3-D Fault Geometries and Interactions Associated With Multiphase Extension*

Martha O. Withjack[1], Alissa A. Henza[2], and Roy W. Schlische[1]

Search and Discovery Article #41729 (2015)**
Posted November 30, 2015

*Adapted from oral presentation given at 2015 AAPG Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

[1]Earth and Planetary Sciences, Rutgers University, Piscataway, New Jersey (drmeow3@rci.rutgers.edu)
[2]BHP Billiton Petroleum, Houston, Texas

Abstract

Many rift basins have undergone multiple episodes of extension, commonly with differing extension directions. The resultant fault patterns are complex, potentially affecting both hydrocarbon migration and entrapment. We used experimental (analog) modeling to examine the 3D fault geometries and interactions that developed during multiphase extension. In the models, a homogeneous layer of wet clay underwent two phases of extension whose directions differed by 45°. Additional clay was added after each phase of extension. To examine the deformation within the models, we created closely spaced (1 mm apart) serial sections, interpreted them, and imported our interpretations into Petrel software. The serial sections and Petrel images showed that first-phase faults (striking sub-perpendicular to the first-phase extension direction) were most common at the base of the models, and second-phase faults (striking sub-perpendicular to the second-phase extension direction) were most common at shallow levels. The attitude of many faults varied with depth, striking sub-perpendicular to the first-phase extension direction near the base of the model and oblique to both extension directions at shallower levels. Displacement profiles on these faults indicated that they formed at depth during the first phase of extension. As they propagated upward during the second phase of extension, their strike rotated, becoming more optimally oriented relative to the second-phase extension direction. Additionally, the dips of these faults varied along strike. Many second-phase faults nucleated at first-phase faults and propagated upward and outward, some terminated into first-phase faults, and others cut and offset first-phase faults. The linkage of the second-phase faults with the first-phase faults created composite faults with zig-zag geometries in both cross-sectional and map views. The 3D fault patterns in the models are similar to those documented in basins that have undergone multiple phases of extension (e.g., the North Malay basin, offshore Thailand; the Taranaki basin, offshore New Zealand; the Jeanne d'Arc basin, offshore Newfoundland, Canada).

References Cited

Nixon, C.W., D.J. Sanderson, S.J. Dee, J.M. Bull, R.J. Humphreys, and M.H. Swanson, 2014, Fault interactions and reactivation within a normal-fault network at Milne Point, Alaska: AAPG Bulletin, v. 98/10, p. 2081–2107.

McIntyre, J., N. DeSilva, and T. Thompson, 2004, Updated regional mapping of Jeanne d'Arc Basin based on released 3-D seismic data: Canada-Newfoundland Offshore Petroleum Board, Open file GP-CNOPB-04-01.

3D Fault Geometries and Interactions Associated with Multiphase Extension

Martha Oliver Withjack
Alissa A. Henza
Roy W. Schlische

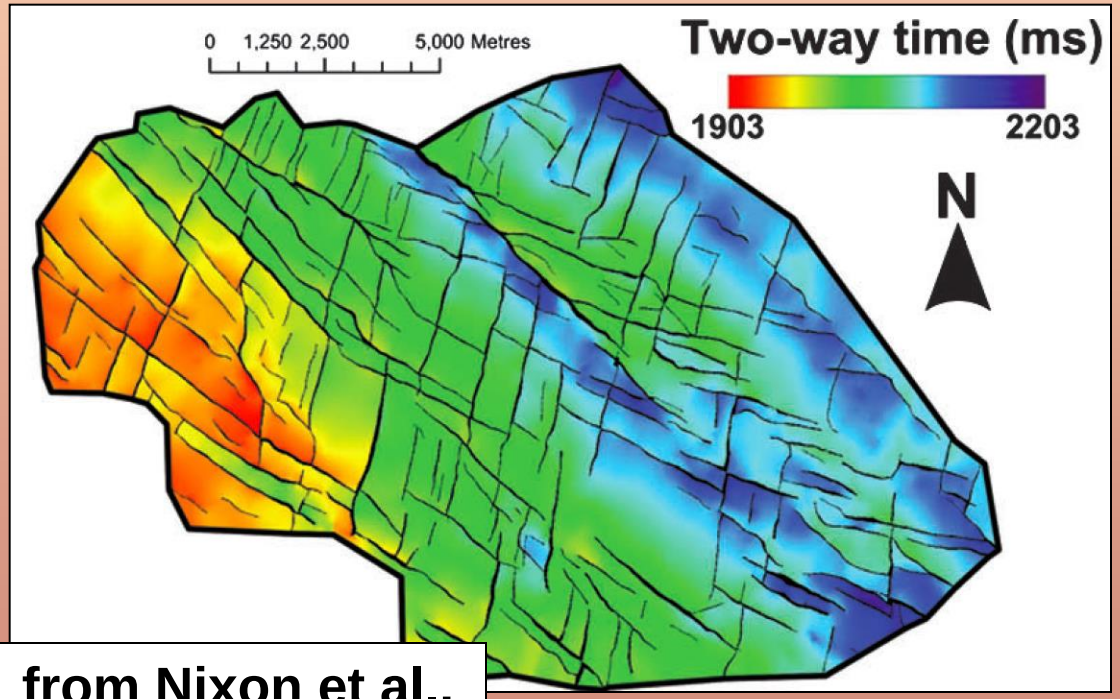
Rutgers University
Structural Geology & Tectonics Research Group

Support provided by NSF, Husky Energy, and Schlumberger

Introduction

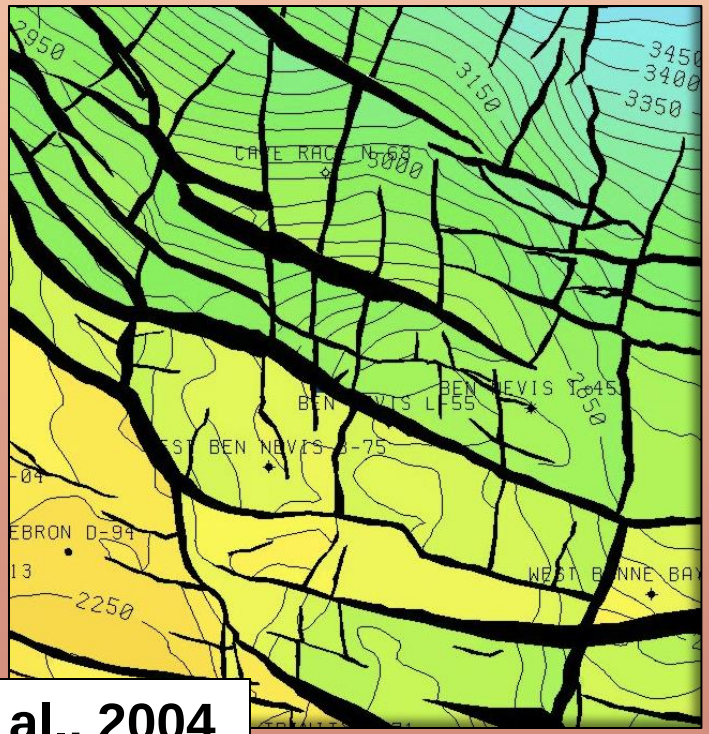
- **Many basins have undergone multiple phases of extension with differing extension directions**

Milne Point, Alaska North Slope



from Nixon et al., 2014

Jeanne d'Arc basin, offshore Newfoundland

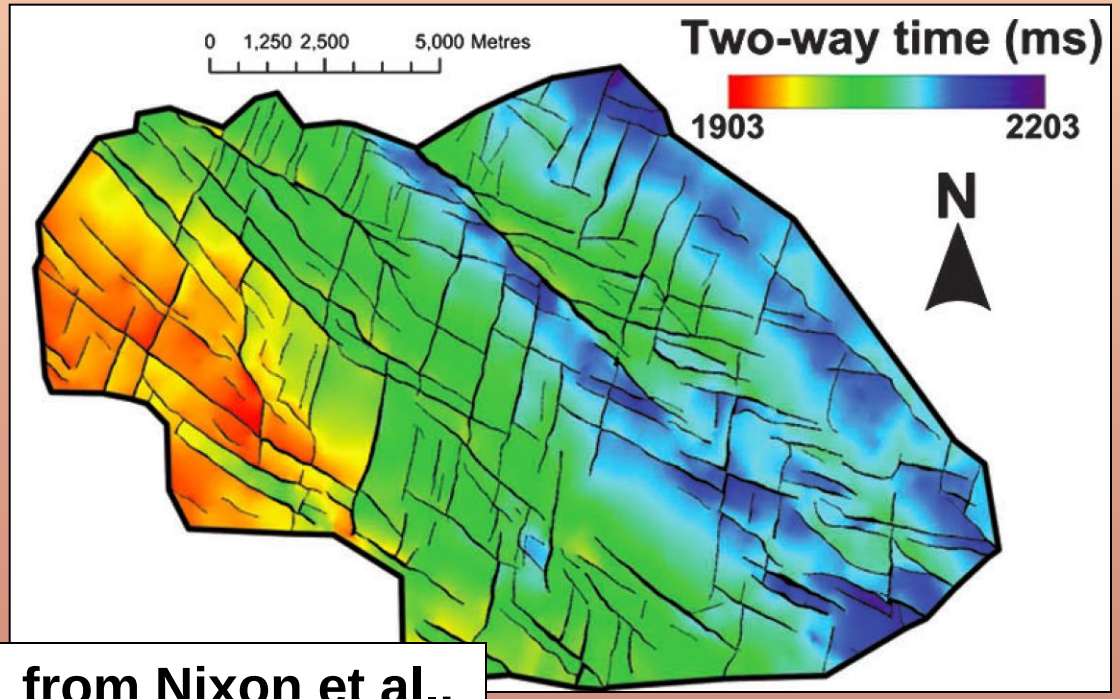


from McIntrye et al., 2004

Introduction

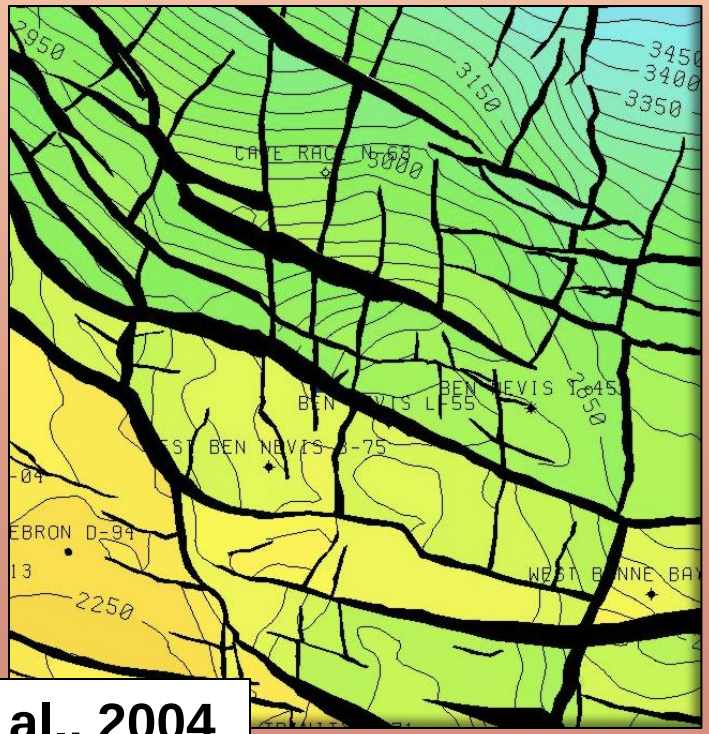
- **Fault patterns are complex with multiple fault trends and a variety of fault interactions**

Milne Point, Alaska North Slope



from Nixon et al., 2014

Jeanne d'Arc basin, offshore Newfoundland



from McIntrye et al., 2004

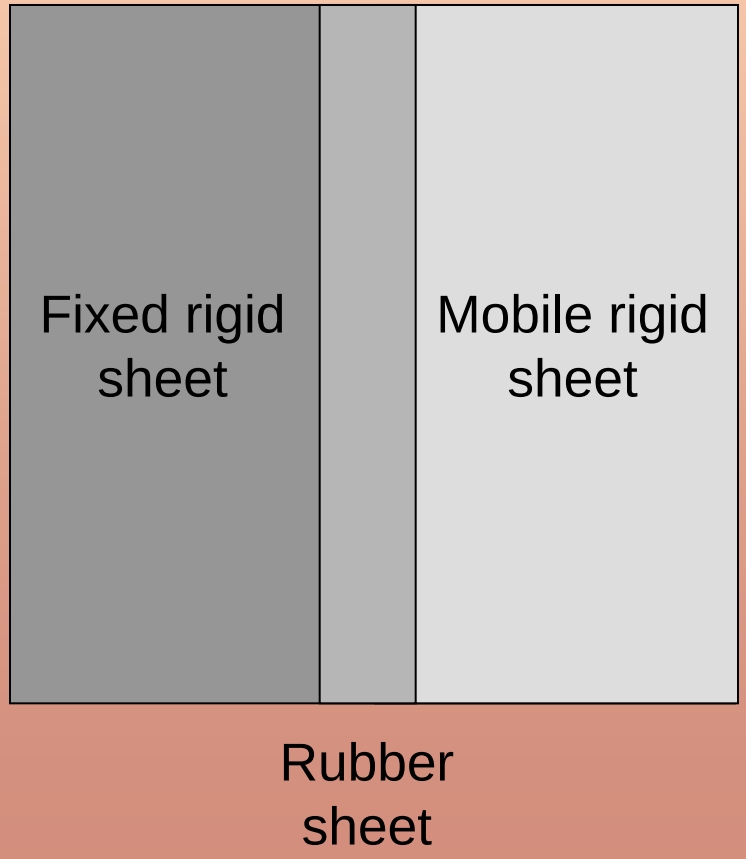
Approach and objective

Use scaled experimental models to address the following questions:

- What types of faults develop during multi-phase extension?
- Does style of faulting vary with depth?
- Do strikes of faults vary with depth?
- What types of fault interactions develop?
- What do these interactions look like in both map and cross-sectional views?

Experimental setup

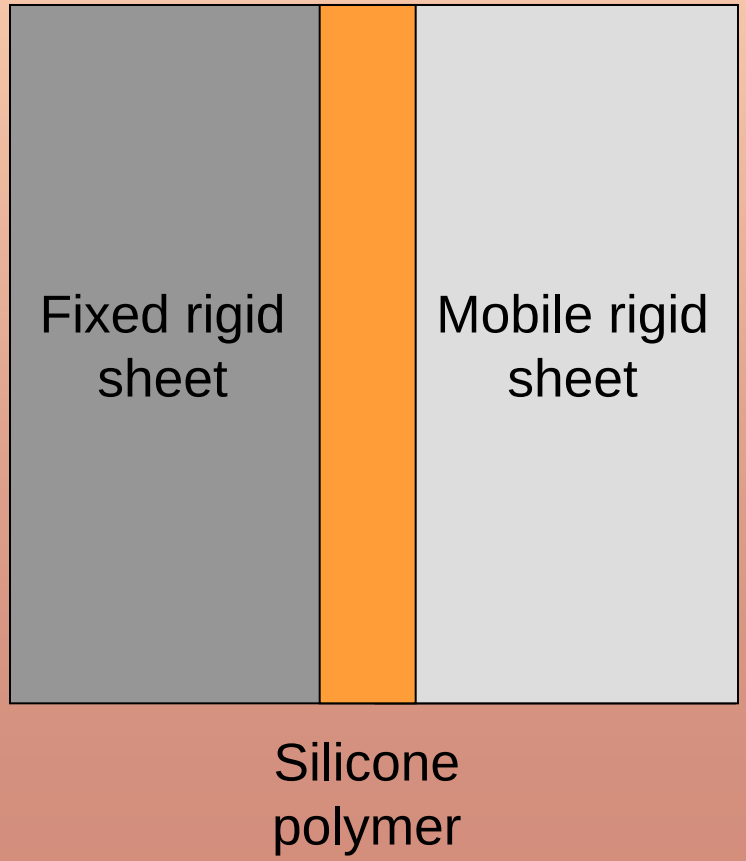
Map view



• 8-cm wide **rubber sheet** attached to a **fixed rigid sheet** and a **mobile rigid sheet**

Experimental setup

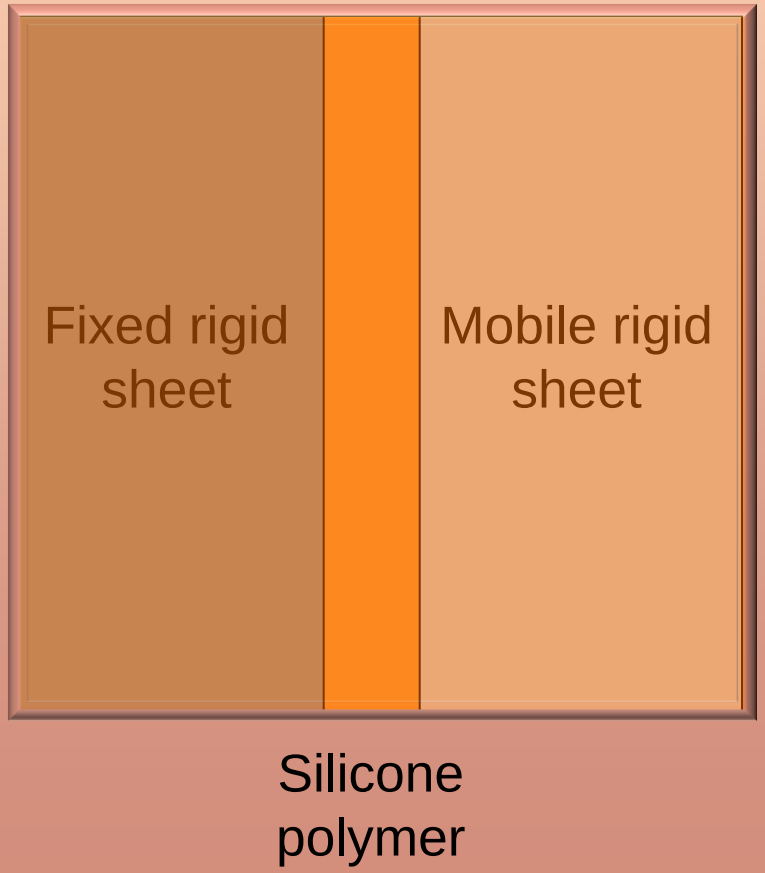
Map view



- 0.5-cm thick layer of **silicone polymer** overlies the rubber sheet

Experimental setup

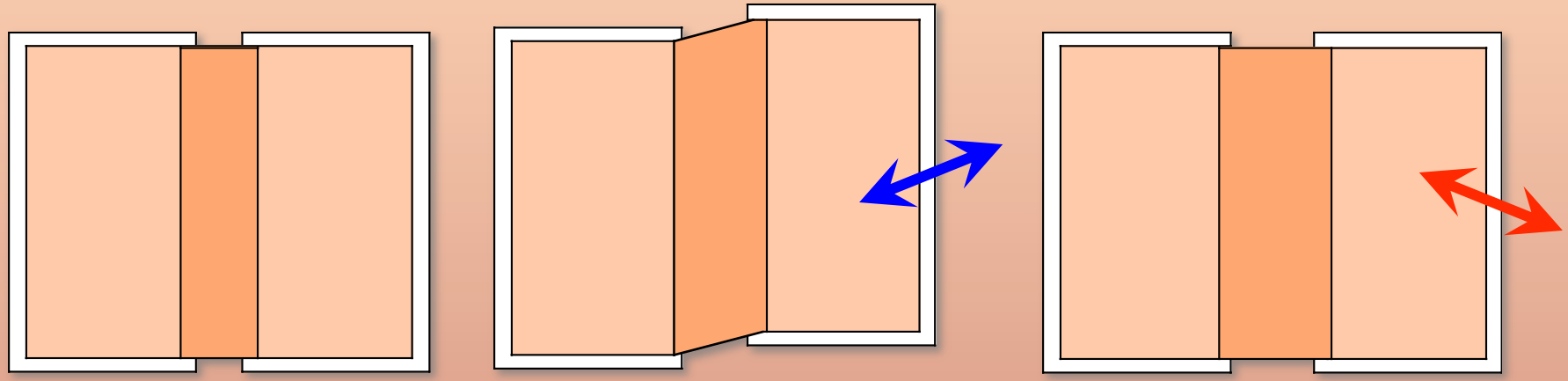
Map view

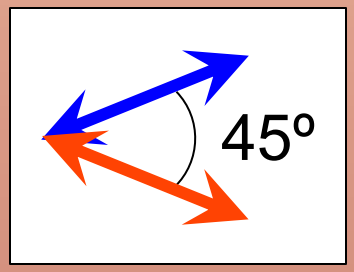


- **Wet clay** (~ 4-cm thick) overlies mobile and fixed rigid sheets and silicone polymer

