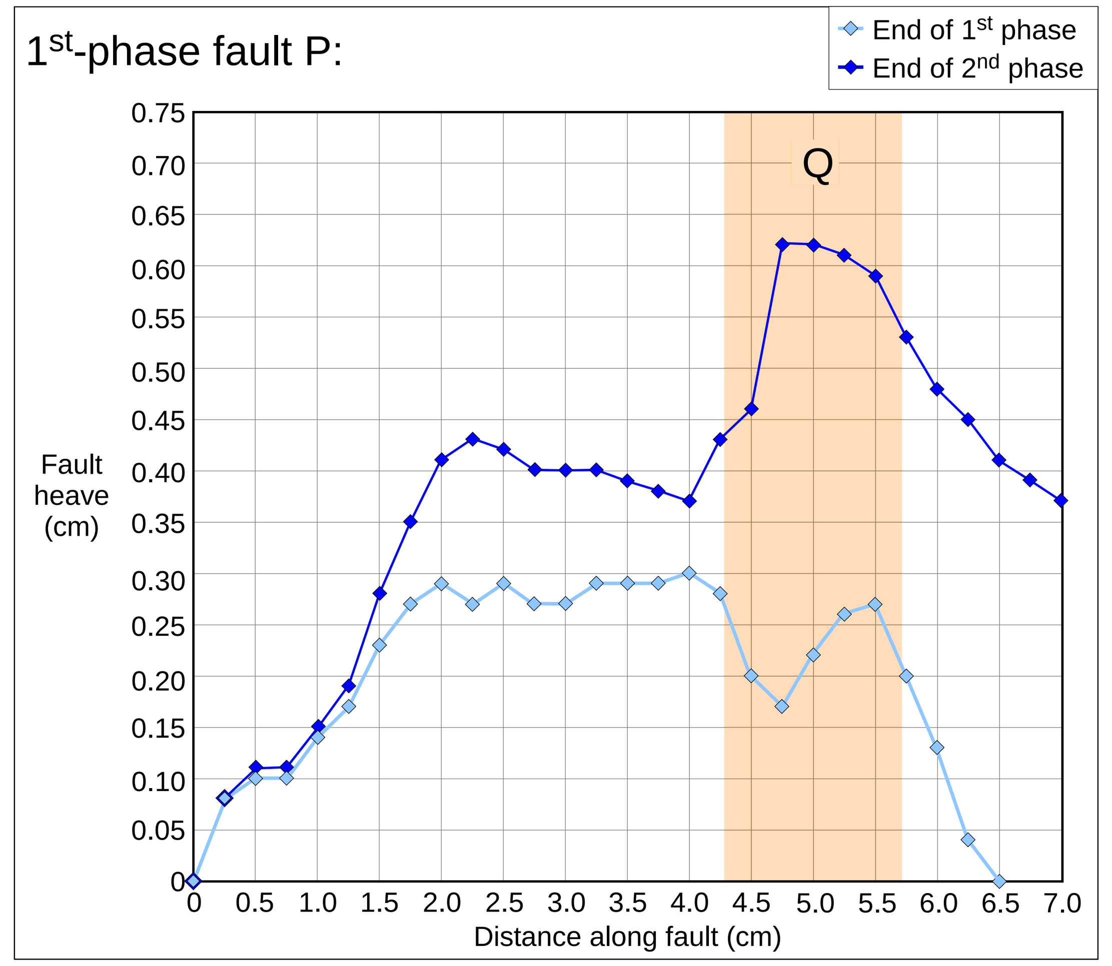
Antithetic 2nd-phase fault





- 1st-phase fault P has anomalously large heave where cut by antithetic 2nd-phase fault Q
- 2nd-phase fault Q has anomalously small heave (relative to expected heave, black dashed line) where it overlaps 1st-phase fault P
- 1st-phase fault P inhibited accrual of heave on 2nd-phase fault Q





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Summary

Fault nucleation:

- New 2nd-phase normal faults commonly nucleate at 1st-phase faults and propagate outward

