National Central University Graduate Institute of Applied Geology **111-2** seminar

True three-dimensional trishear: A kinematic model for strike-slip and oblique-slip deformation

2004

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Review Paper
Chuan Ding, 2023.6.9

Why true-3D Trishear?

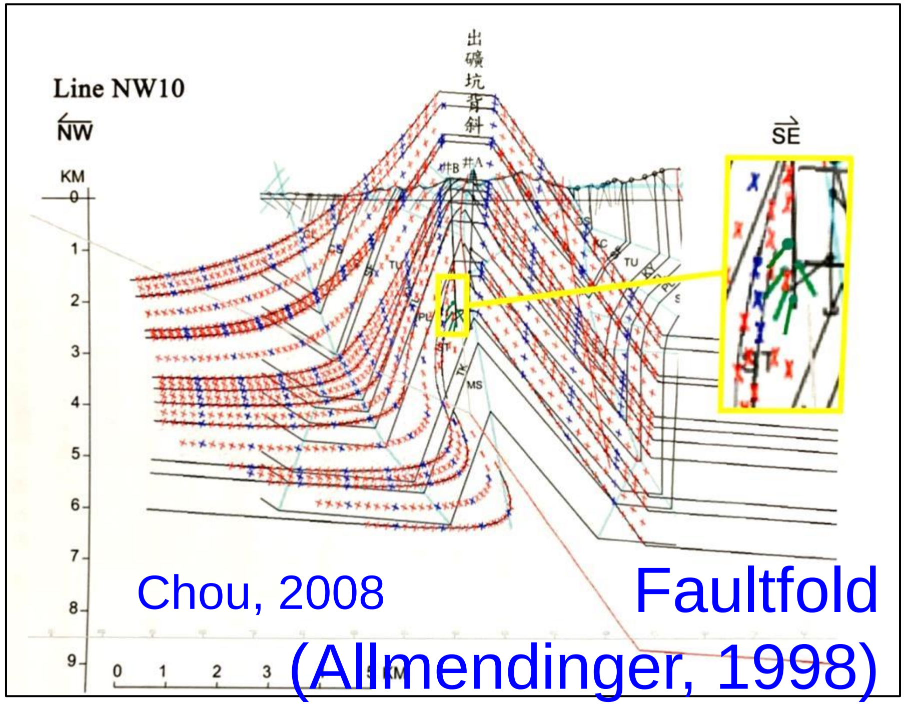
2D, pseudo 3D — a series of parallel 2-D cross sections

- Dip-slip fault

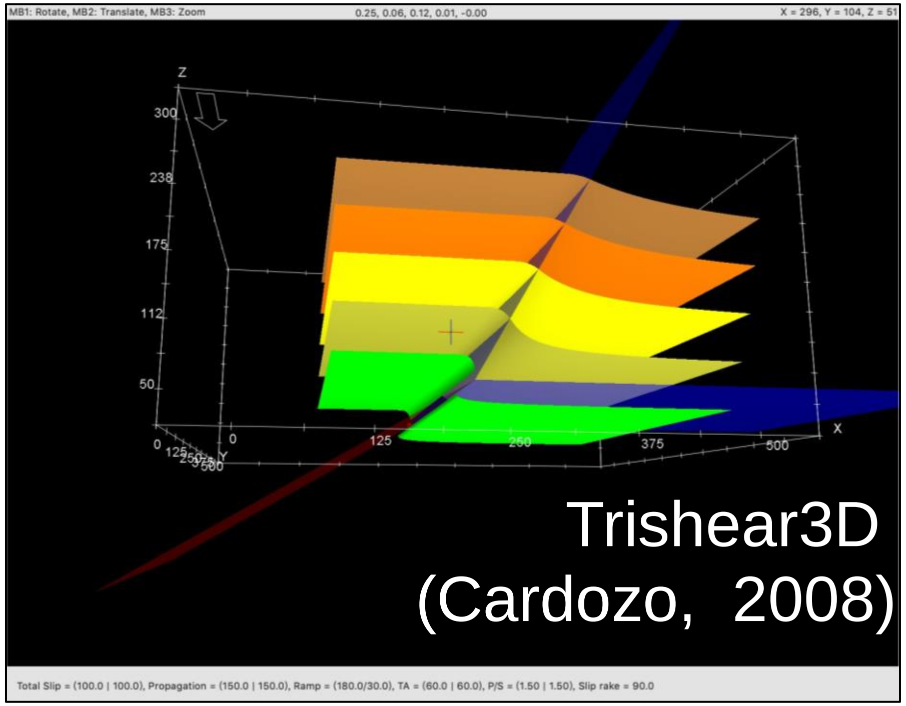
True 3D

- Oblique slip fault
- Strike slip fault

Chequalin Fault



Chou, 2008
Faultfold (Allmendinger, 1998)