Experimental setup

Initial model **1st phase** **2nd phase**

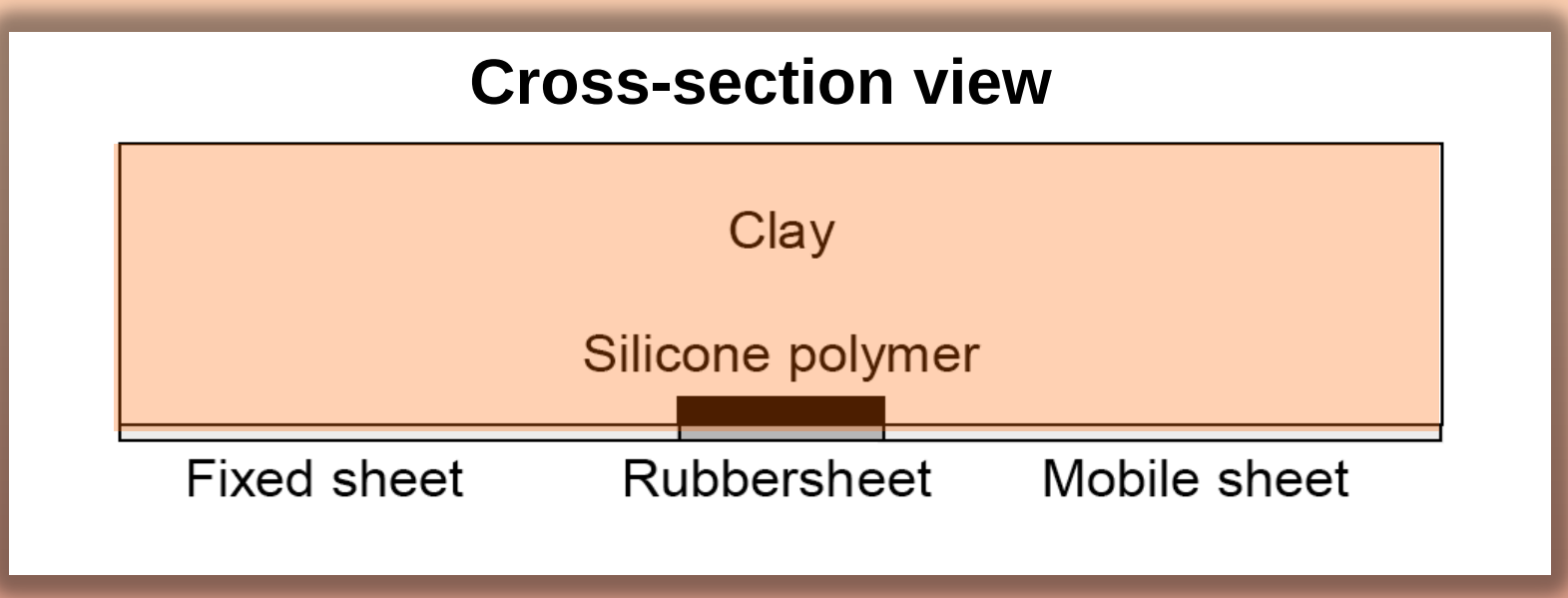




- Two phases of oblique extension
- Extension directions differ by 45˚

Experimental setup

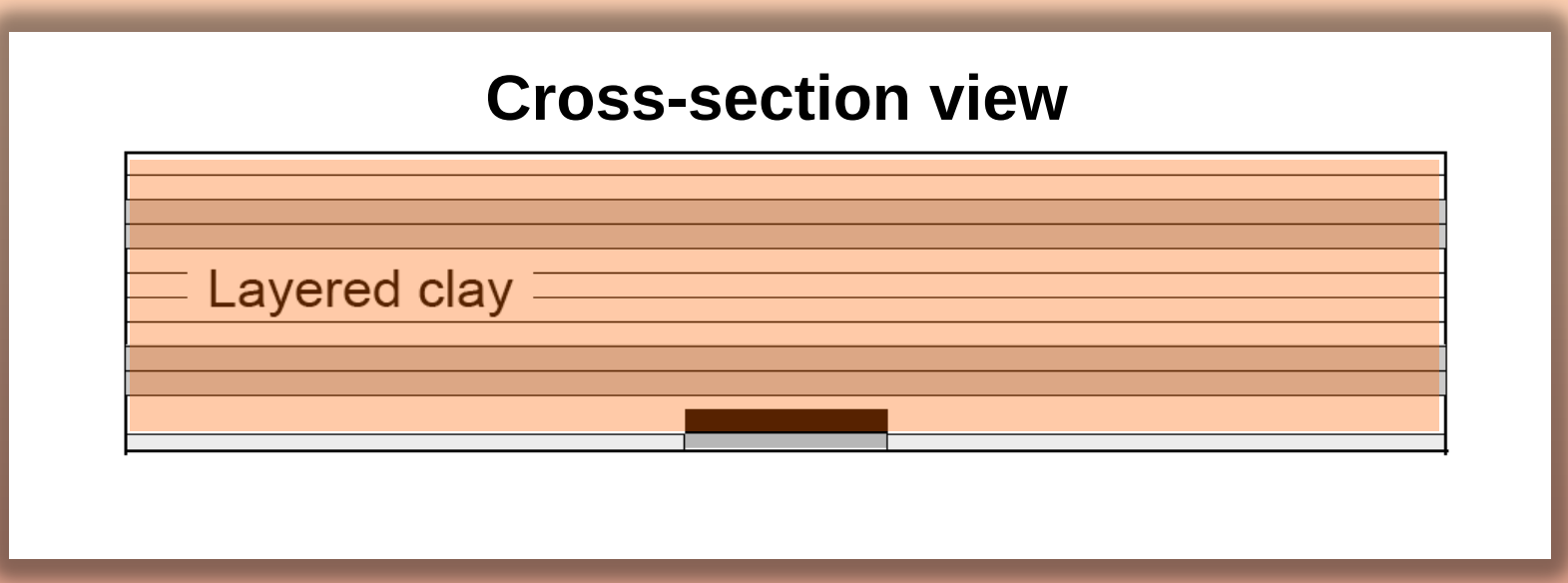
Single-layer model - no infill after each phase



• Provides information about **fault development on the model surface** during both phases of extension

Experimental setup

Layered model - infill after each phase



- Provides information about **fault geometries and interactions within model** after 2nd phase of deformation

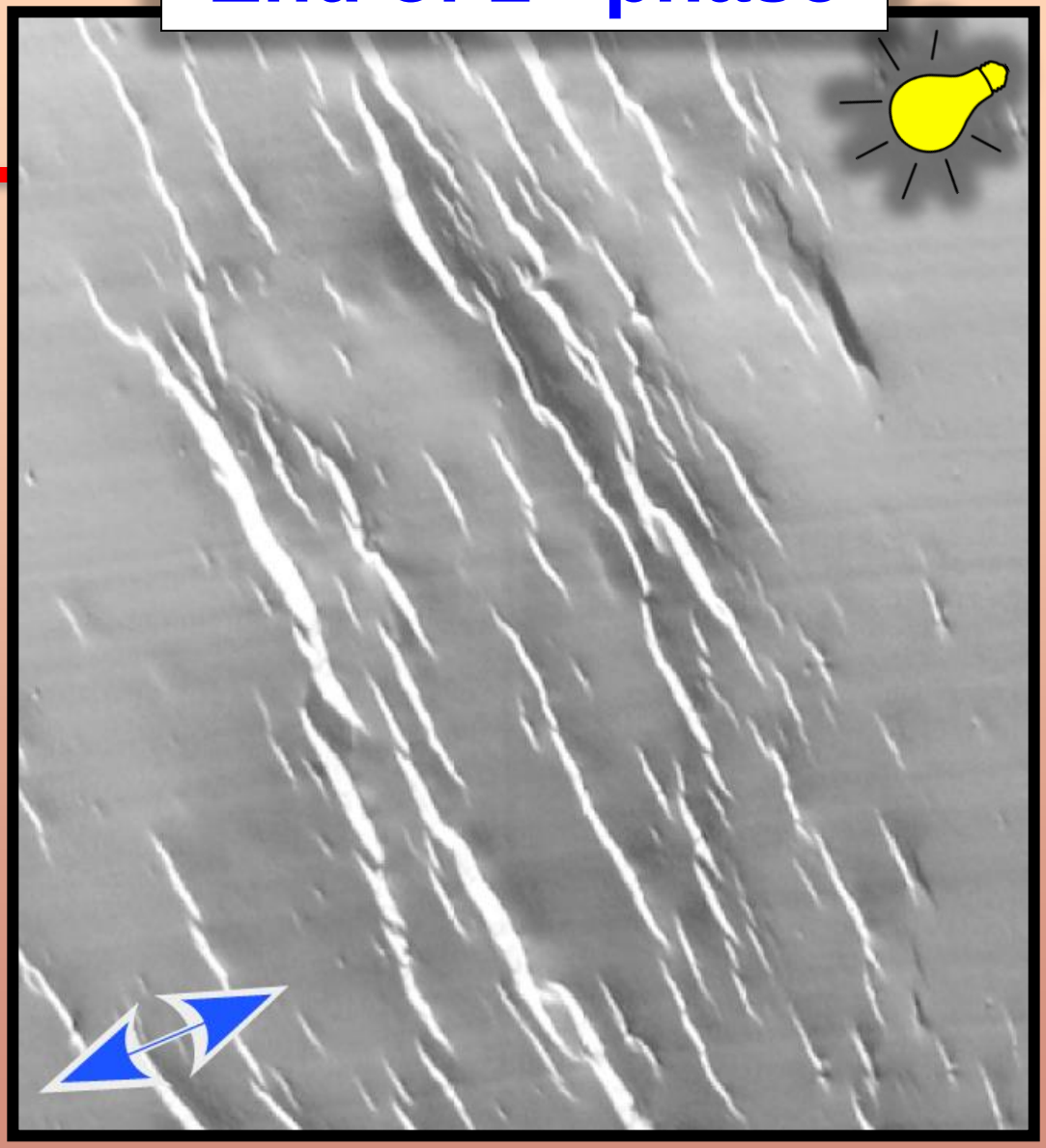
Objectives

- **What types of faults develop during multi-phase extension?**
- Does style of faulting vary with depth?
- Do strikes of faults vary with depth?
- What types of fault interactions develop?
- What do these interactions look like in both map and cross-sectional views?

Surface deformation

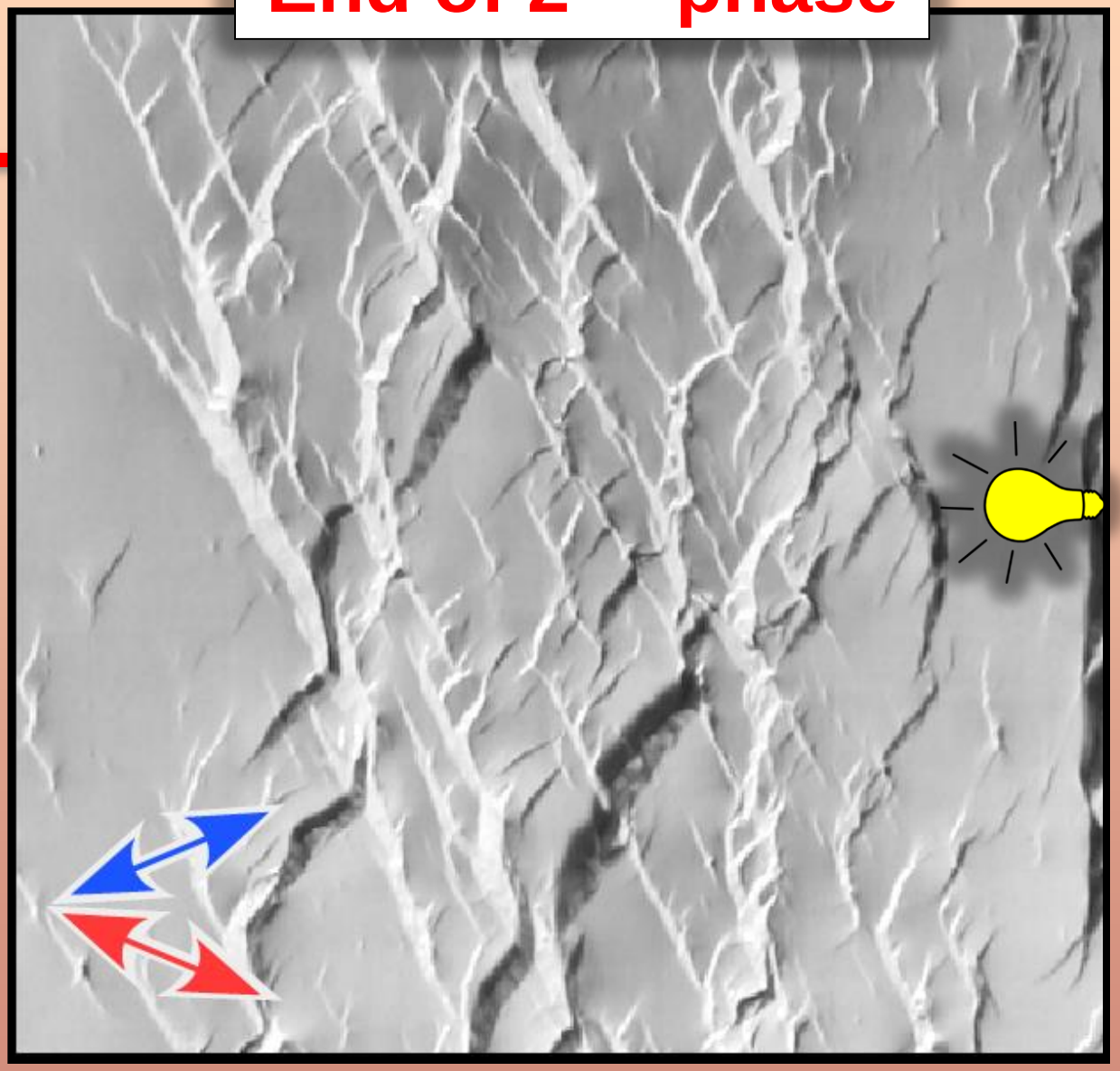
- Normal faults develop during **1st phase** of extension

- Strike perpendicular (within 10 degrees) to **1st-phase** extension direction



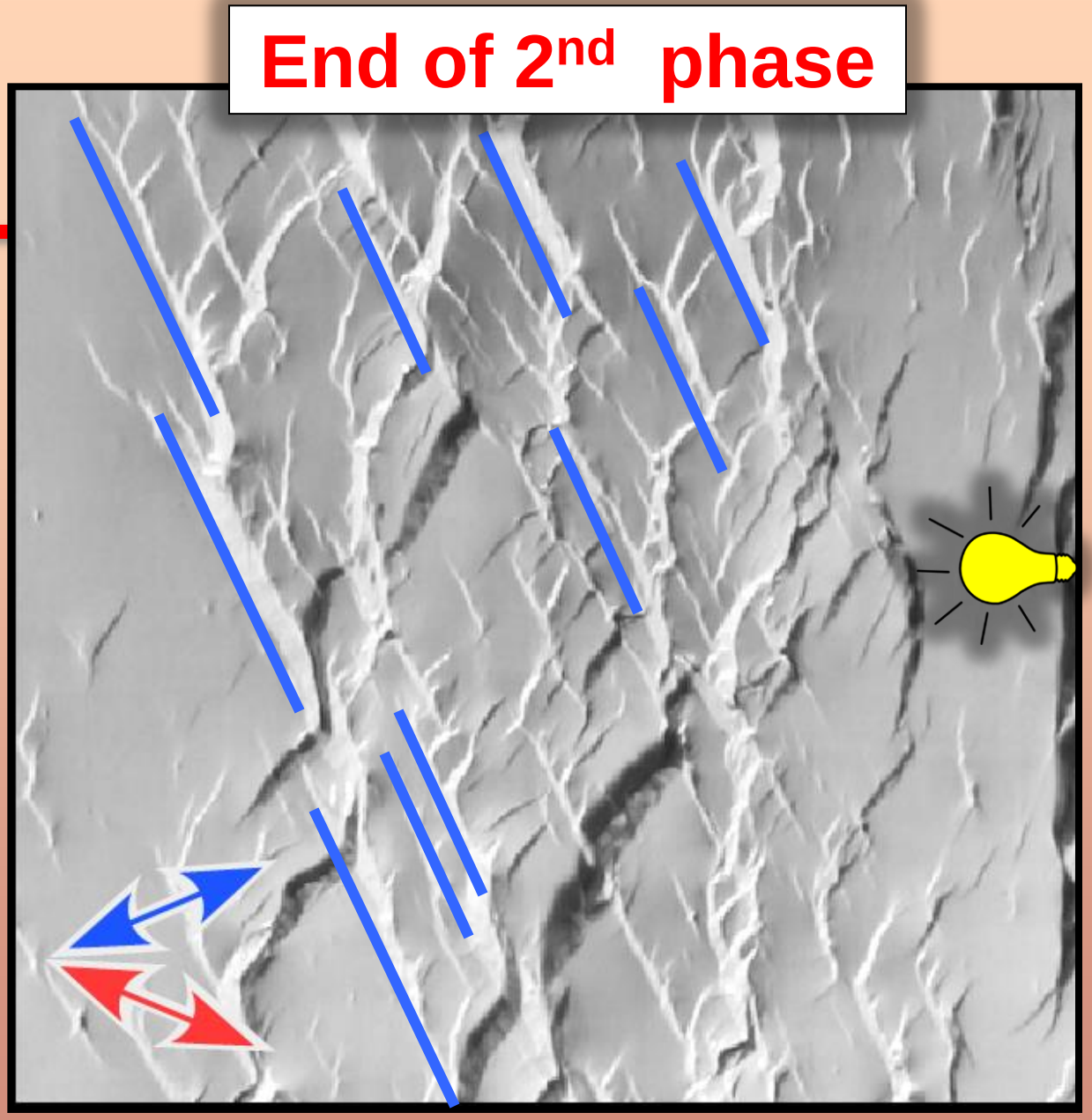
Surface deformation

- Many (but not all) **1st-phase** faults reactivated with oblique slip during **2nd phase** of extension

