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

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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


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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 McIntyre et al., 2004
Introduction

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

Milne Point, Alaska North Slope

Jeanne d’Arc basin, offshore Newfoundland

from Nixon et al., 2014

from McIntyre 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

- 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

Cross-section view

- Provides information about fault geometries and interactions within model after 2nd phase of deformation
• 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 the 1st phase of extension.
- Strike perpendicular (within 10 degrees) to the 1st-phase extension direction.
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 1\textsuperscript{st}-phase faults had oblique slip (normal and right-lateral) during 2\textsuperscript{nd} phase of extension.
Surface deformation

• New 2\textsuperscript{nd}-phase faults also form

• They are normal faults striking obliquely to orthogonally to 2\textsuperscript{nd}-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 1\textsuperscript{st}-phase faults, and which are 2\textsuperscript{nd}-phase faults?
Internal deformation: serial cross sections

- Need map views of faults
- Strike indicates whether faults formed during 1\textsuperscript{st} phase or 2\textsuperscript{nd} phase of extension
Internal deformation: map views

2\textsuperscript{nd}-phase faults

1\textsuperscript{st}-phase faults

Increasing depth

Horizon 1

Horizon 2

Horizon 3

Horizon 4

Bottom
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

45°
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 1\textsuperscript{st}-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 1\textsuperscript{st}-phase and 2\textsuperscript{nd}-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 1\textsuperscript{st}-phase and 2\textsuperscript{nd}-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

- Infill layers

- 2nd-phase faults
- 1st-phase faults

Dimensions: 720.0x540.0
Fault interactions

- Many faults are hybrid
- Composed of 2\textsuperscript{nd}-phase segments that emanate from tips of deep, reactivated \textsuperscript{1}st-phase faults
Infill layers

Fault interactions

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

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

2nd-phase segment

1st-phase segment

Increasing depth
Fault interactions

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

Less steep 2nd-phase segment

Steeper 2nd-phase segment

1st-phase segment
Fault interactions

• Two broad categories of interactions between 1\textsuperscript{st}-phase and 2\textsuperscript{nd}-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

• 2\textsuperscript{nd}-phase faults nucleate on and propagate away from 1\textsuperscript{st}-phase faults
Fault interactions

- Typical 2\textsuperscript{nd}-phase fault that nucleates on and propagates away from 1\textsuperscript{st}-phase fault
Infill layers

Fault interactions

• Branch line between 1st-phase fault and 2nd-phase splay plunges
Fault interactions

- Branch line between 1\textsuperscript{st}-phase fault and 2\textsuperscript{nd}-phase splay plunges
Fault interactions

- 2\(^{nd}\)-phase faults nucleate on and propagate away from 1\(^{st}\)-phase fault creating fault splays
Fault interactions

- 2\textsuperscript{nd}-phase faults nucleate on and propagate away from 1\textsuperscript{st}-phase fault creating fault splays
Fault interactions

- Two broad categories of interactions between 1\textsuperscript{st}-phase and 2\textsuperscript{nd}-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

- 2\textsuperscript{nd}-phase fault links two 1\textsuperscript{st}-phase faults creating zig-zag fault traces in map view.

Cross-section view

Map view

1 cm

45°
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

- 2\textsuperscript{nd}-phase faults cut and offset 1\textsuperscript{st}-phase faults
Fault interactions

- 2\textsuperscript{nd}-phase fault cuts and offsets 1\textsuperscript{st}-phase faults

Cross-section view in thin section
Fault interactions

Map view

1 cm

45°
Conclusions

• What types of faults develop during multi-phase extension?
  - Reactivated 1\textsuperscript{st}-\textbf{phase} faults (with oblique slip)
  - New 2\textsuperscript{nd}-\textbf{phase} normal faults
Does style of faulting vary with depth?

- Depends on abundance of $1^{\text{st}}$-phase faults

- Reactivated $1^{\text{st}}$-phase oblique-slip faults accommodate most deformation at depth where $1^{\text{st}}$-phase faults are abundant

- New $2^{\text{nd}}$-phase normal faults accommodate most deformation at shallow levels where $1^{\text{st}}$-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