Trishear3D (Cardozo, 2008)

What is Trishear? (Erslev,1991)

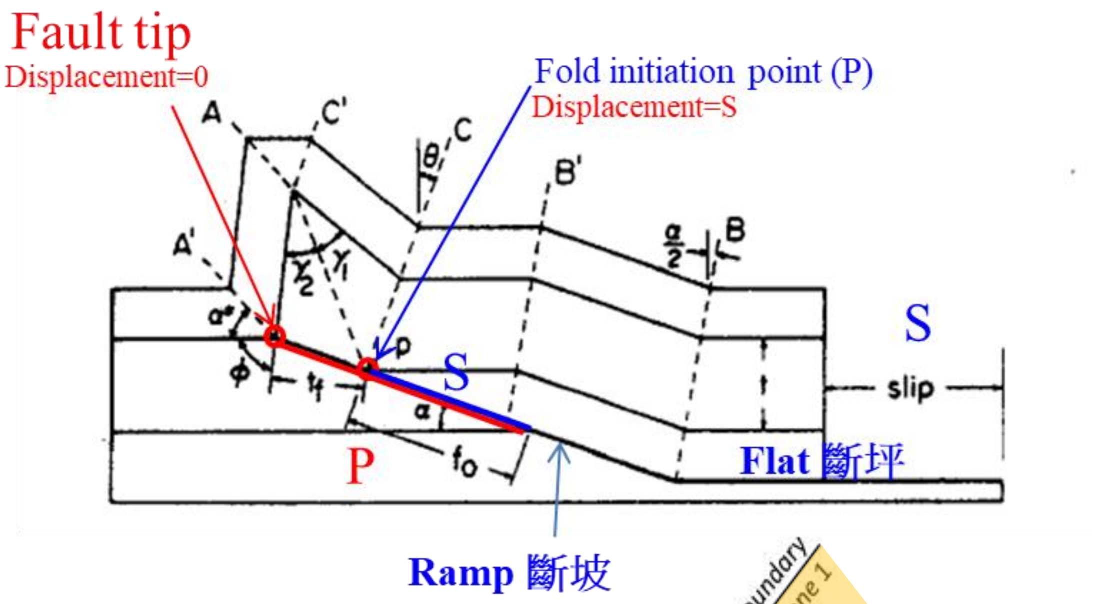
- kinematics of Fault Propagation Fold (Thin skin Theory)
- Numerical and physical models
- Analyze Geometry of structures/ strata
- Predict strain and fracture distribution
  - Velocity field within Trishear
  - Mechanics theory

Key parameters:

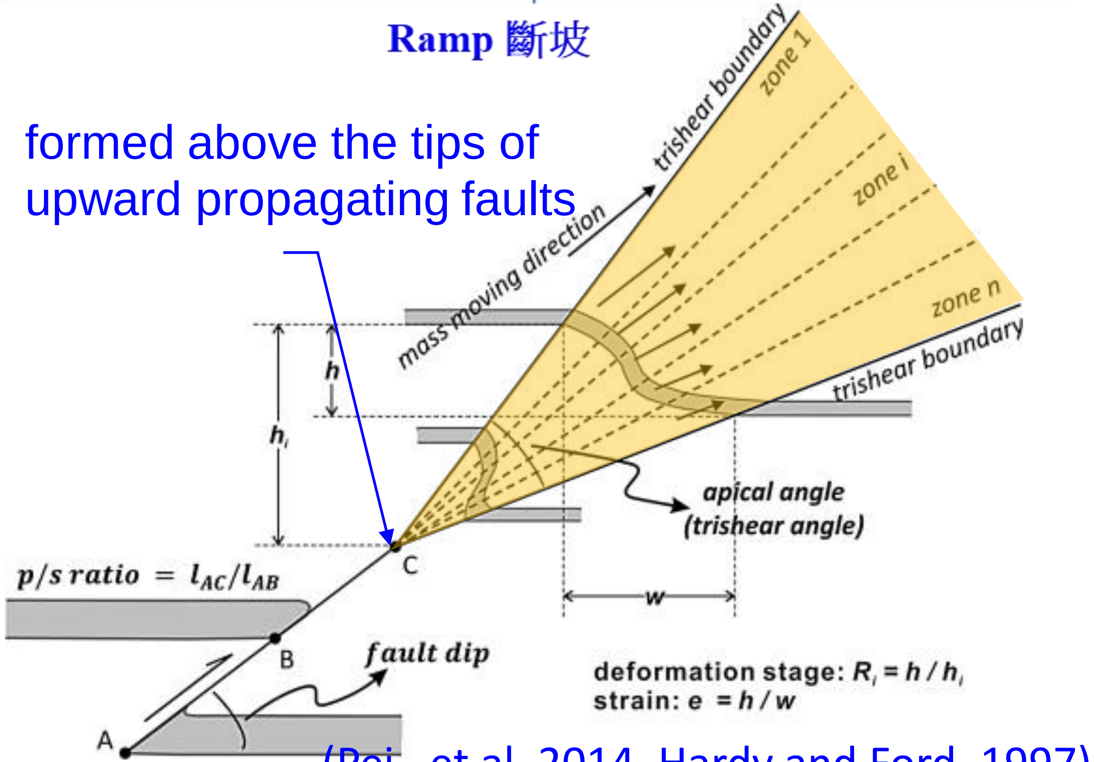
- Ramp (Fault dip)
- Location of Fault tip
- Fault Slip (S)