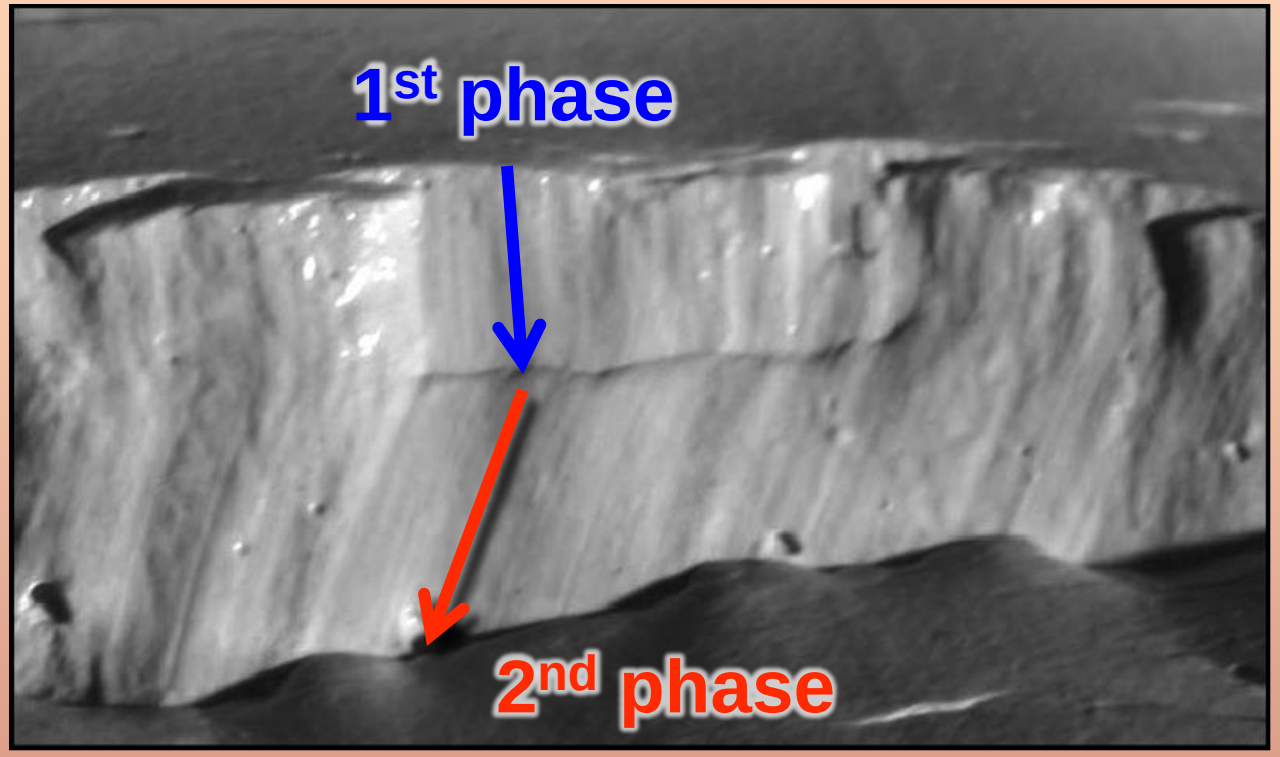


Surface deformation

- Many (but not all) **1st-phase** faults reactivated with oblique slip during **2nd phase** of extension



Surface deformation

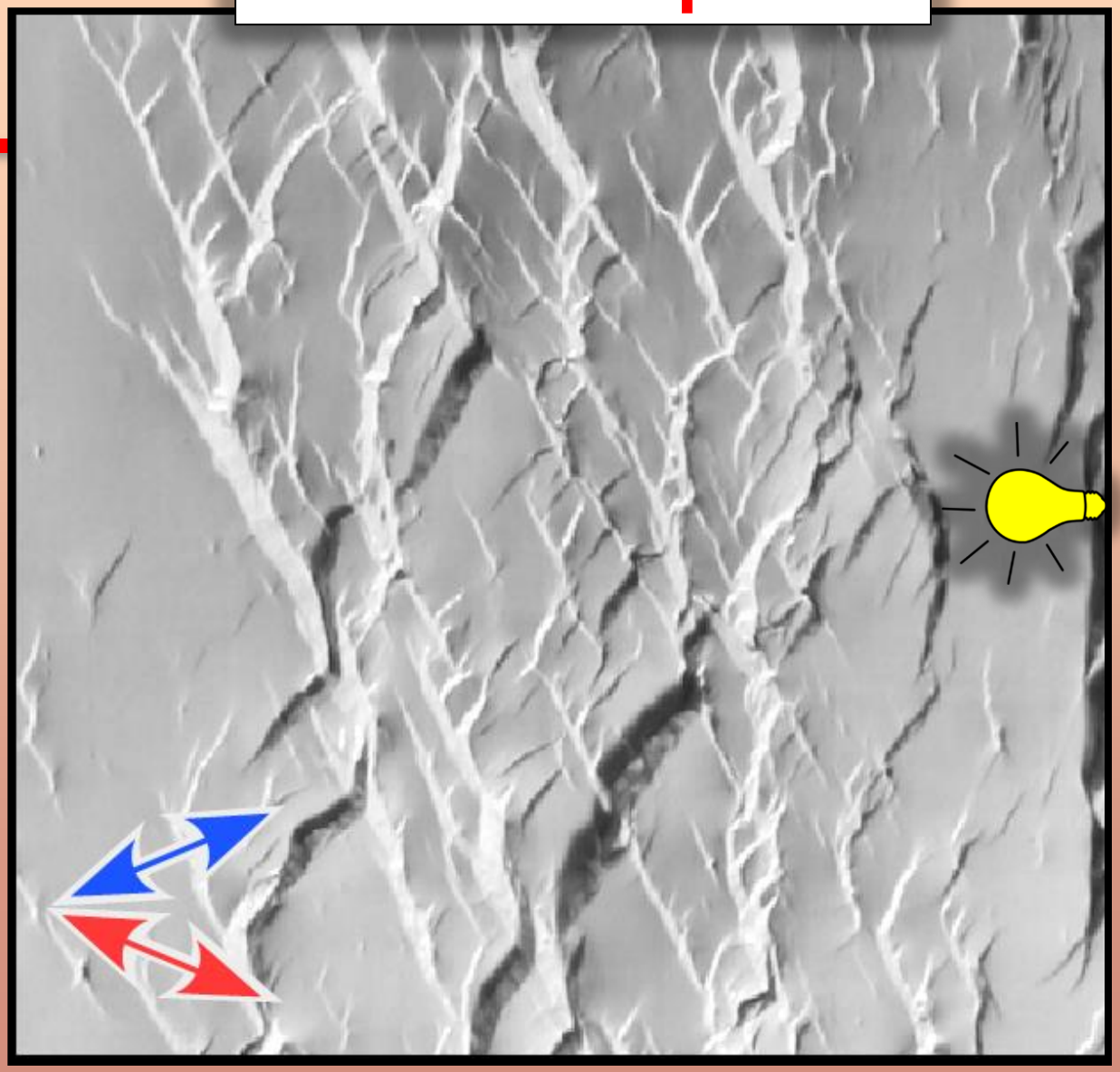


- **Fault corrugations** show that reactivated **1st-phase** faults had oblique slip (normal and right-lateral) during **2nd phase** of extension

Surface deformation

- New **2nd-phase** faults also form

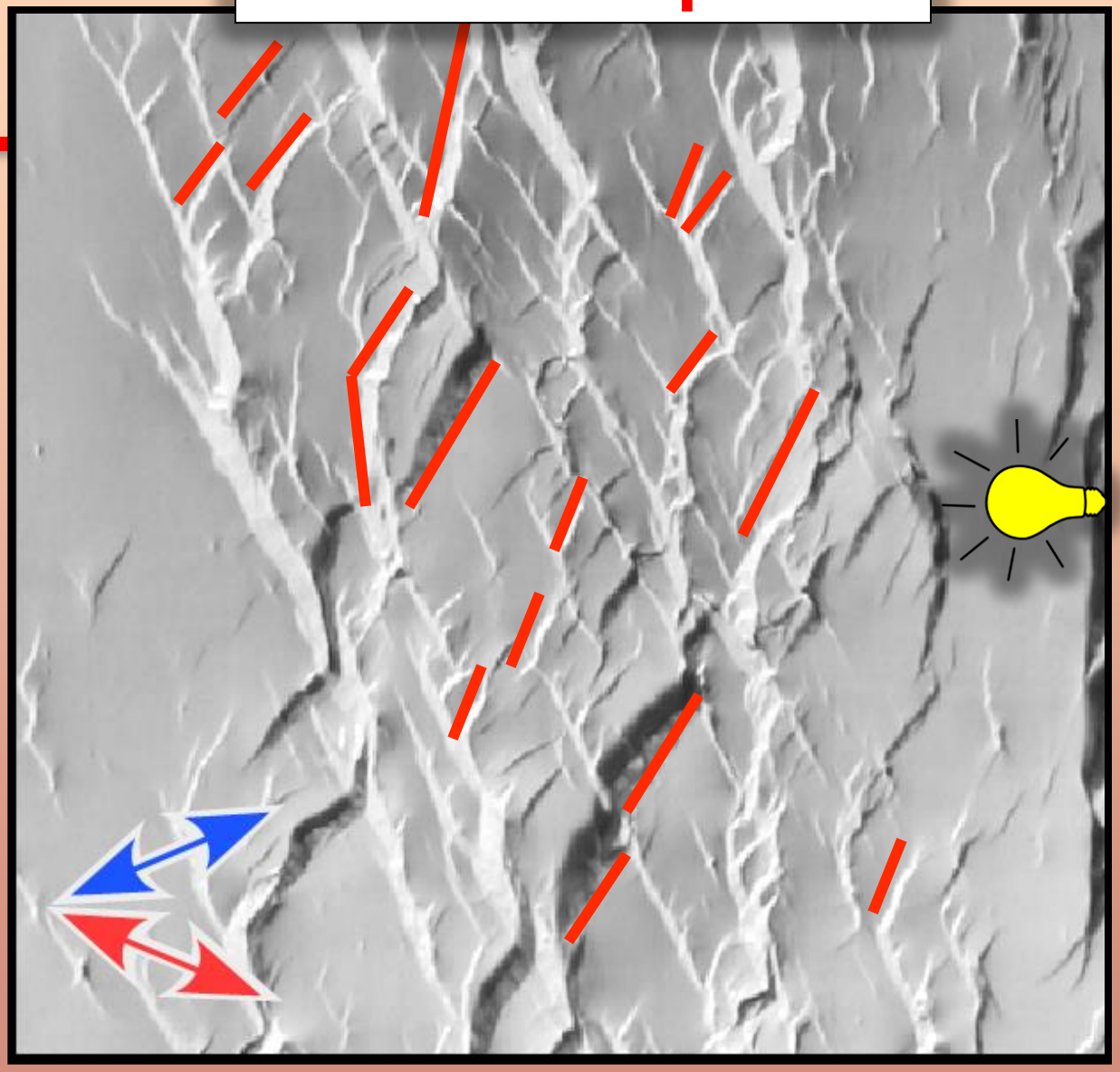
- They are normal faults striking obliquely to orthogonally to **2nd-phase** extension direction



Surface deformation

- New **2nd-phase** faults also form

- They are normal faults striking obliquely to orthogonally to **2nd-phase** extension direction

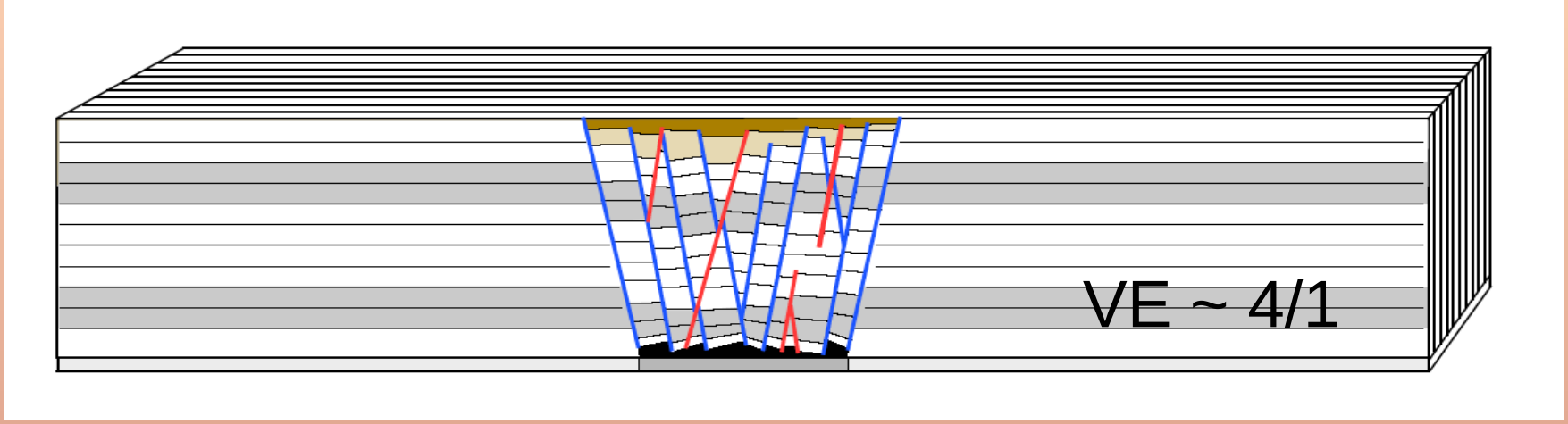


Objectives

- What types of faults develop during multi-phase extension?
- **Does style of faulting vary with depth?**
- Do strikes of faults vary with depth?
- What types of fault interactions develop?
- What do these interactions look like in both map and cross-sectional views?

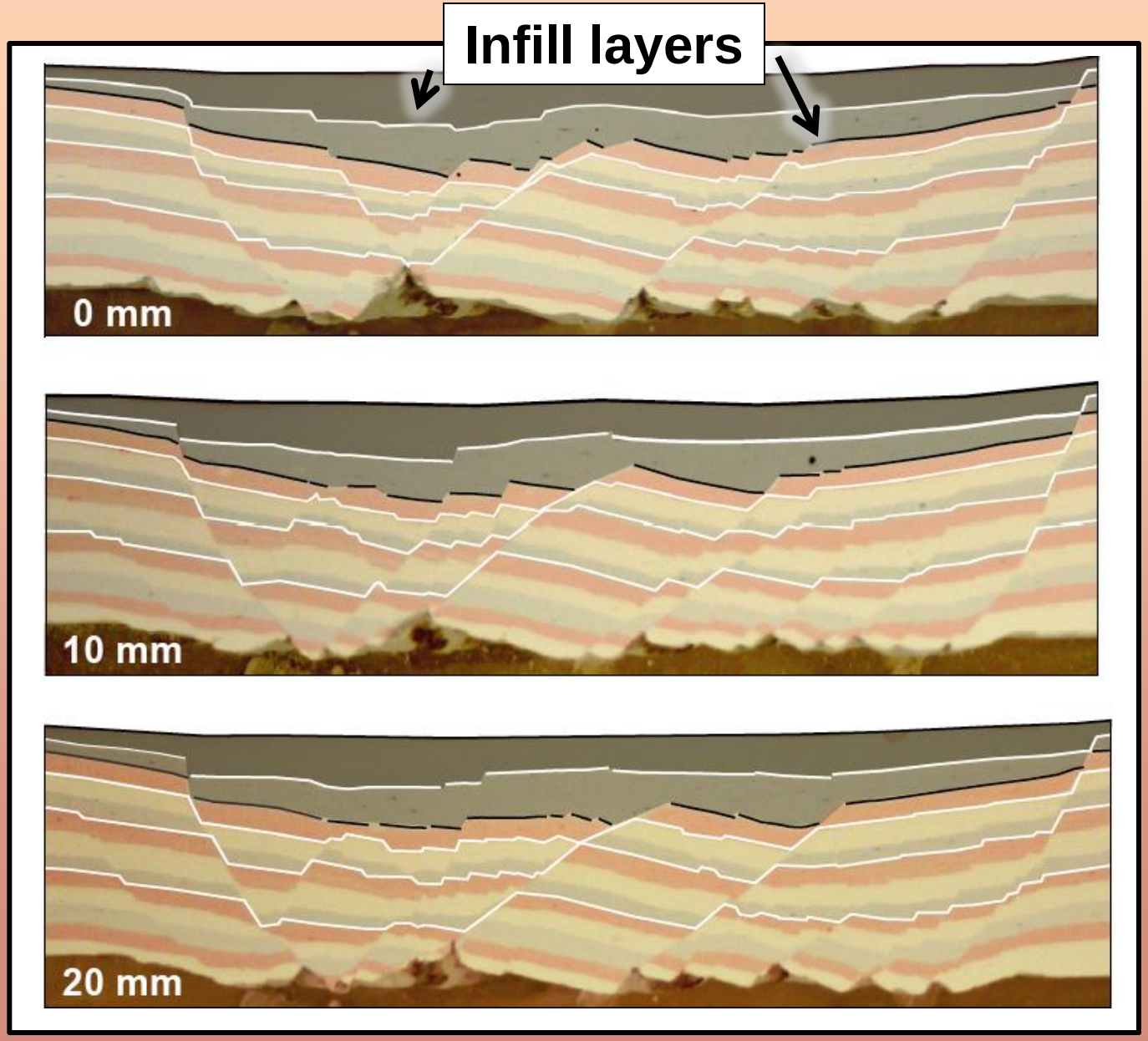
Internal deformation

Layered model - infill after each phase



- Create and interpret 21 serial sections (~ 1-mm apart)
- Create thin-sections for additional detailed analysis

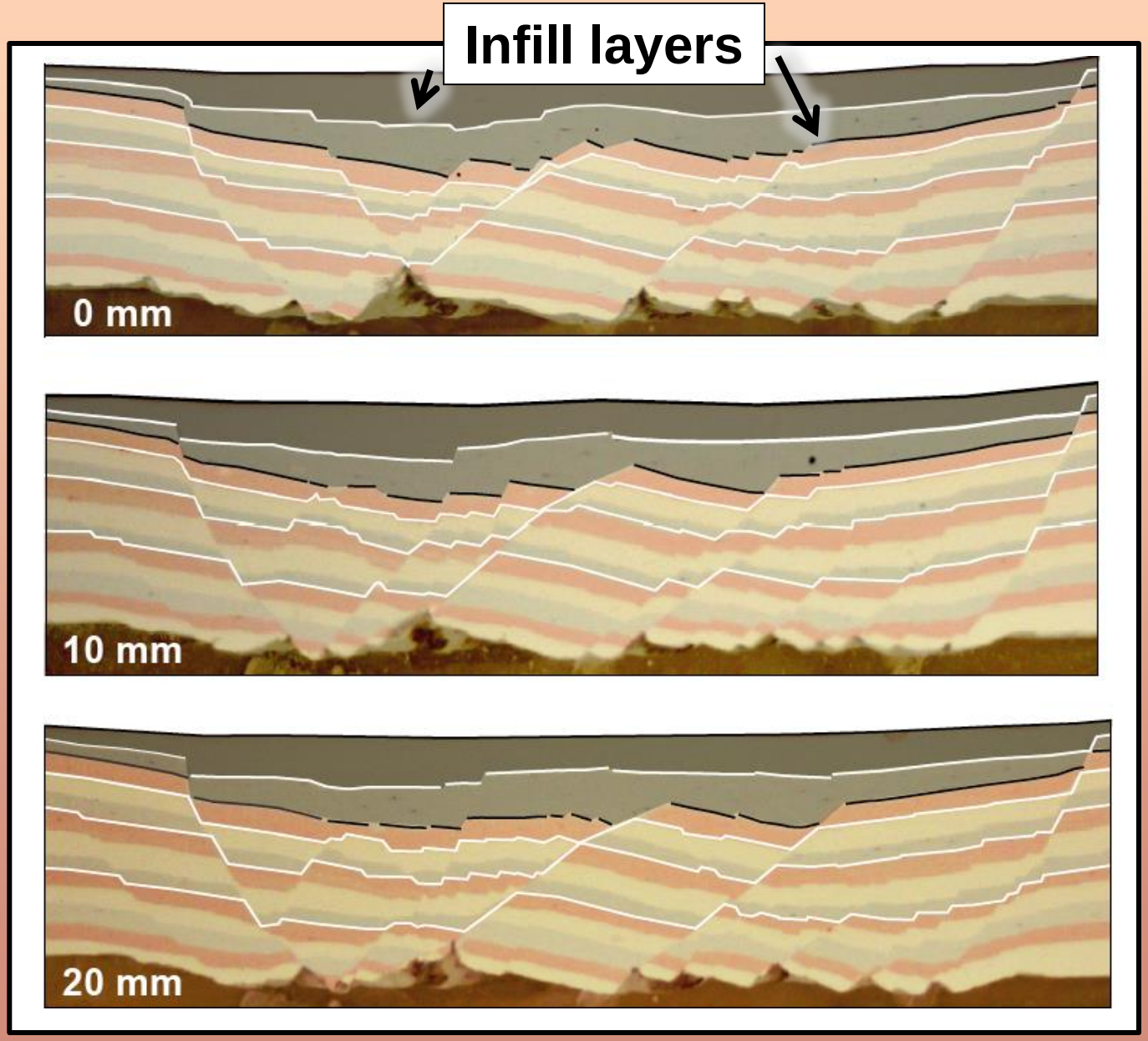
Internal deformation: serial cross sections



- Numerous faults with normal separation

- Which are **1st-phase** faults, and which are **2nd-phase** faults?