- 2nd-phase faults have displacement maximum at branch point with 1st-phase fault and displacement decreases in direction of fault propagation

Cutting and offsetting:

- Displacement profile for 1st-phase offset by 2nd-phase fault (either synthetic or antithetic) has anomalously high value near intersection location

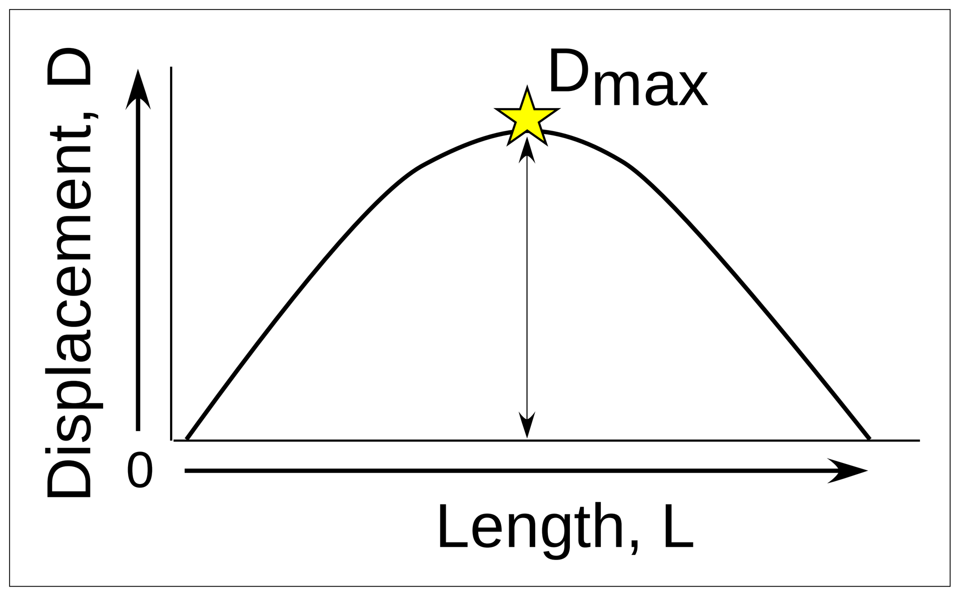
Composite faults:

- Displacement profile on 1st-phase and 2nd-phase fault segments is preserved after segments link