- Propagation (P)
- P/S ratio
- apical / trishear angle

Chester & Chester(1990)



formed above the tips of upward propagating faults

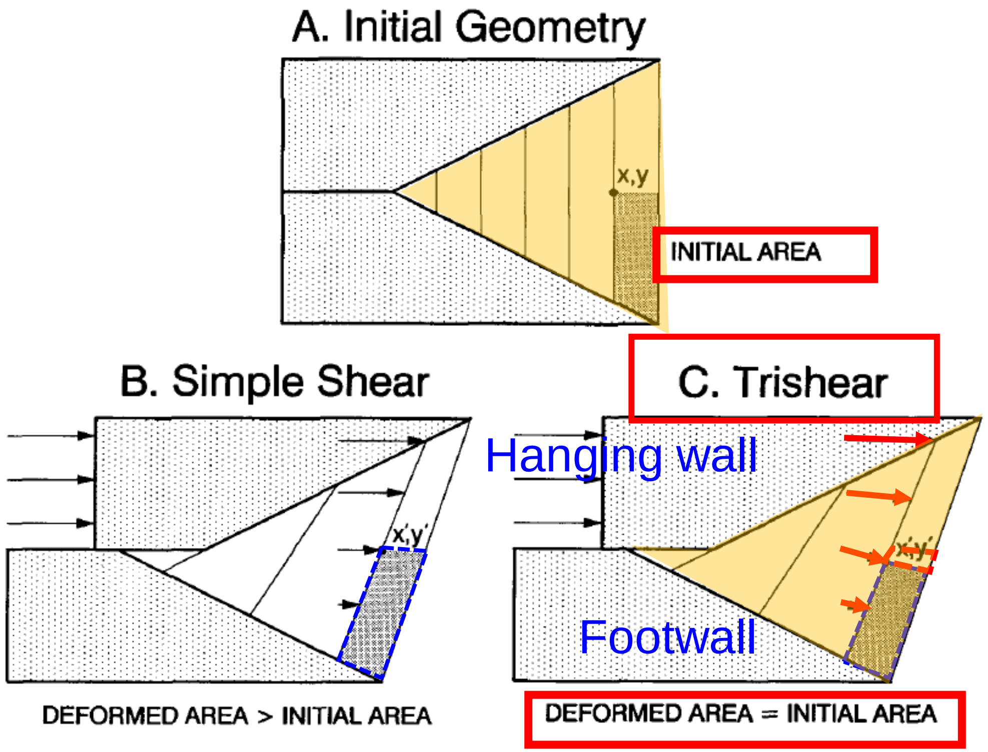


(Pei., et al. 2014, Hardy and Ford, 1997)

Basic assumptions

2D/ pseudo 3D

- **Area-conserving** velocity fields
- Flow incompressibility
- Fixed footwall



Chester & Chester (1990)

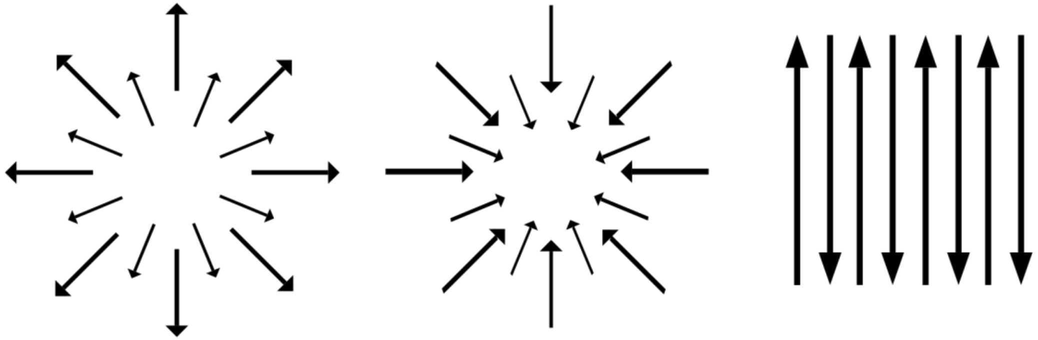
where $\frac{\partial v_x}{\partial x}$ = *change in fault slip velocity in the x direction with respect to x,*