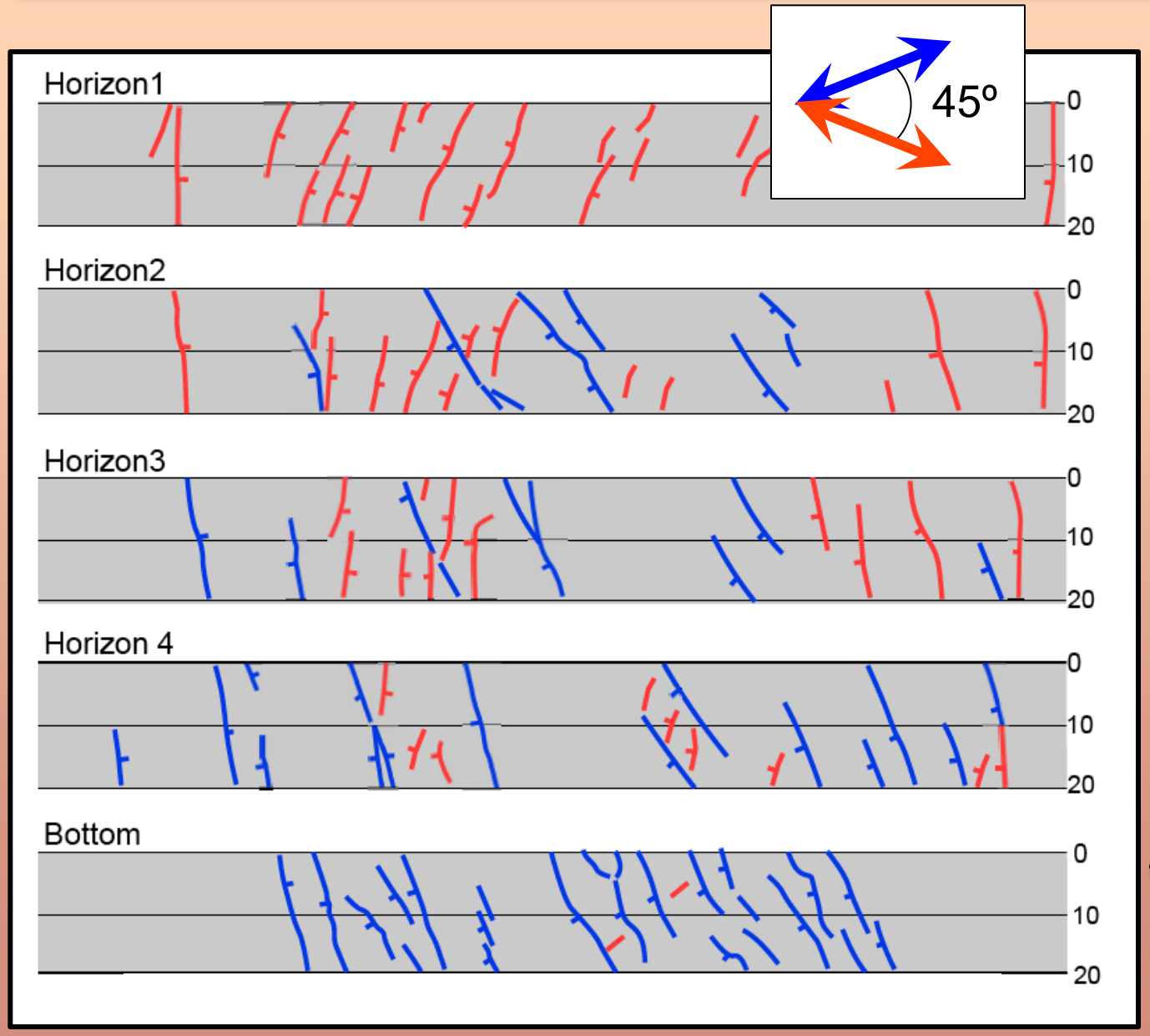
Internal deformation: serial cross sections



- Need **map views** of faults

- Strike indicates whether faults formed during 1st phase or 2nd phase of extension

Internal deformation: map views

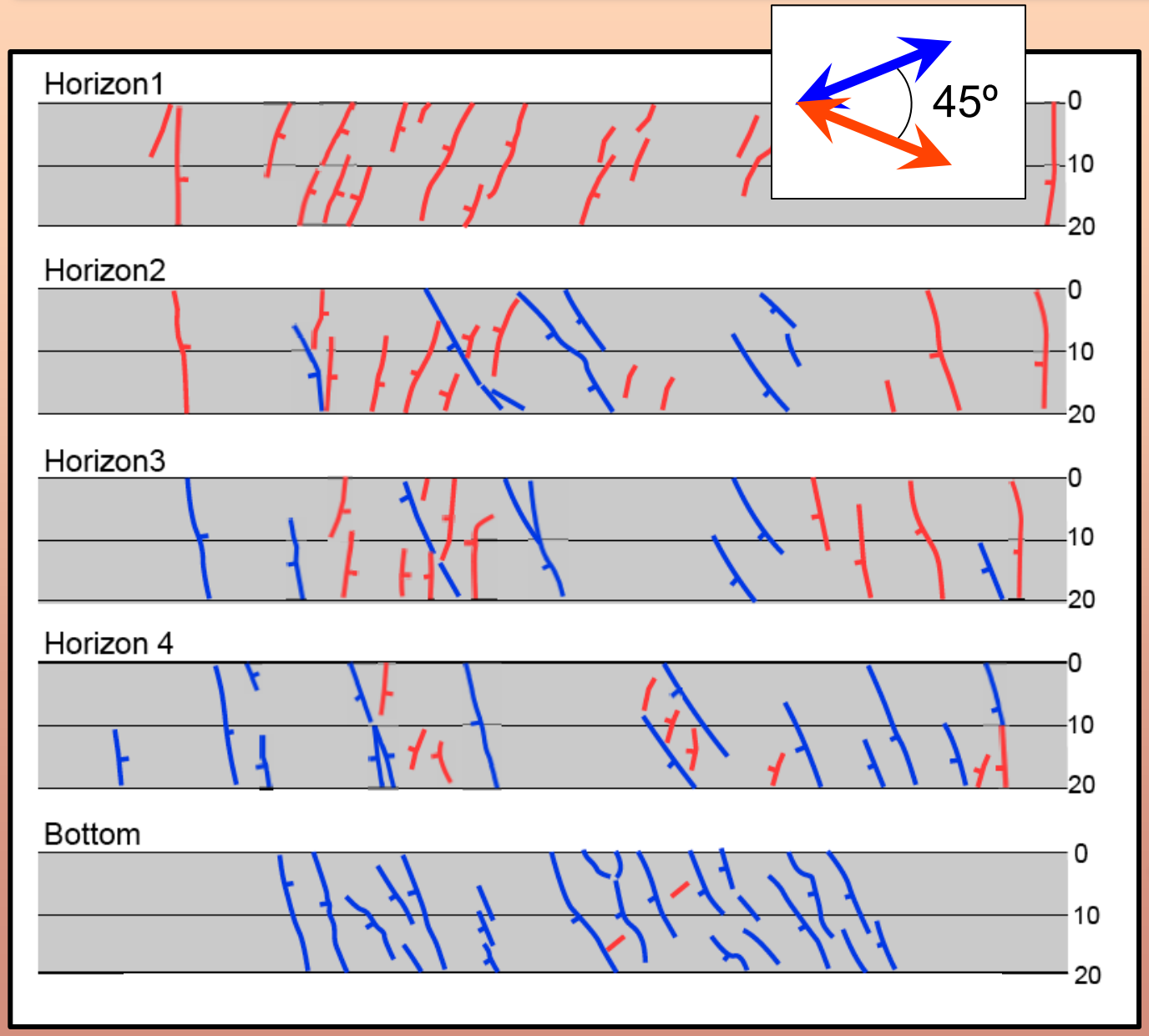


2nd-phase faults

1st-phase faults

Increasing depth

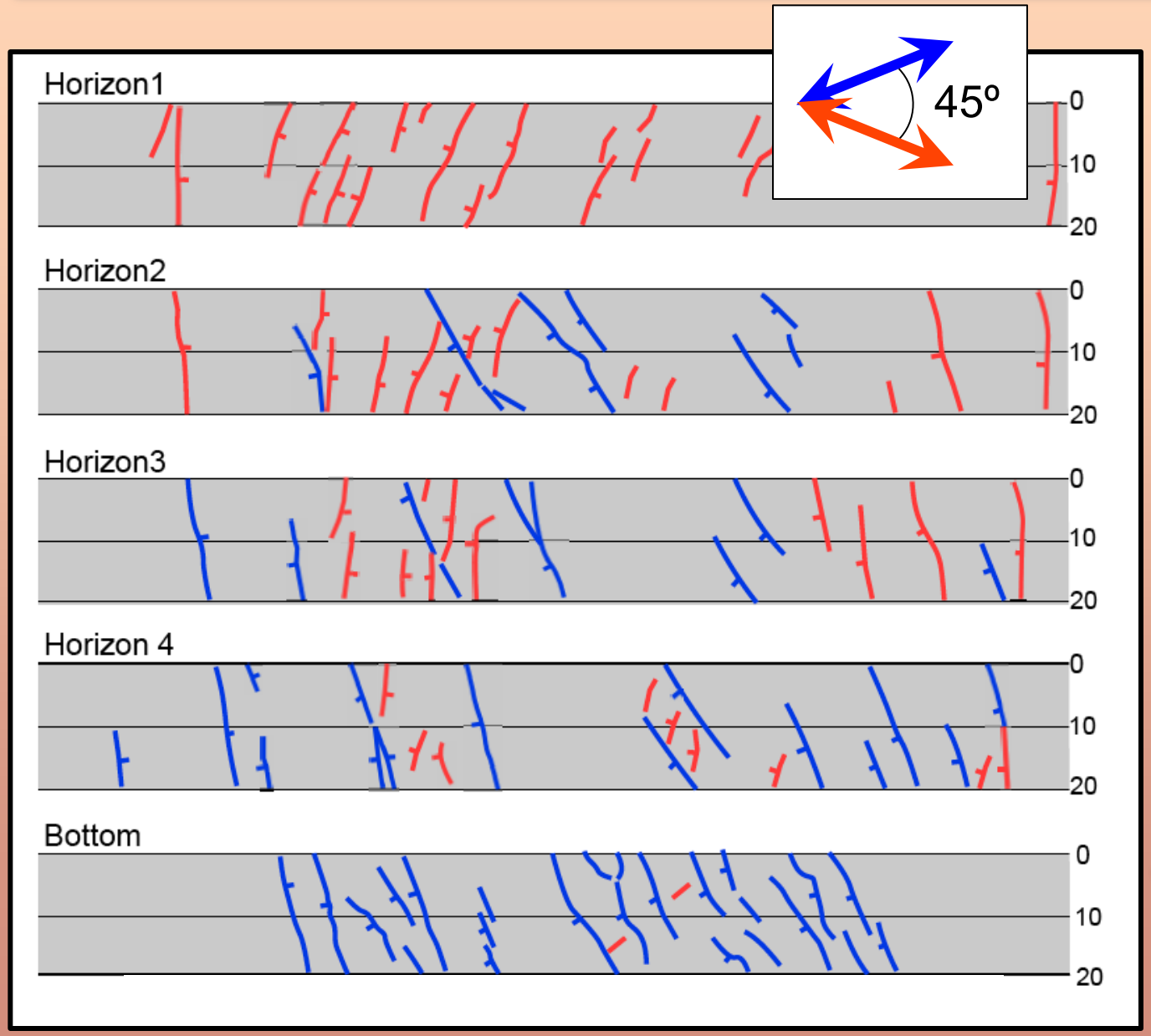
Internal deformation: map views



- **2nd-phase faults** more common at shallow levels
- **1st-phase faults** more common at depth

Increasing depth

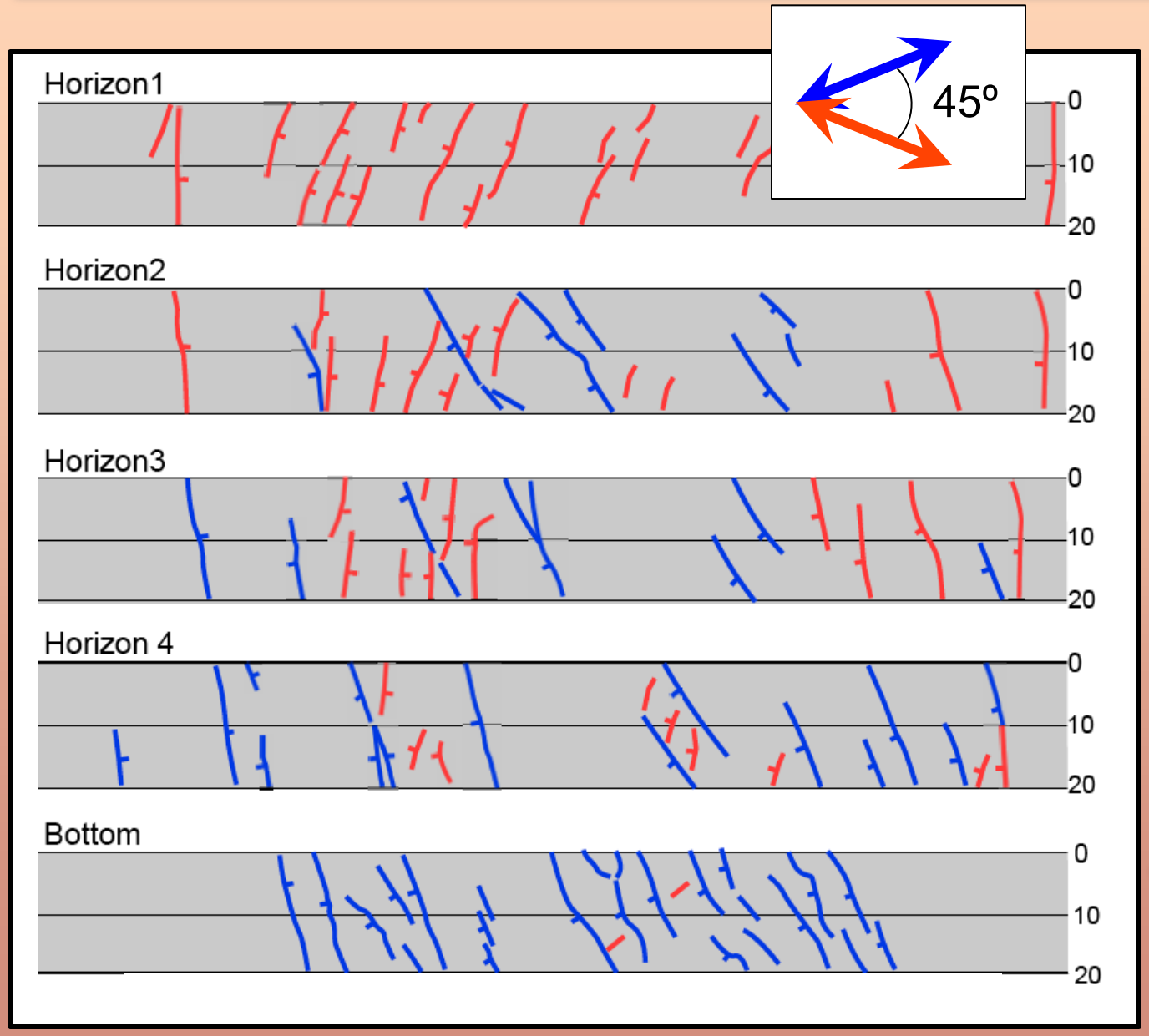
Internal deformation: map views



- **Style of faulting varies with depth**

Increasing depth

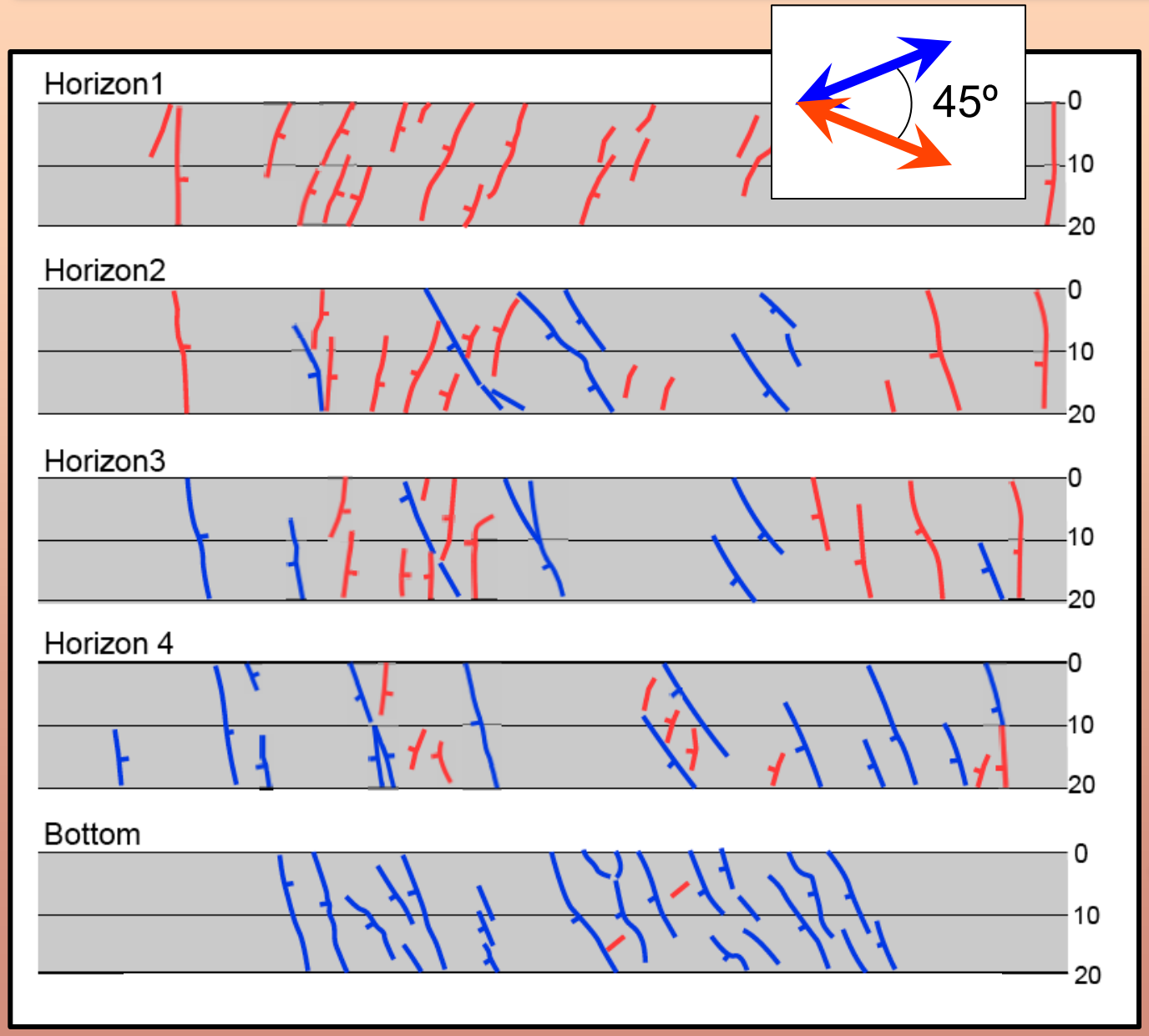
Internal deformation: map views



- Normal faulting occurs at shallow levels where **1st-phase faults** are less common