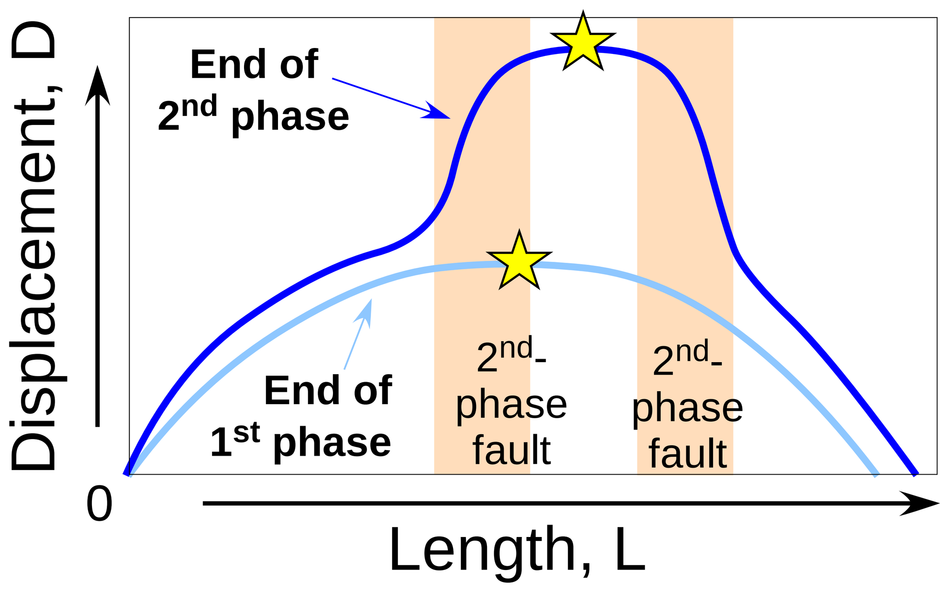
Multiphase extension & D-x plots

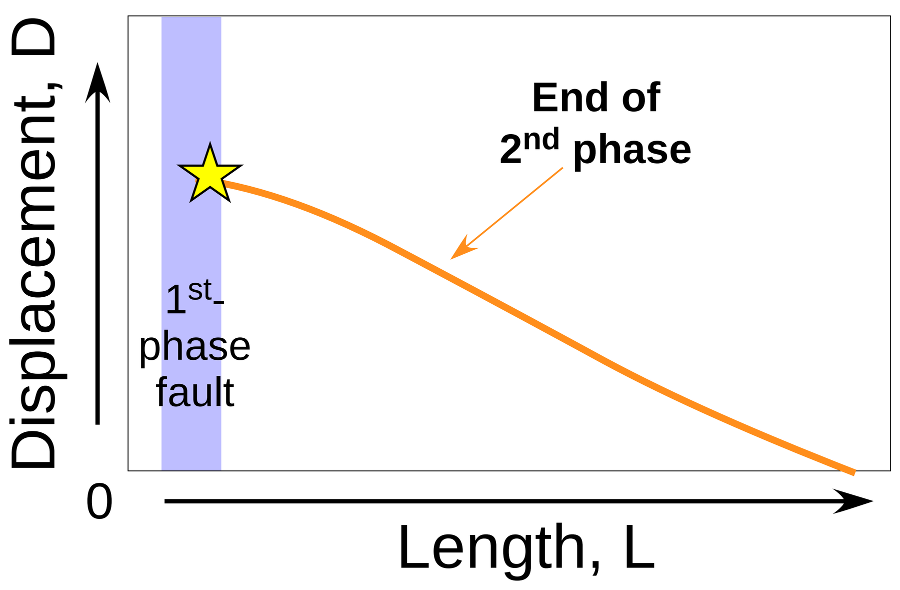
Idealized normal-fault displacement profile:

- Fault nucleation at D_{max}
- Maximum displacement (D_{max}) near center of fault (L/2)
- Displacement smoothly varies along strike



Multiphase faults do not have idealized profile!