$\frac{\partial v_y}{\partial y}$ = *change in the fault slip velocity in the y direction with respect to y*

$$\text{div } \underline{v} \equiv \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} = 0$$

Waltham and Hardy (1995),
Mase and Mase (1992)
Zehnder and Allmendinger (2000)

Divergence



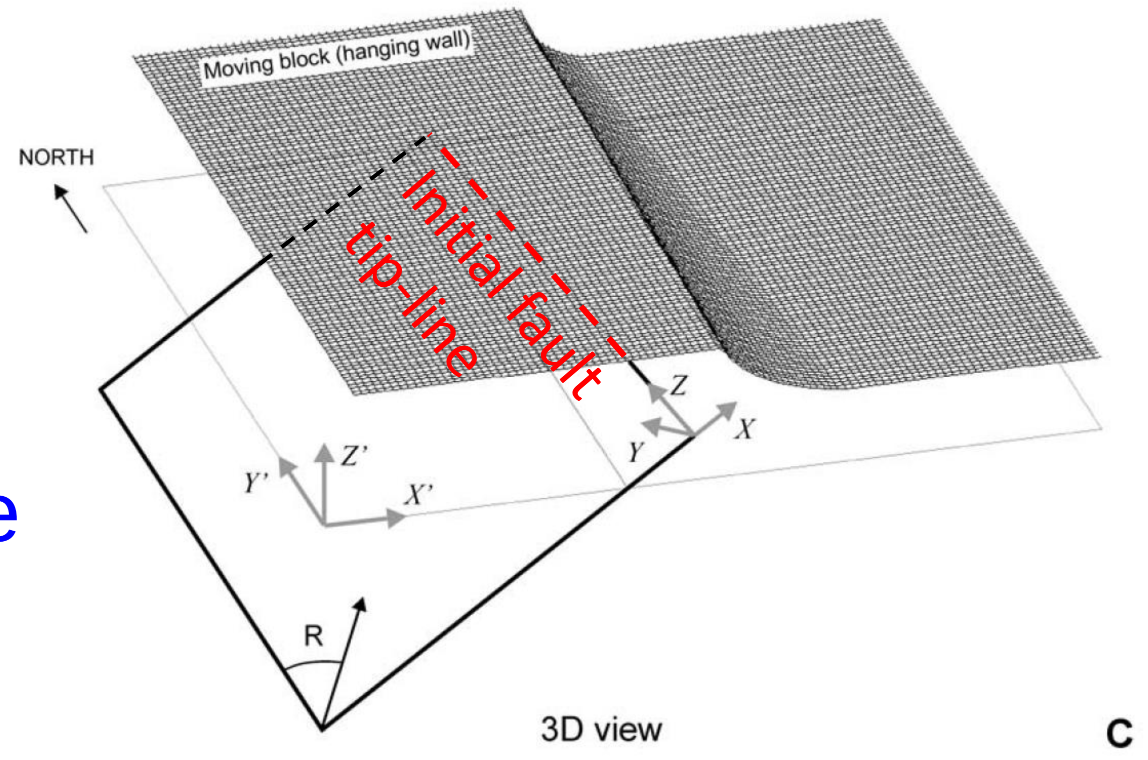
$\partial/\partial x(\mathbf{V}_x) > 0$	$\partial/\partial x(\mathbf{V}_x) < 0$	$\partial/\partial x(\mathbf{V}_x) = 0$
$\partial/\partial y(\mathbf{V}_y) > 0$	$\partial/\partial y(\mathbf{V}_y) < 0$	$\partial/\partial y(\mathbf{V}_y) = 0$
$\nabla \bullet (\mathbf{V}) > 0$	$\nabla \bullet (\mathbf{V}) < 0$	$\nabla \bullet (\mathbf{V}) = 0$

Basic assumptions

True 3D

- **Volume-conserving** velocity fields
- Flow incompressibility
- Fixed footwall
- 2 right-handed coordinate system
- Fixed Fault angle along strike
- Permit change: Trishear angle, slip along strike
- Arbitrarily choose hanging wall: Vertical fault

$$\mathrm{div}\ v \equiv \frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \boxed{\frac{\partial V_z}{\partial z}} = 0 \qquad \text{(Eq1)}$$



R is the rake of the velocity vector

Cristallini, et al (2004)