Increasing depth

Internal deformation: map views



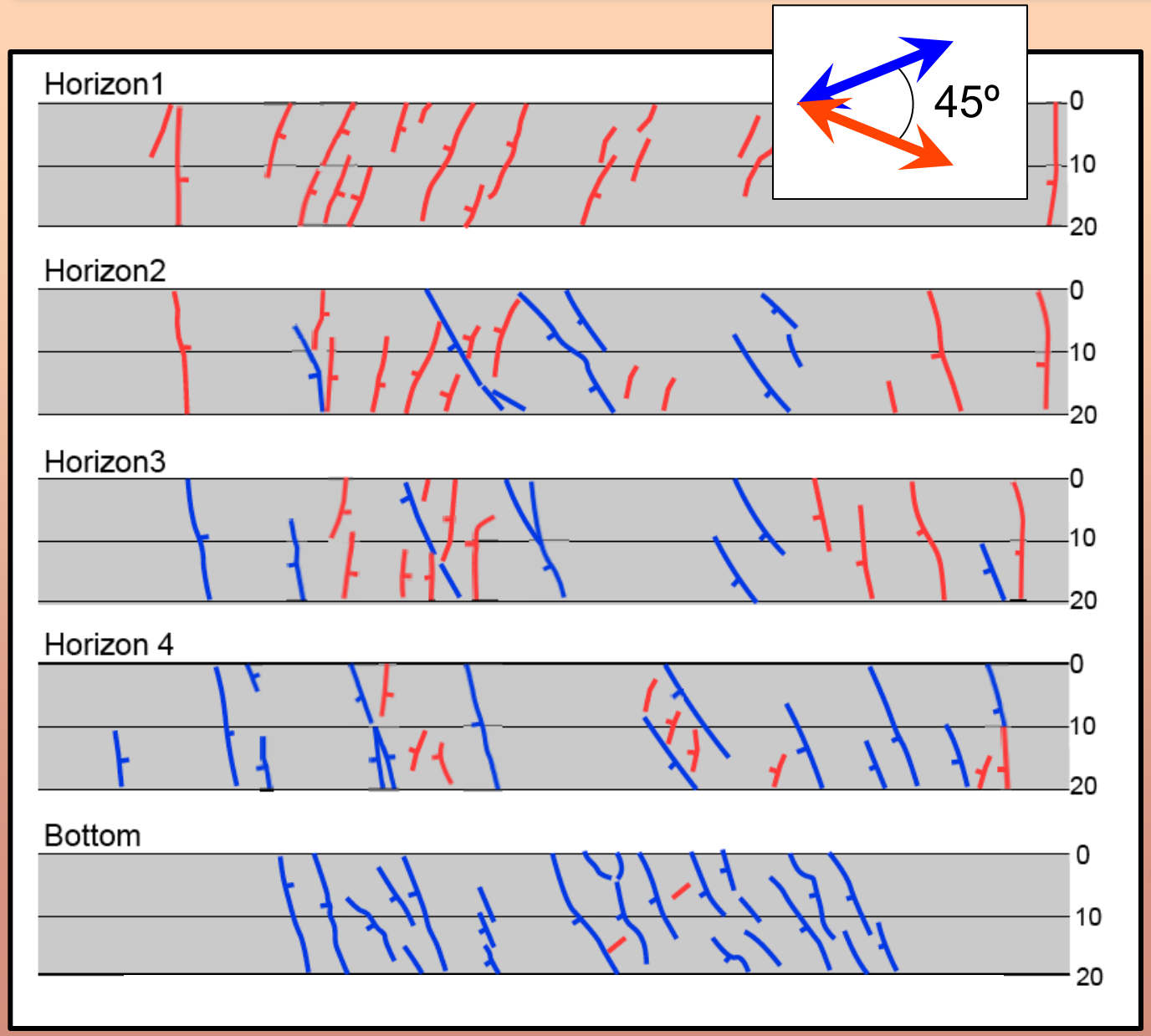
- Oblique-slip faulting occurs at depth where **1st-phase faults** are more common

Increasing depth

Objectives

- What types of faults develop during multi-phase extension?
- Does style of faulting vary with depth?
- **Do strikes of faults vary with depth?**
- What types of fault interactions develop?
- What do these interactions look like in both map and cross-sectional views?

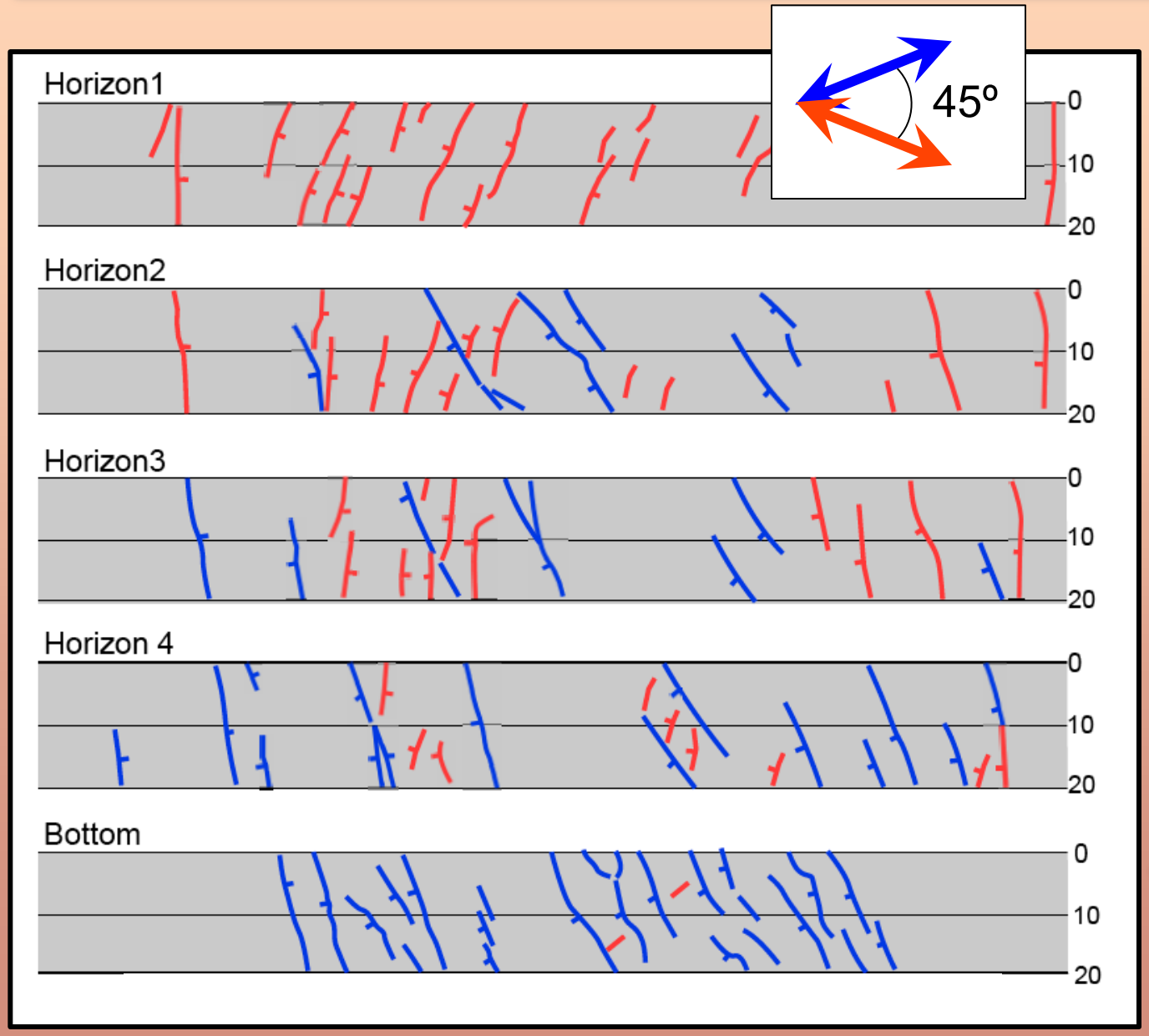
Internal deformation: map views



- Strike of **1st-phase faults** consistent with depth

Increasing depth

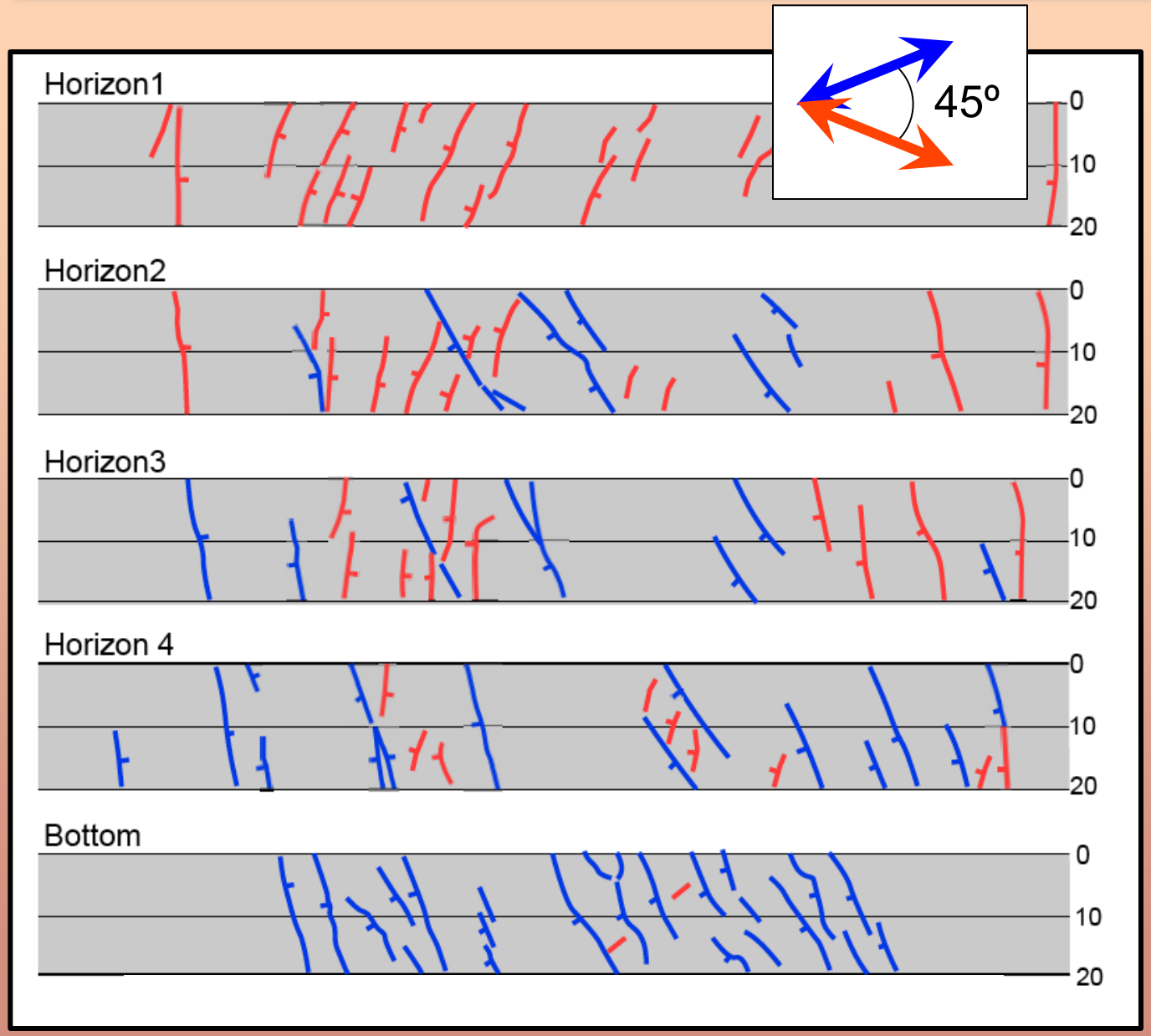
Internal deformation: map views



- Strike of **2nd-phase faults** varies with depth

Increasing depth

Internal deformation: map views



- Strike becomes increasingly oblique to **2nd-phase** extension direction with depth

Increasing depth

Objectives

- What types of faults develop during multi-phase extension?
- Does style of faulting vary with depth?
- Do strikes of faults vary with depth?
- **What types of fault interactions develop?**
- **What do these interactions look like in both map and cross-sectional views?**

Fault interactions

- Two broad categories of interactions between **1st-phase** and **2nd-phase** faults

Synthetic – faults dip in same general direction

- Upward propagation from fault tip
- Upward, outward propagation from fault surface
- Linkage

Antithetic – faults dip in opposing directions

- Cut and offset

Fault interactions

- Two broad categories of interactions between **1st-phase** and **2nd-phase** faults

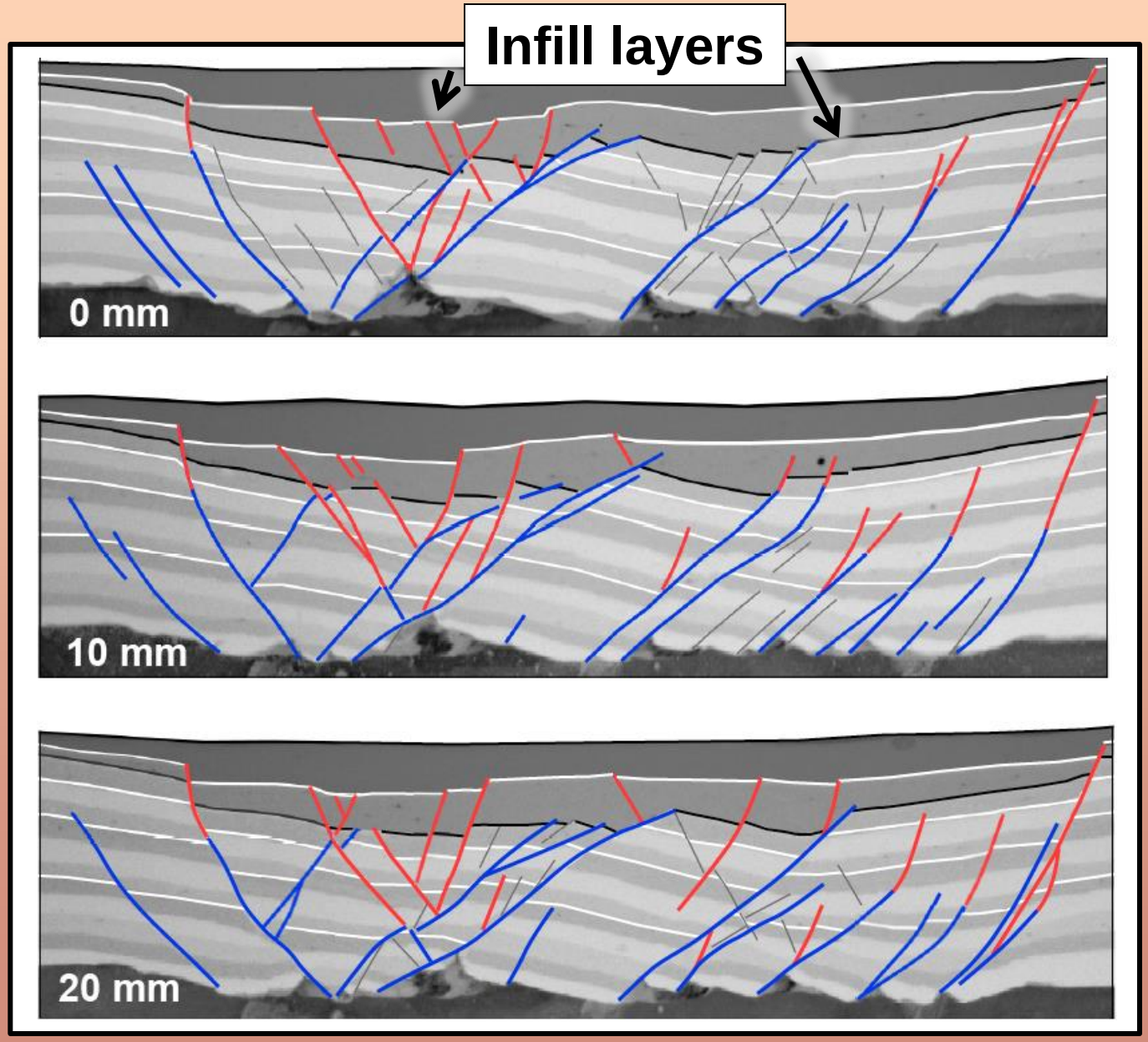
Synthetic – faults dip in same general direction

- Upward propagation from fault tip
- Upward, outward propagation from fault surface
- Linkage