1st-phase faults: Abrupt changes in displacement at 2nd-phase faults

2nd-phase faults: Asymmetric profile with D_{max} at nucleation site

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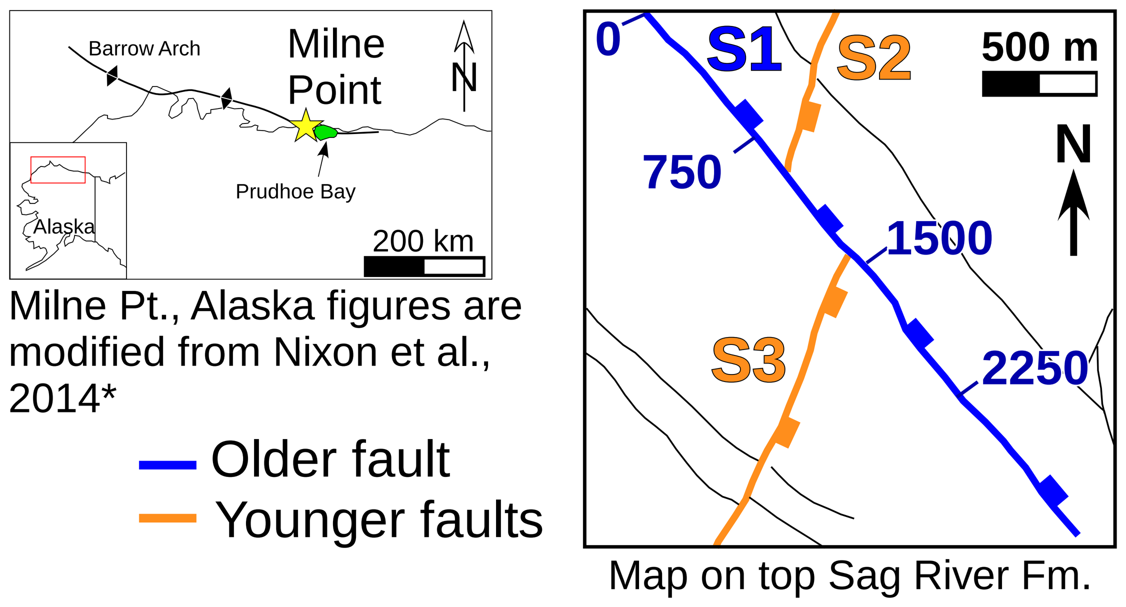
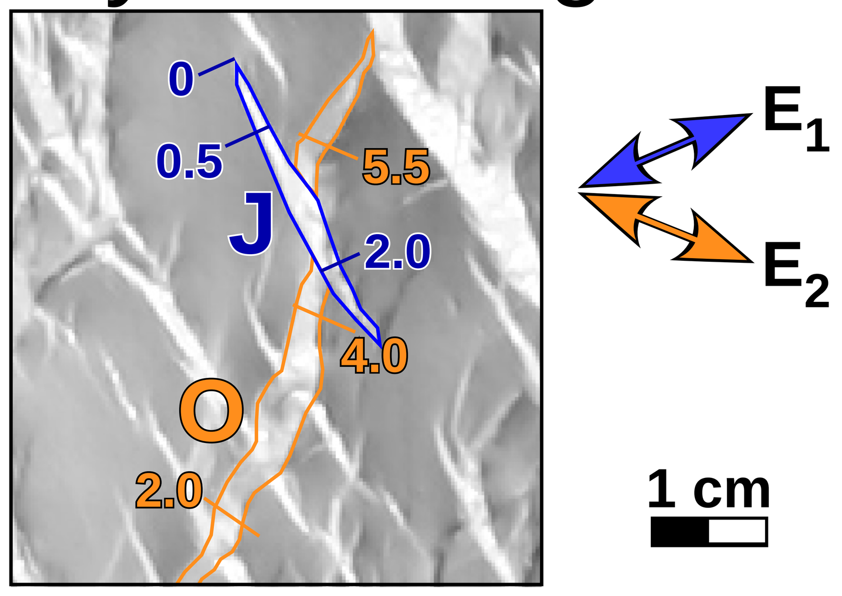
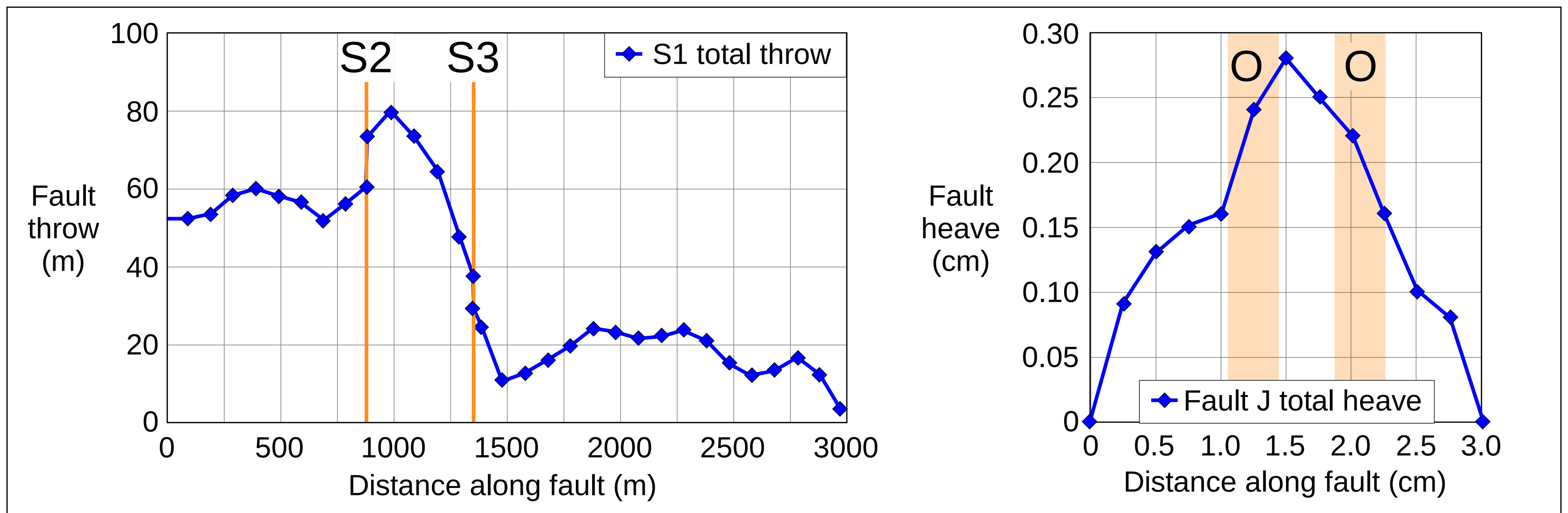
Comparison to natural deformation