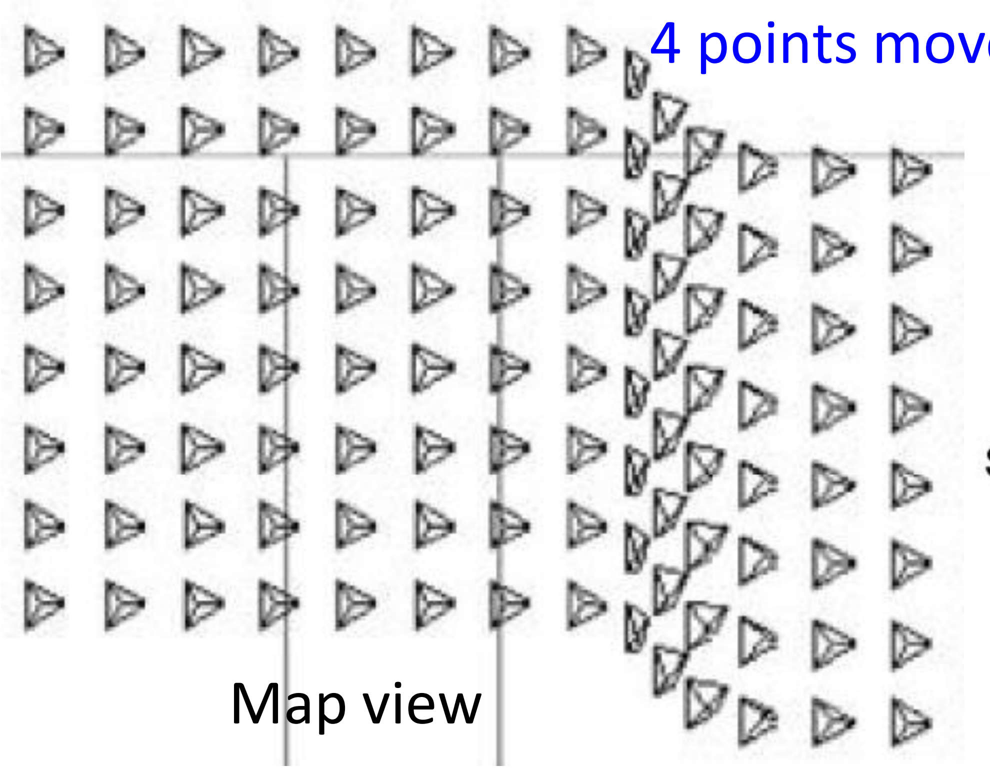
Tetrahedrons stand for each point

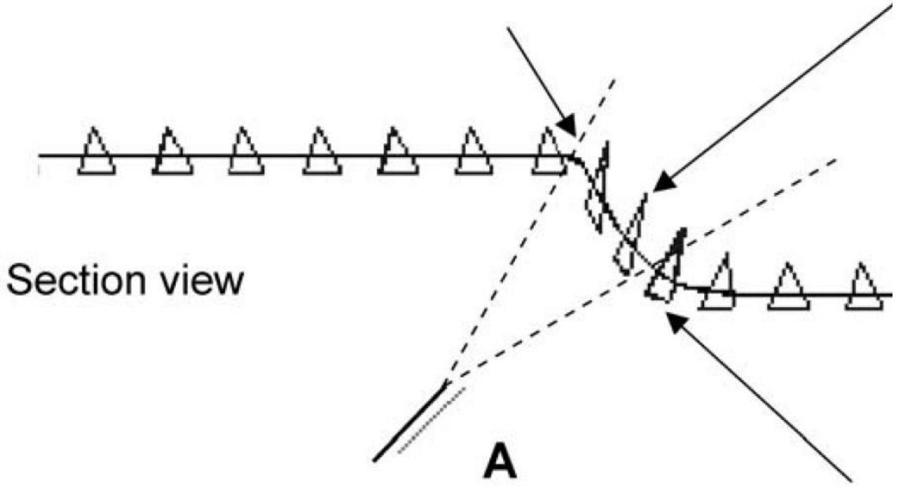
Strain ellipsoid defined by tetrahedron :

More efficient calculation than displacing an array of points defining an initial sphere

Each tetrahedron is moved by 3D trishear velocity field (Eq1)