Antithetic – faults dip in opposing directions

- Cut and offset

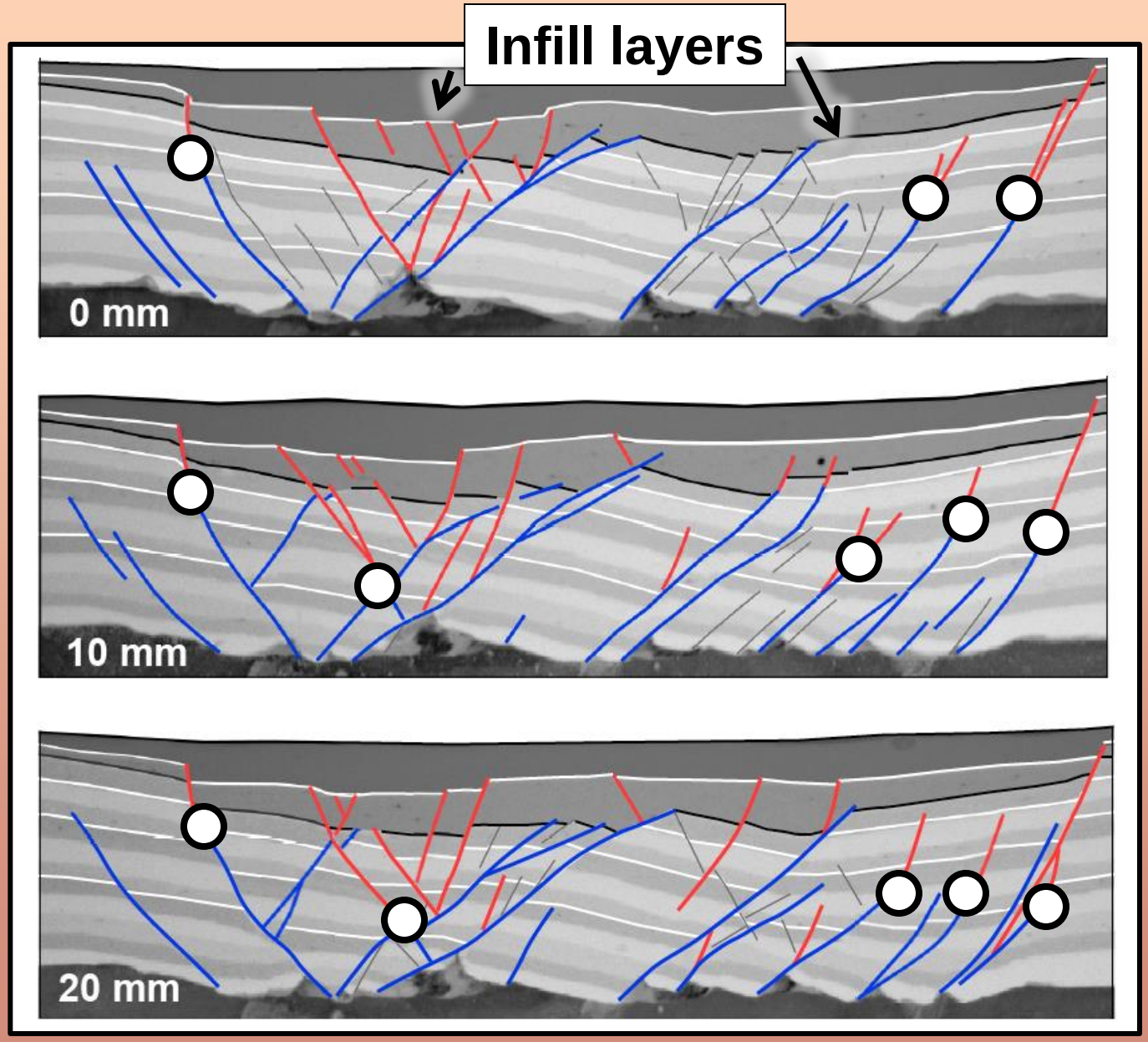
Fault interactions



2nd-phase faults

1st-phase faults

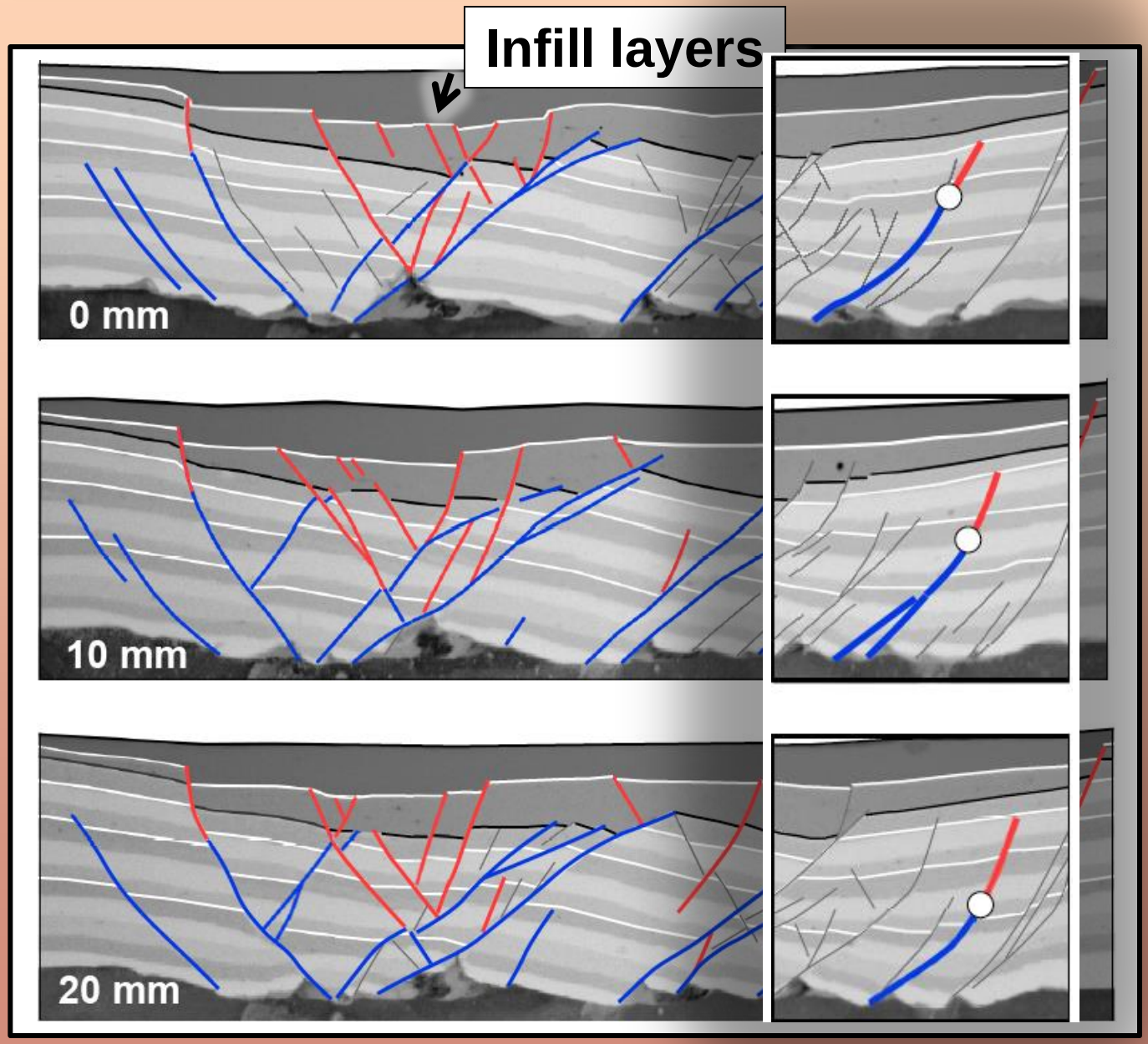
Fault interactions



- Many faults are hybrid

- Composed of **2nd-phase segments** that emanate from tips of deep, reactivated **1st-phase faults**

Fault interactions

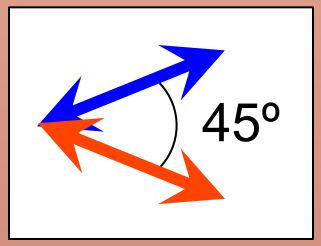


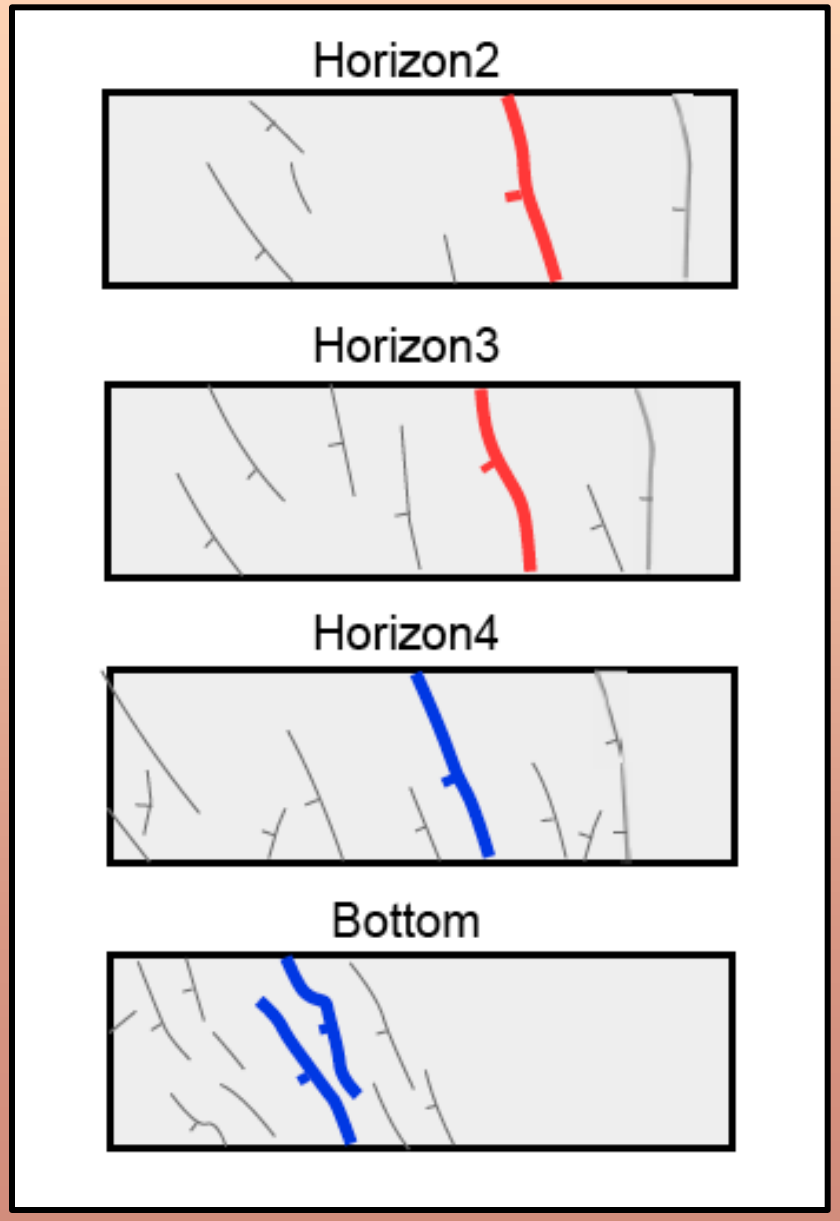
- Typical hybrid fault with **2nd-phase segment** emanating from tip of deep, reactivated **1st-phase fault**

Fault interactions

2nd-phase segment

1st-phase segment

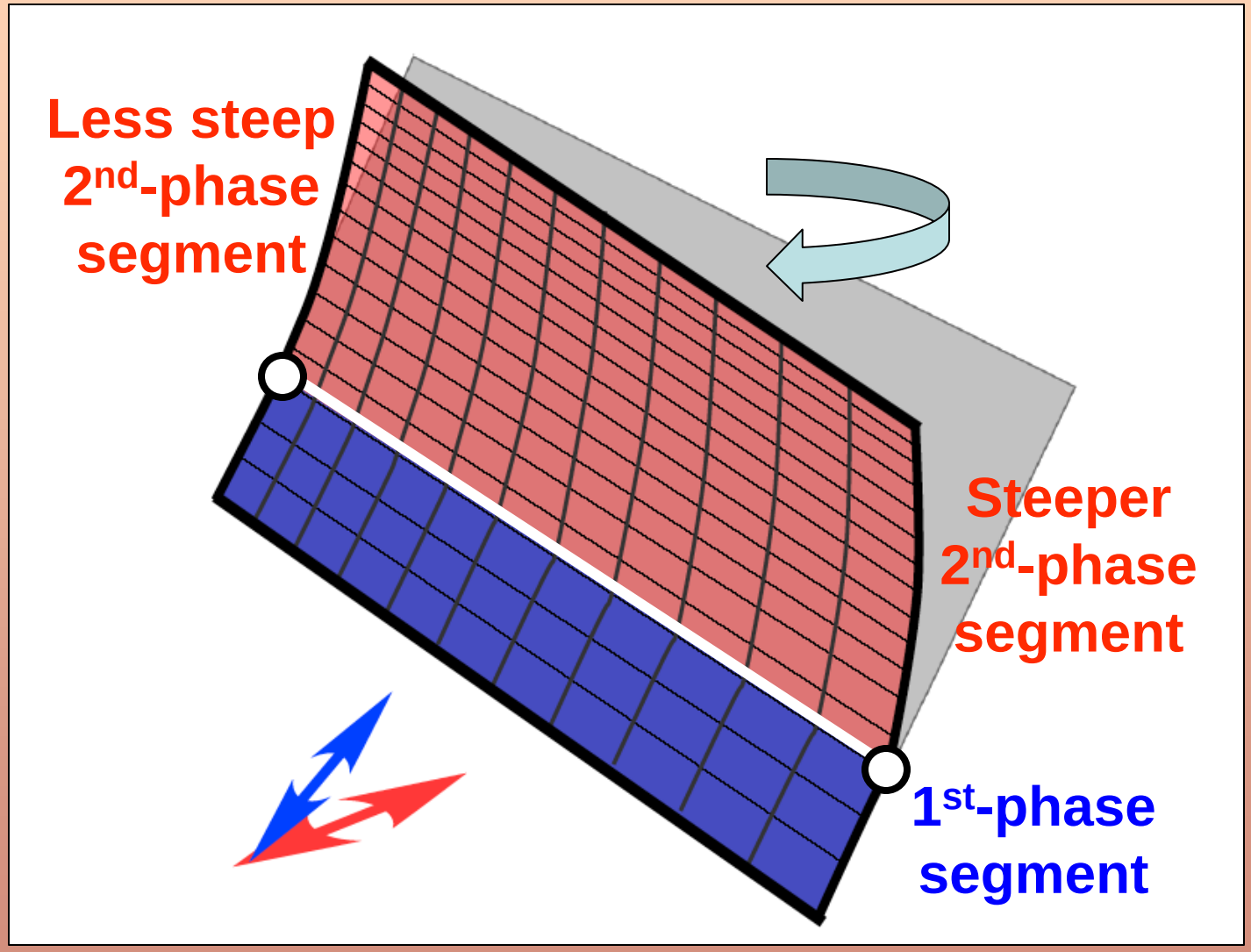




Increasing depth

- Strike changes with depth, rotating ~20° CW during its upward propagation

Fault interactions



- Strike changes with depth, rotating ~20° CW during upward propagation

Fault interactions

- Two broad categories of interactions between **1st-phase** and **2nd-phase** faults

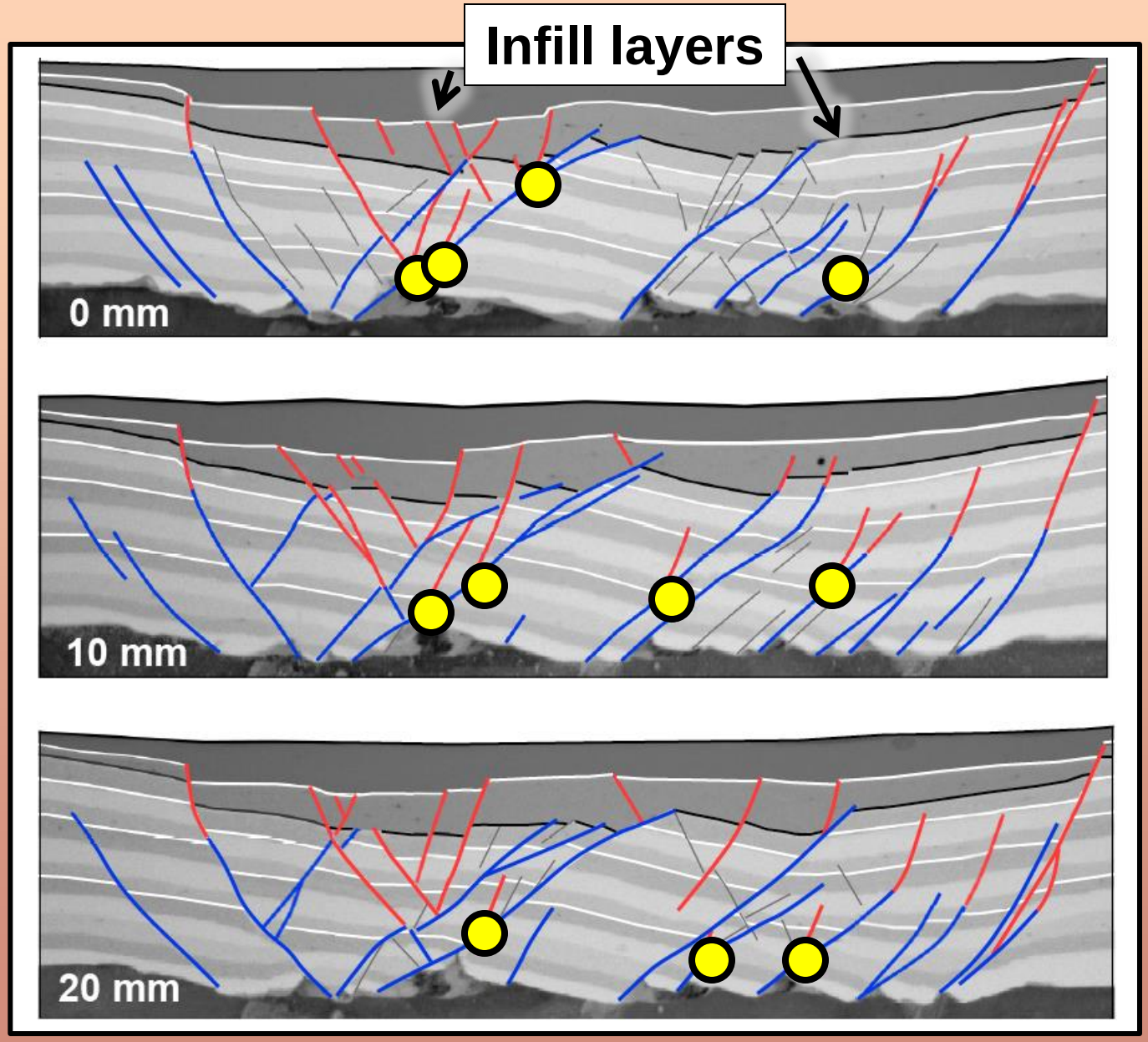
Synthetic – faults dip in same general direction

- Upward propagation from fault tip
- ⇨ Upward, outward propagation from fault surface
- Linkage

Antithetic – faults dip in opposing directions

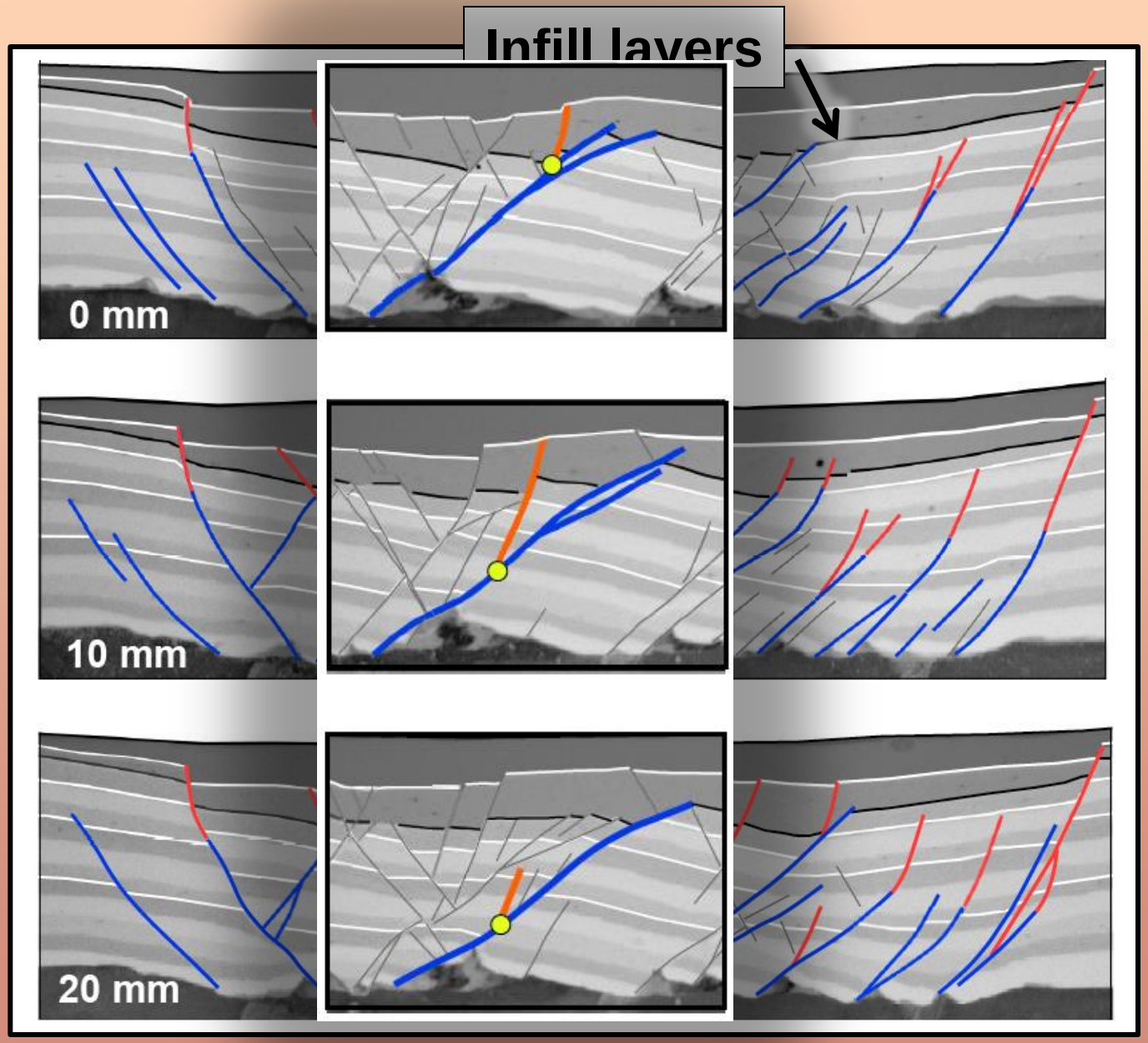
- Cut and offset

Fault interactions



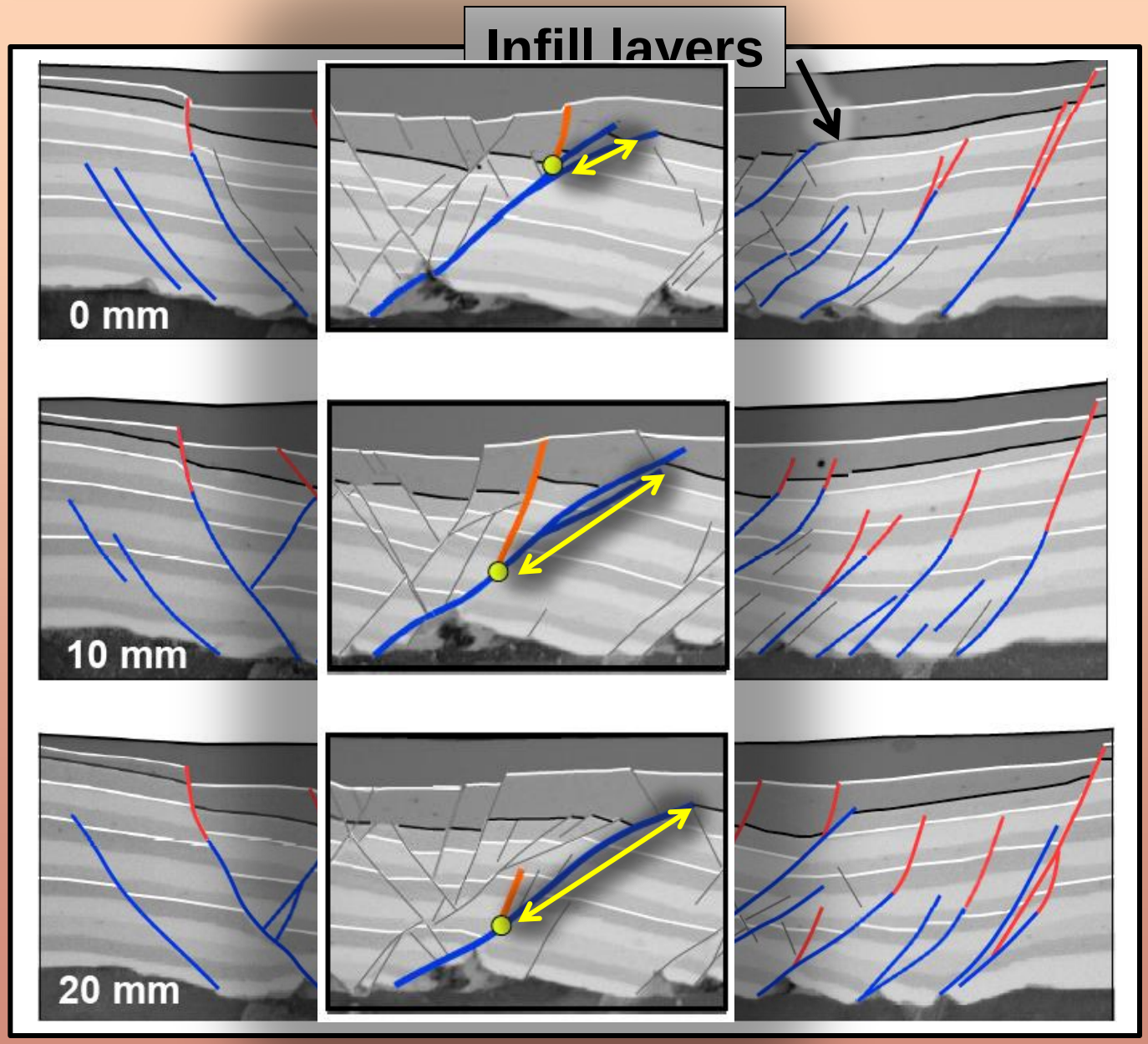
- **2nd-phase faults** nucleate on and propagate away from **1st-phase faults**