Milne Pt., Alaska



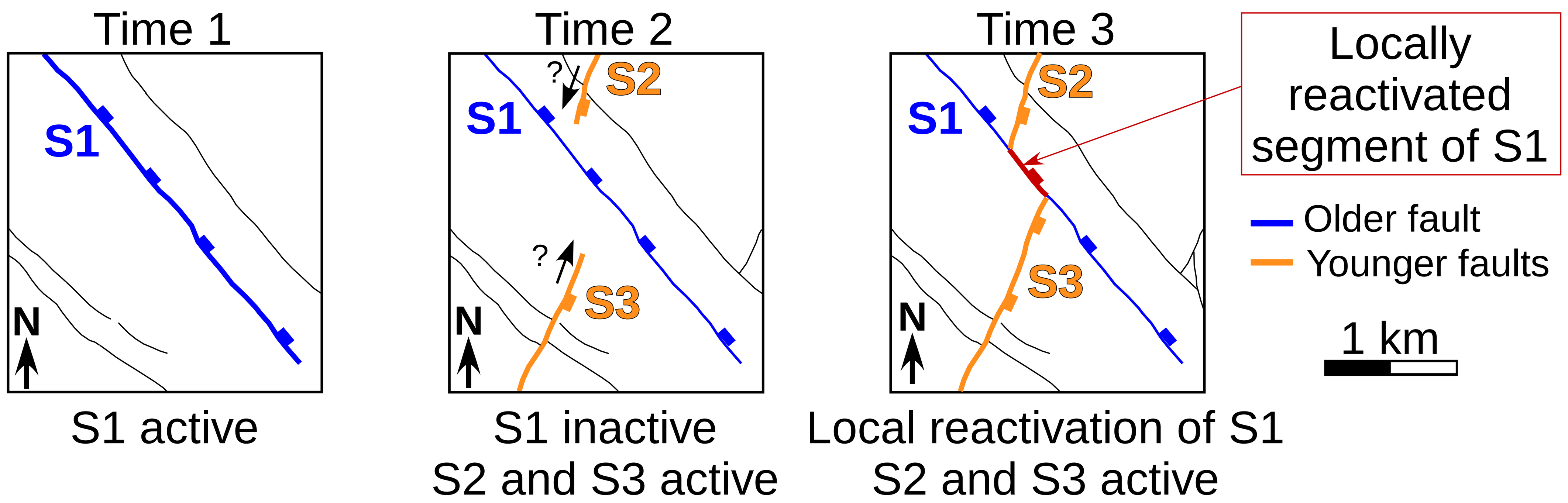
Clay Modeling





Increase in displacement on faults S1 and J between younger faults during later phase of extension

Nixon et al. (2014): movement on S2 and S3 during later phase of deformation caused local reactivation of S1



Clay modeling: widespread reactivation on 1st-phase faults; increase in heave on 1st-phase faults common where 1st-phase faults and 2nd-phase faults have linked