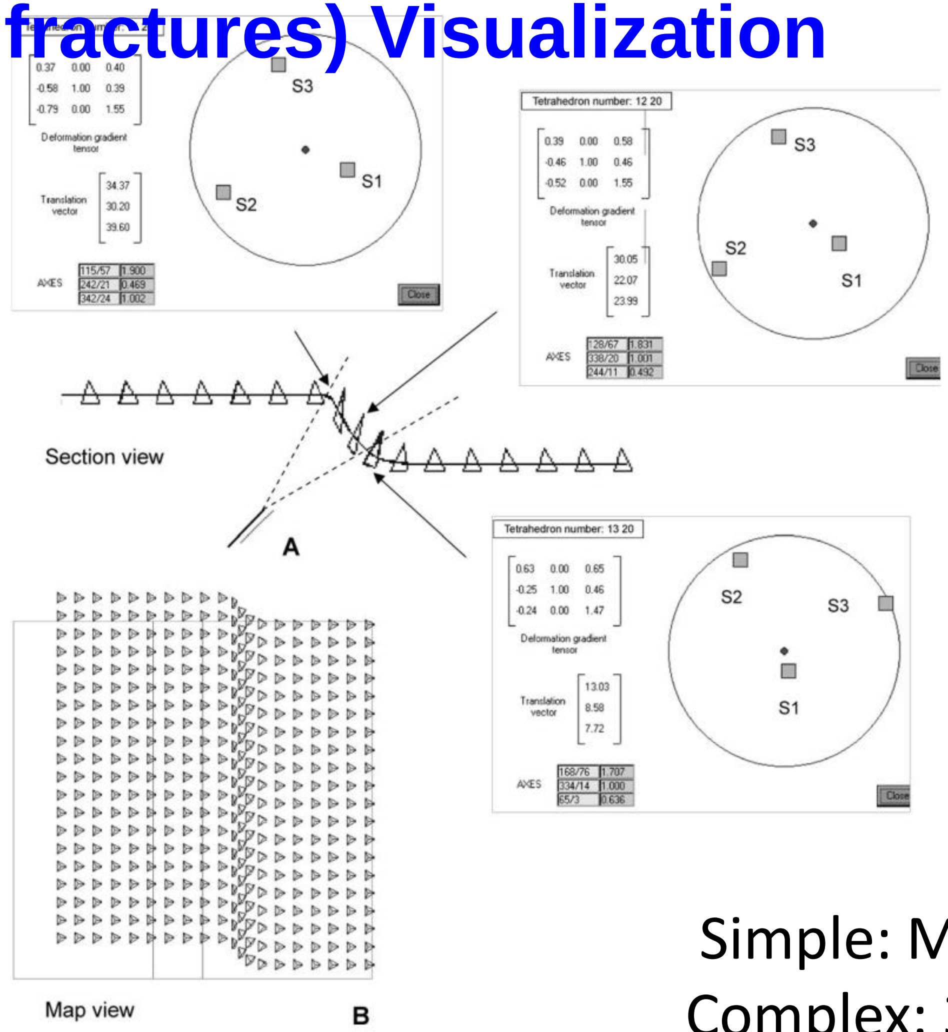
4 points movement

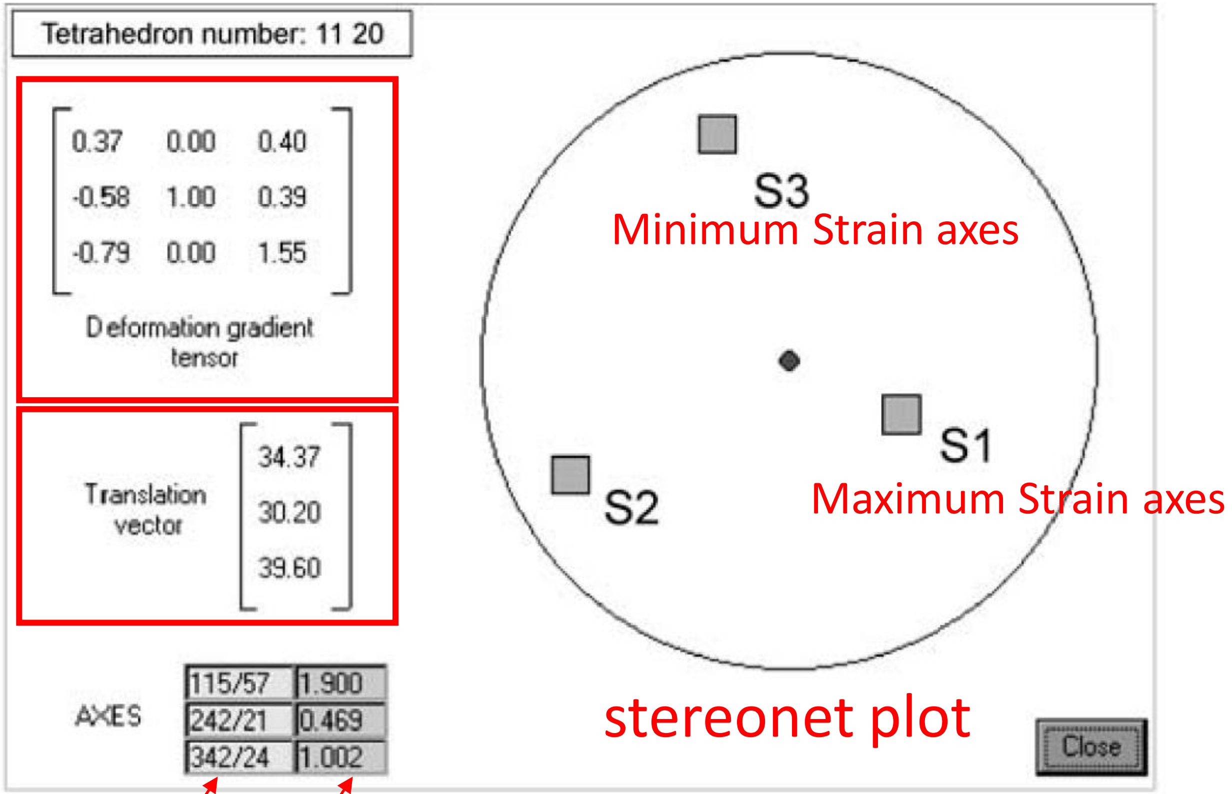




homogeneous deformation

Strain analysis (predict fractures) Visualization





Orientation ; lengths of principal strain axes

Internal friction angle: 30°

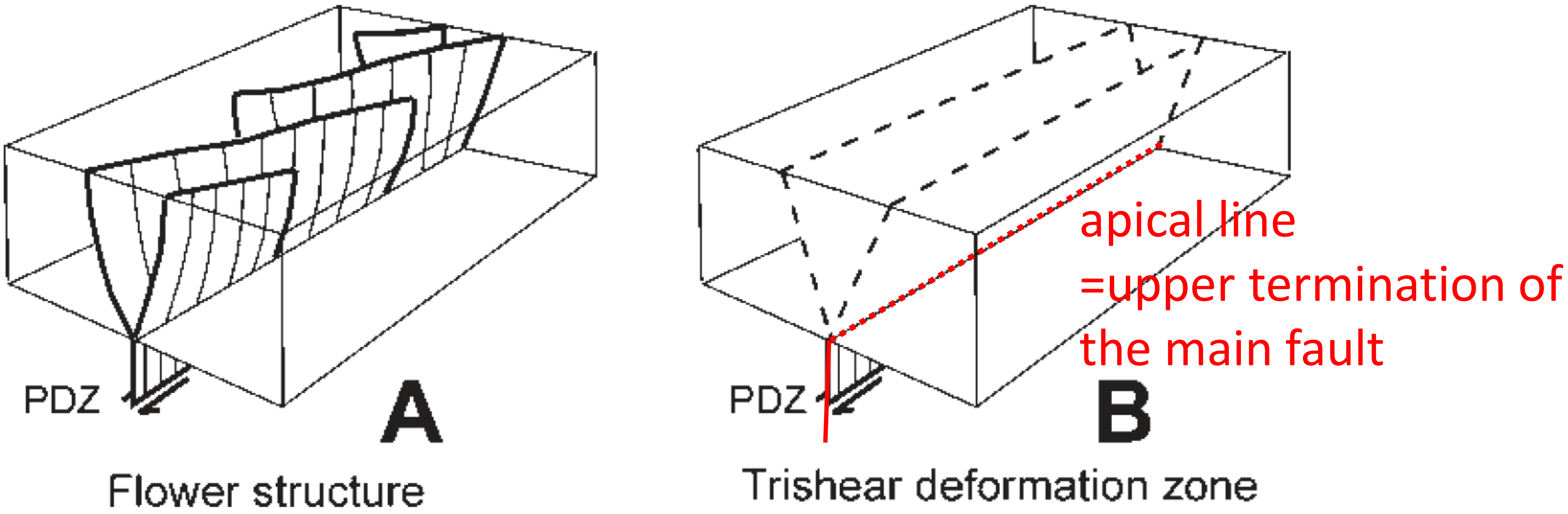
Simple: Mohr-Coulomb failure criterion

Complex: 3D fractures, shear and tensile fractures

Figure 3. Strain analysis using tetrahedrons in an oblique-slip three-dimensional trishear deformation. The deformation-gradient tensor and the translation vector can be calculated for any three-dimensional position. The orientations and lengths of the principal axes can be derived (see discussion in text). (A) Section view of the model. (B) Map view of the model. Each box is a window of the program showing the information for a specific tetrahedron (as shown by the arrows), where the circle is a stereographic projection of the principal strain axes (S1—maximum, S2—intermediate, S3—minimum).