Fault interactions



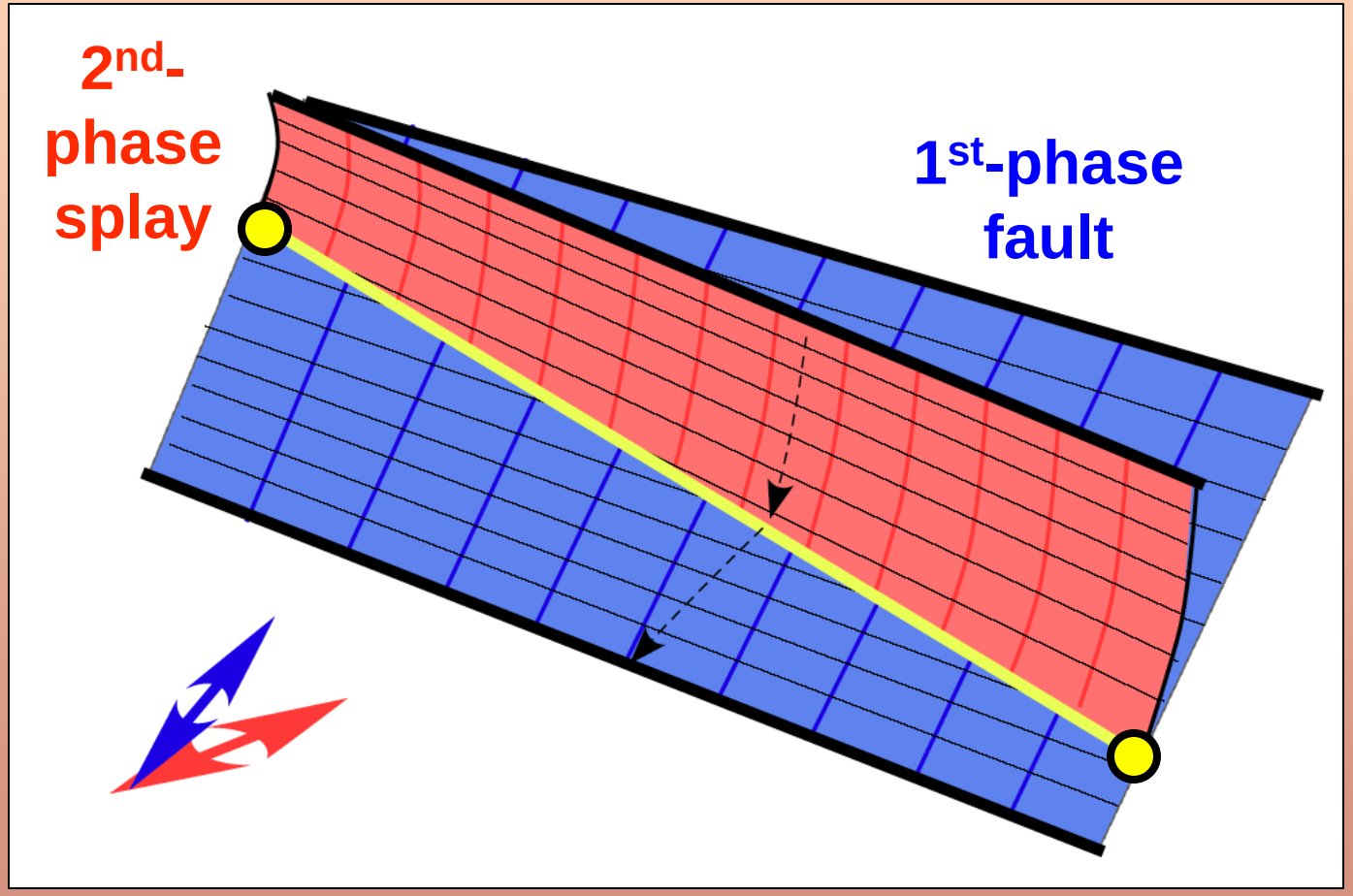
- Typical **2nd-phase fault** that nucleates on and propagates away from **1st-phase fault**

Fault interactions



- Branch line between **1st-phase fault** and **2nd-phase splay** plunges

Fault interactions

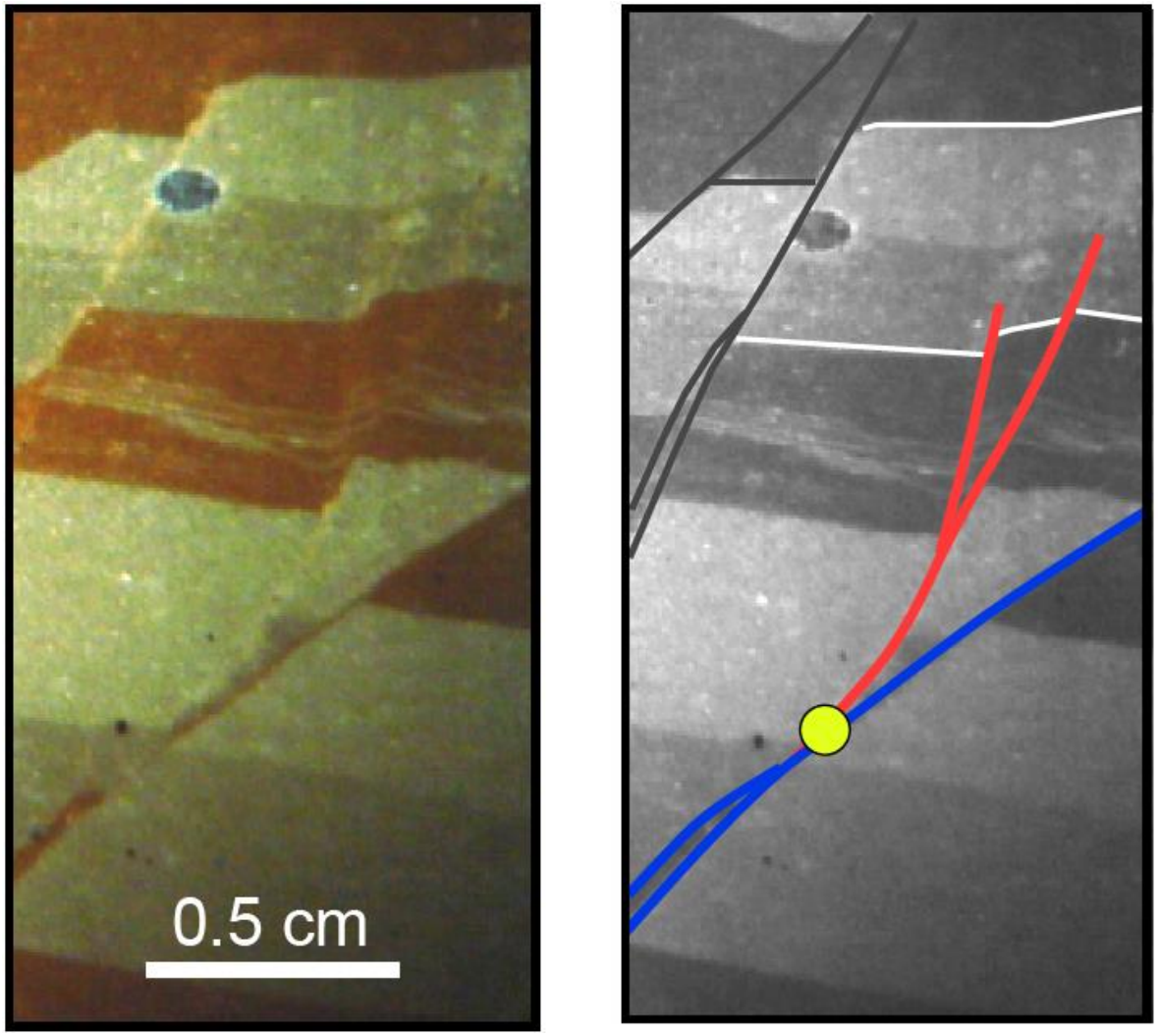


- Branch line between **1st-phase fault** and **2nd-phase splay** plunges

Fault interactions

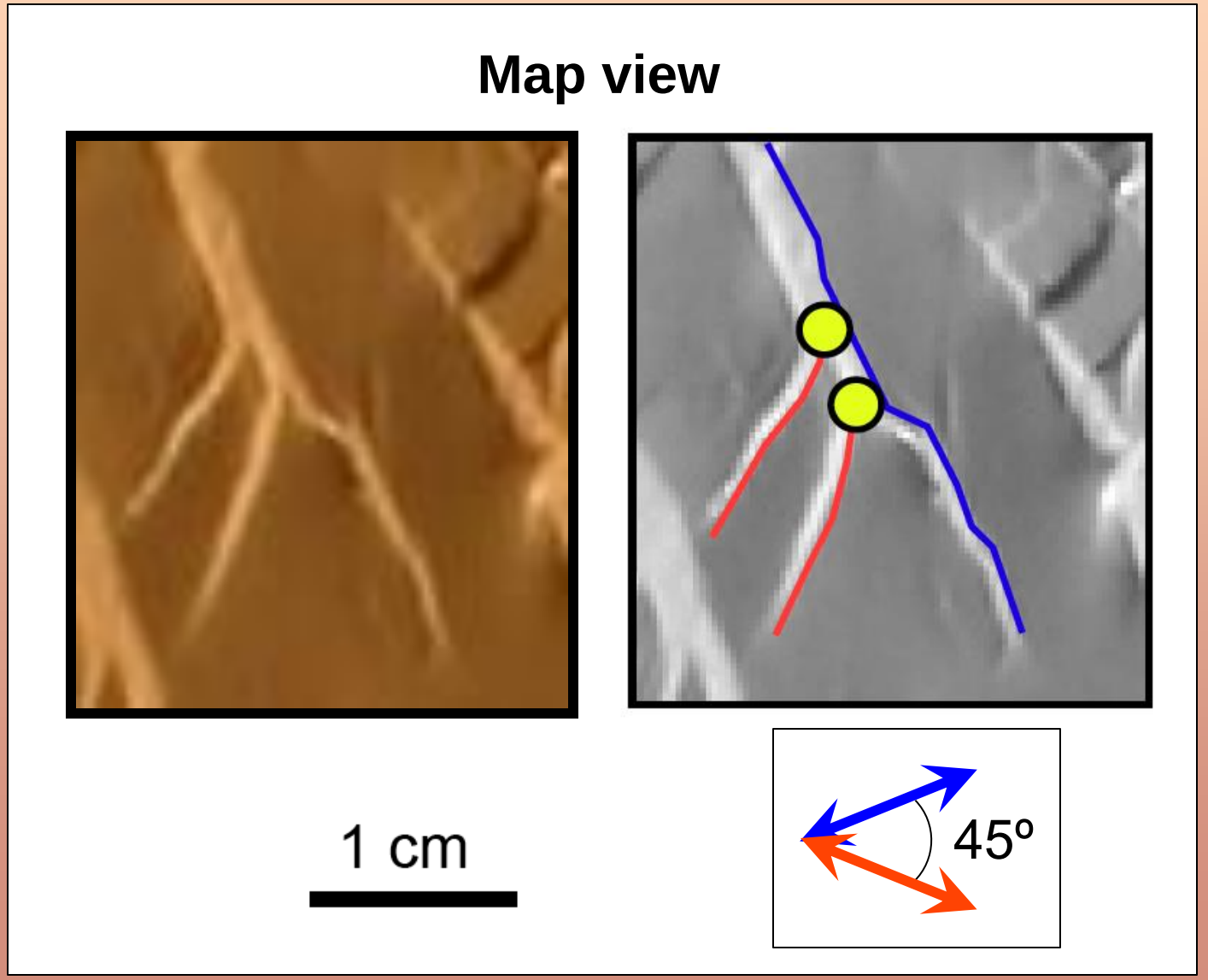
- **2nd-phase faults** nucleate on and propagate away from **1st-phase fault** creating fault splays

Cross-section view in thin section



Fault interactions

- **2nd-phase faults** nucleate on and propagate away from **1st-phase fault** creating fault splays



Fault interactions

- Two broad categories of interactions between **1st-phase** and **2nd-phase** faults

Synthetic – faults dip in same general direction

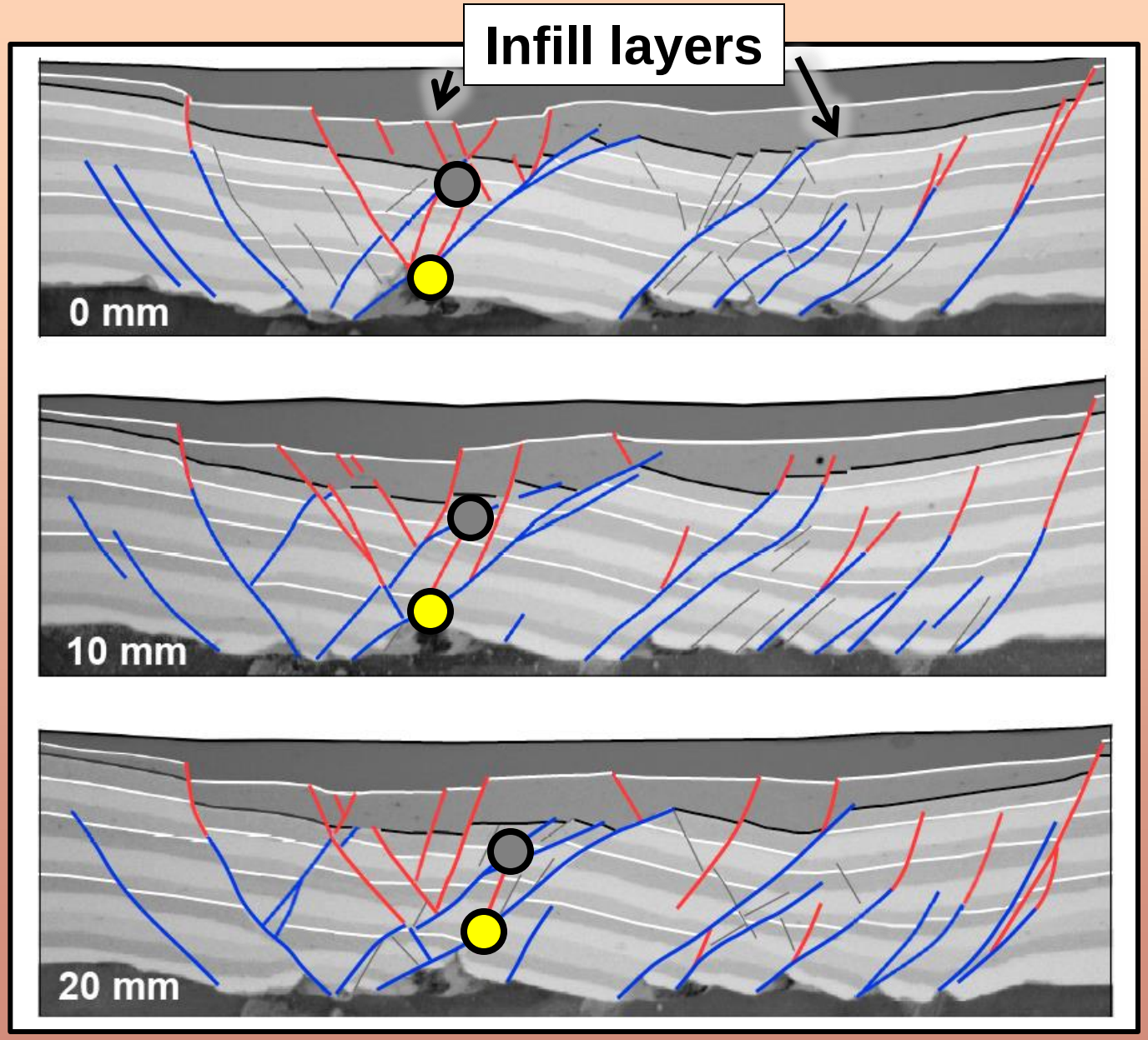
- Upward propagation from fault tip
- Upward, outward propagation from fault surface

⇨ Linkage

Antithetic – faults dip in opposing directions

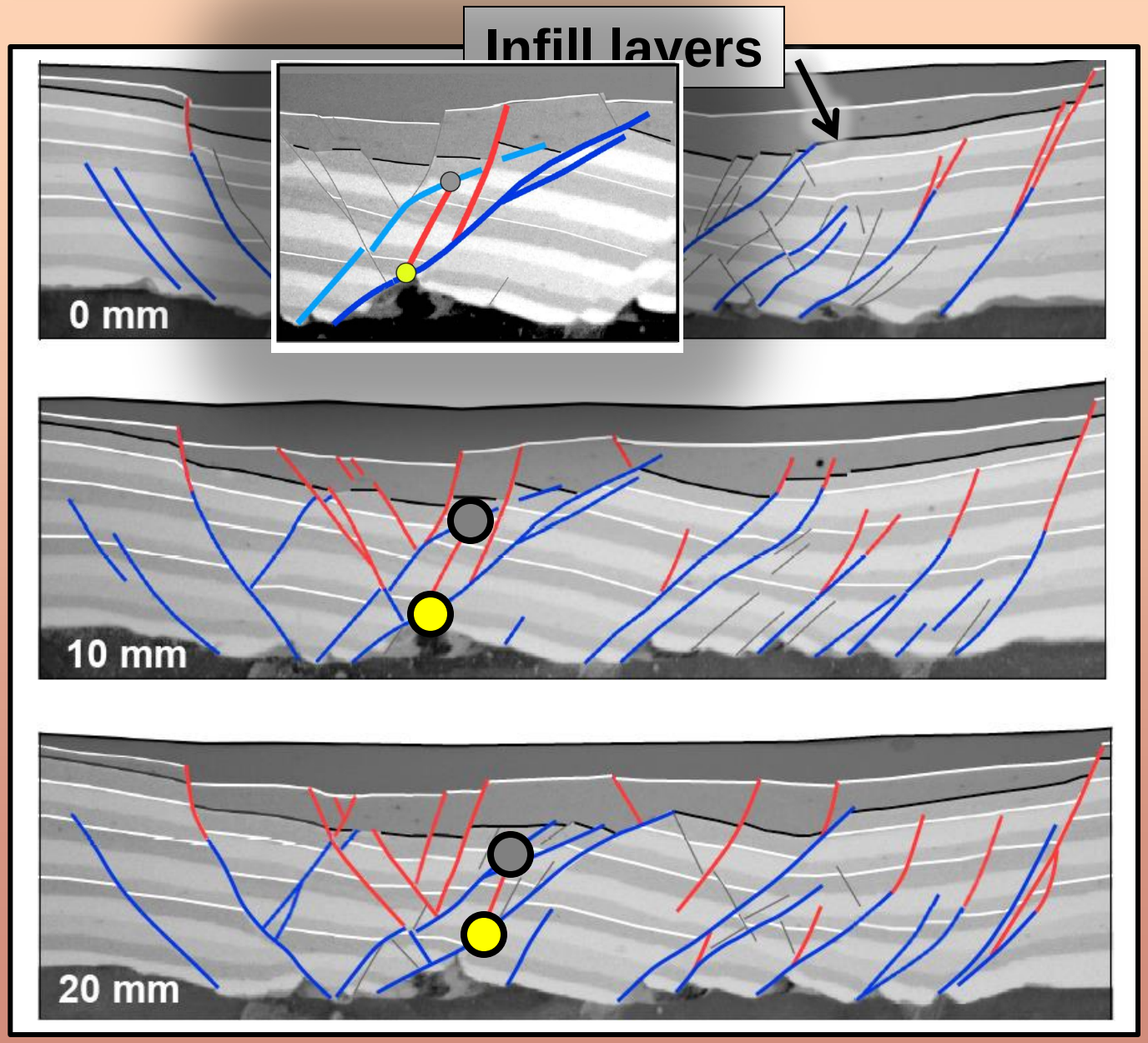
- Cut and offset

Fault interactions



- **2nd-phase faults** link **1st-phase faults**

Fault interactions

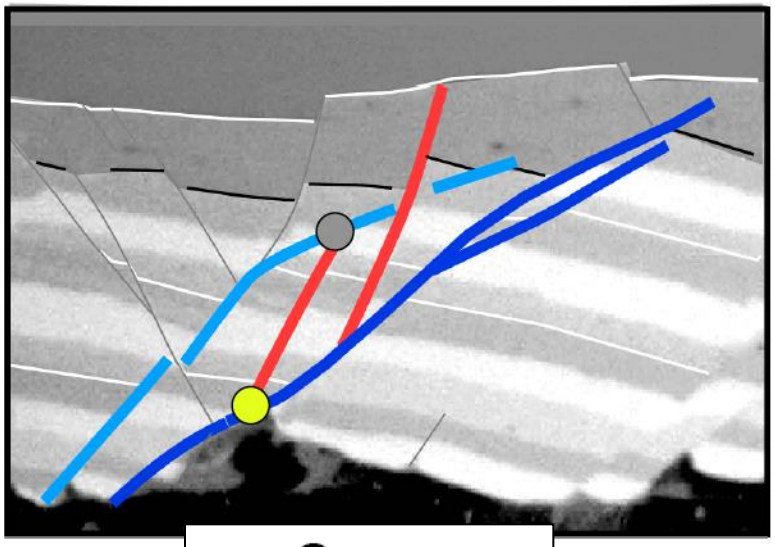


- **2nd-phase faults** link **1st-phase faults**

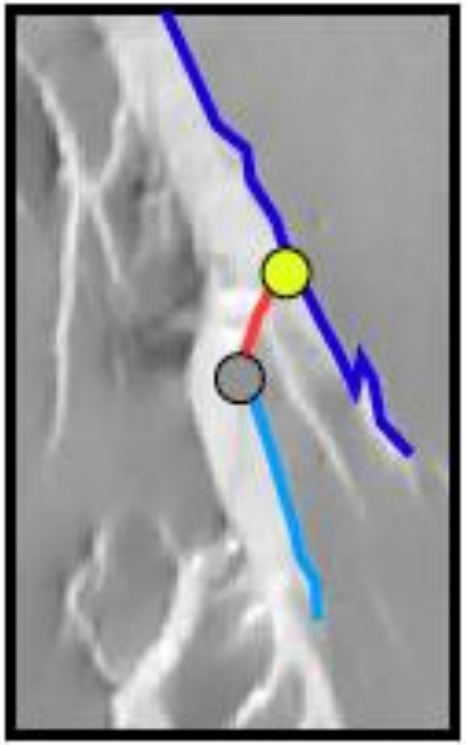
Fault interactions

- **2nd-phase fault** links two **1st-phase faults** creating zig-zag fault traces in map view

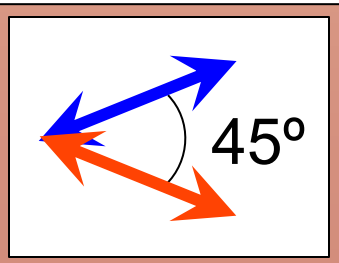
Cross-section view



Map view



1 cm



Fault interactions

- Two broad categories of interactions between **1st-phase** and **2nd-phase** faults

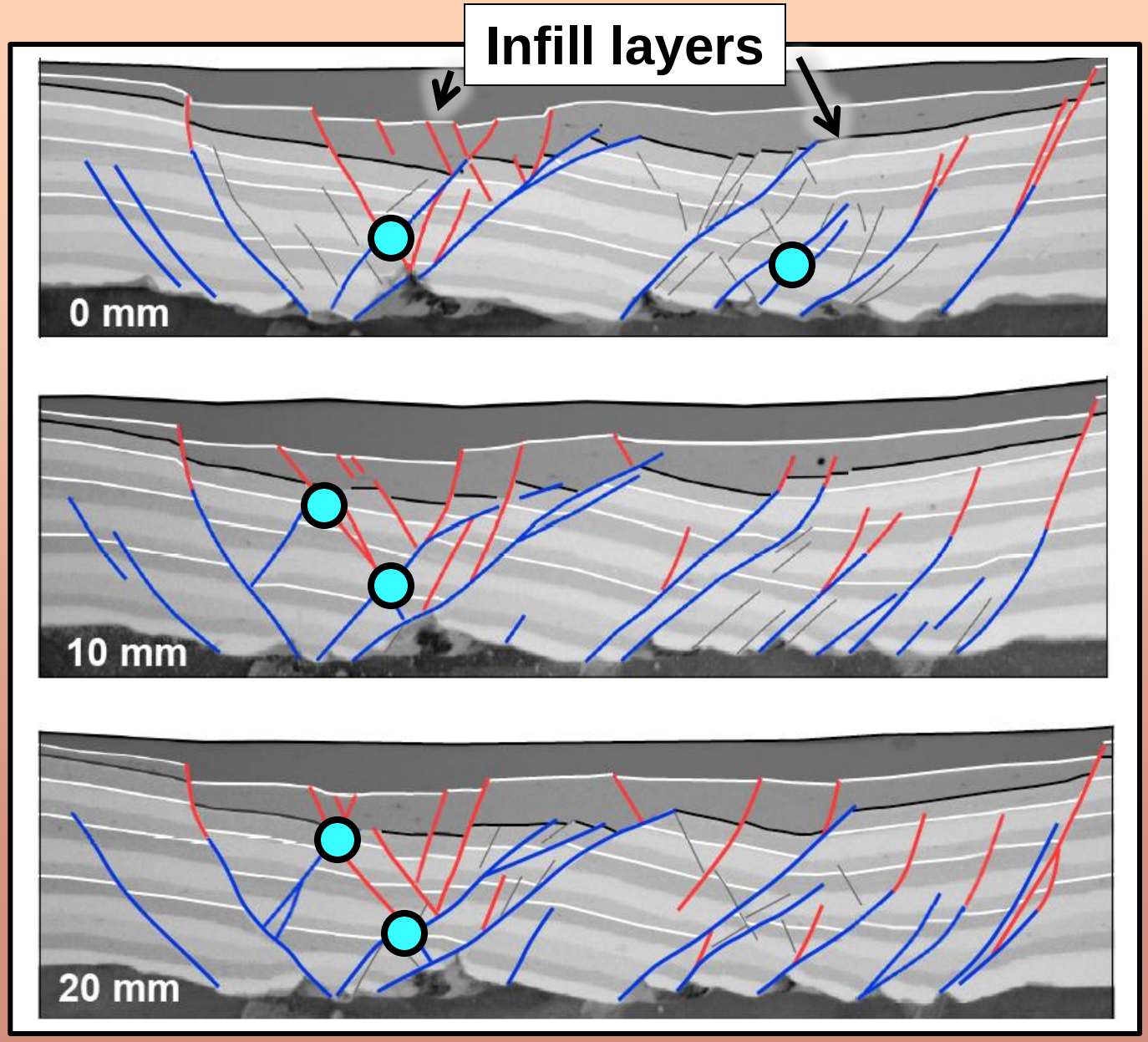
Synthetic – faults dip in same general direction

- Upward propagation from fault tip
- Upward, outward propagation from fault surface
- Linkage

Antithetic – faults dip in opposing directions

⇨ Cut and offset

Fault interactions

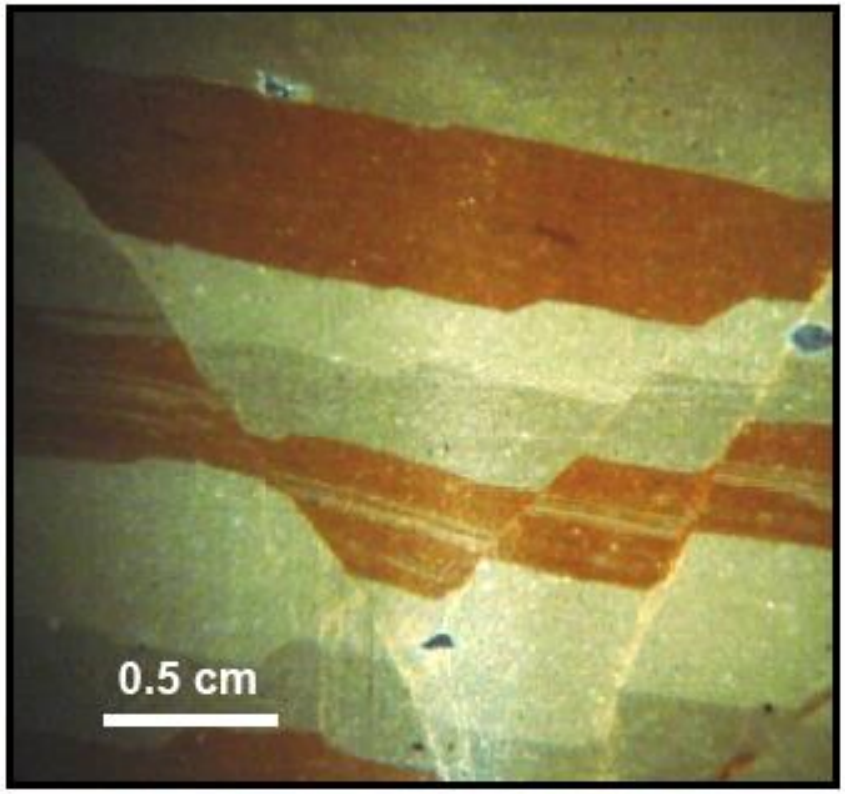


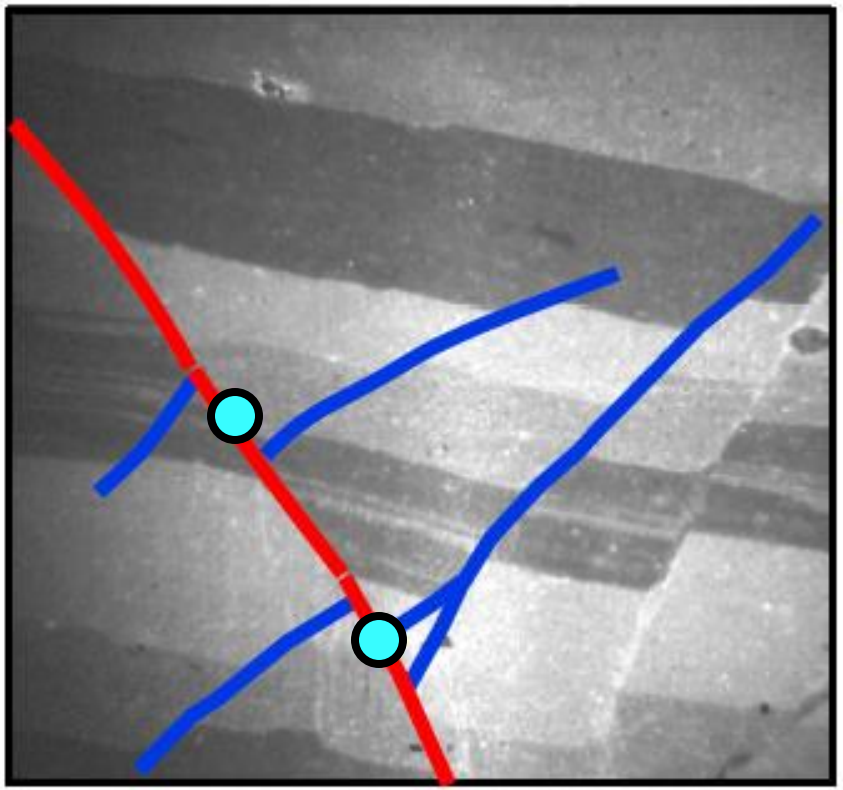
- **2nd-phase faults** cut and offset **1st-phase faults**

Fault interactions

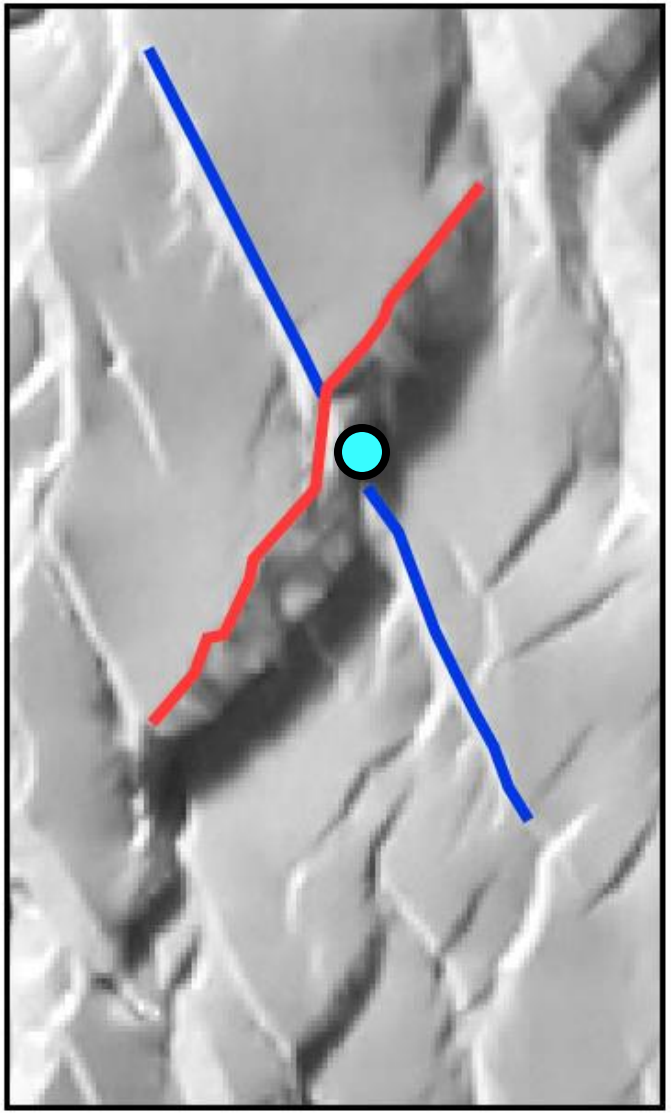
- **2nd-phase fault** cuts and offsets **1st-phase faults**

Cross-section view in thin section



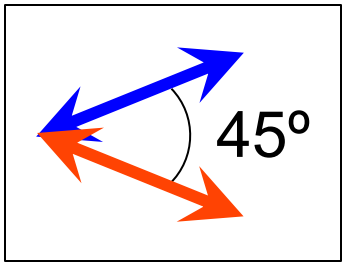


Fault interactions



Map view

1 cm



Conclusions

- **What types of faults develop during multi-phase extension?**

*-Reactivated **1st-phase** faults (with oblique slip)*

*-New **2nd-phase** normal faults*

Conclusions

- **Does style of faulting vary with depth?**

*-Depends on abundance of **1st-phase** faults*

*-Reactivated **1st-phase** oblique-slip faults accommodate most deformation at depth where **1st-phase** faults are abundant*

*-New **2nd-phase** normal faults accommodate most deformation at shallow levels where **1st-phase** faults are less abundant*

Conclusions

- **Do strikes of faults vary with depth?**

*-Strike of **1st-phase** faults consistent with depth*

*-Strike of **2nd-phase** normal faults varies with depth*

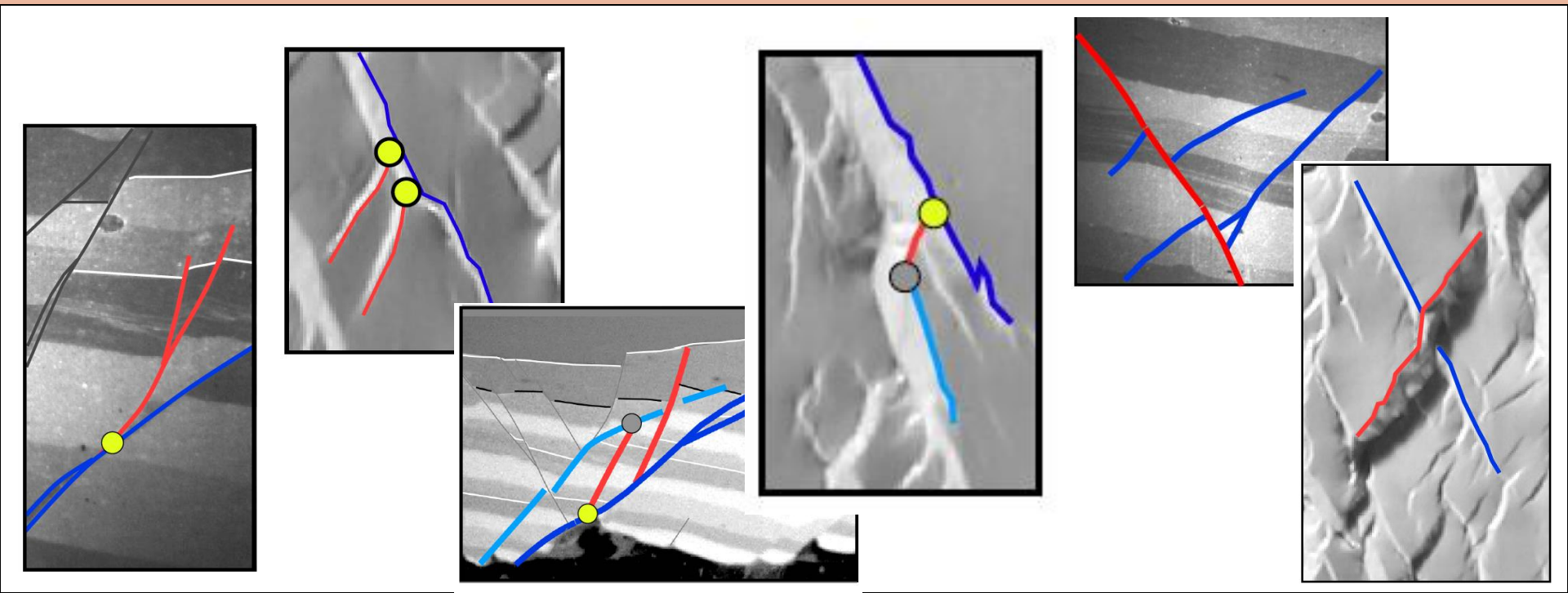
- *Oblique to both extension directions at depth*
- *Orthogonal to **2nd-phase** extension direction at shallow levels*

Conclusions

- **What types of fault interactions develop?**

-Common synthetic interactions involve emanation, nucleation, propagation, and linkage

-Common antithetic interactions involve offset



Conclusions

- **What do these interactions look like in map and cross-sectional views?**

-Synthetic and antithetic interactions have distinctive map and cross-sectional appearances