Cristallini, et al (2004)

- Strike-slip analogue experiments (Naylor et al., 1986)
- Trishear model (Cristallini et al., 2014)



Helicoidal shape
-Not clear why
Need Single basement fault

Figure 1. (A) Helicoidal geometry of Riedel faults (Naylor et al., 1986). PDZ—principal displacement zone. (B) Concept of trishear applied to strike-slip deformation.

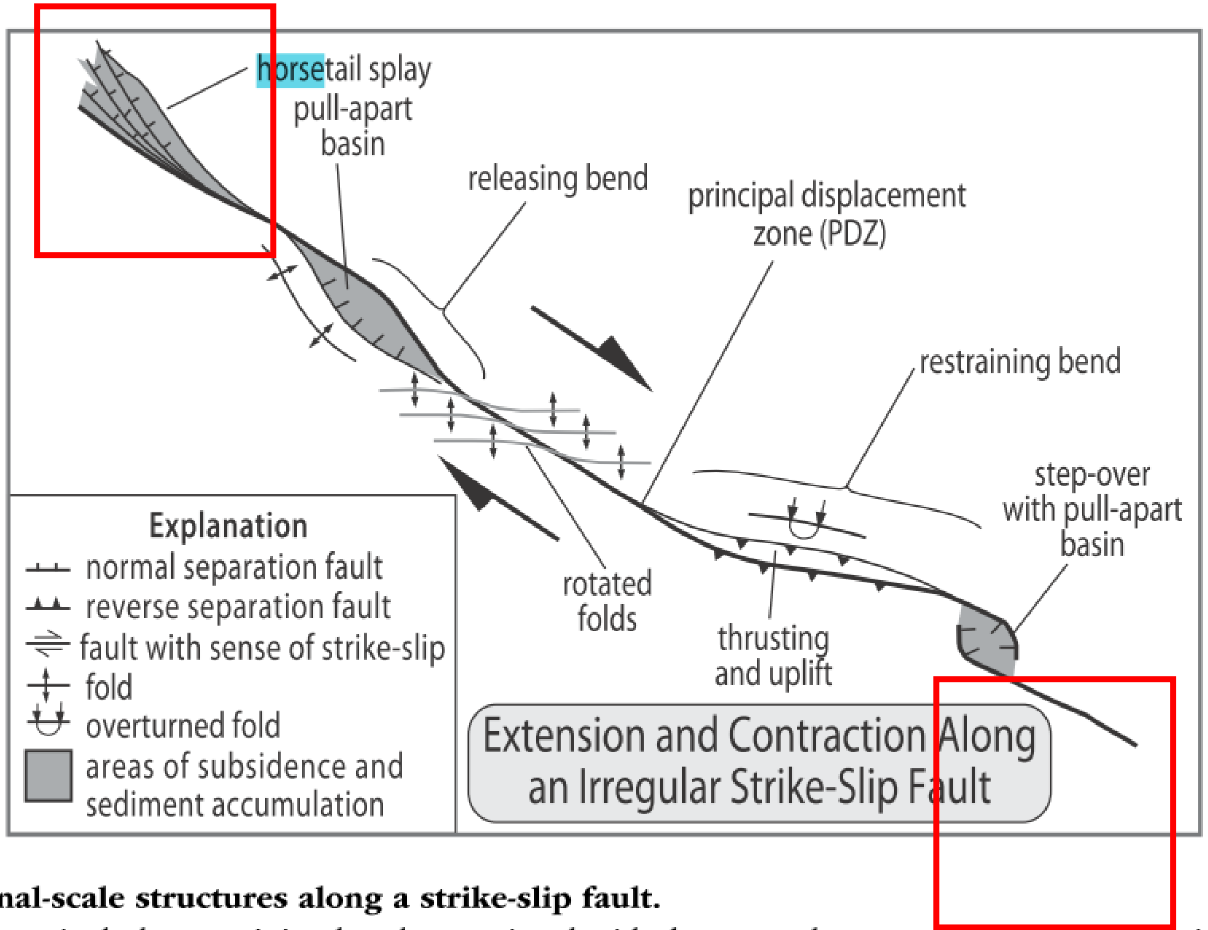


Fig. 4.19 Regional-scale structures along a strike-slip fault.
These structures can include restraining bends associated with thrusts and mountain building, releasing bends associated with basin development and rapid subsidence, and horsetail splays of either normal or reverse faults where deformation is spread over a broader zone. Right-stepping step-overs in a dextral shear zone (as shown here) create pull-apart basins as the fault tips curve toward the continuing fault trace and generate normal slip. Modified after Christie-Blick and Biddle (1985).

Burbank & Anderson, 2012

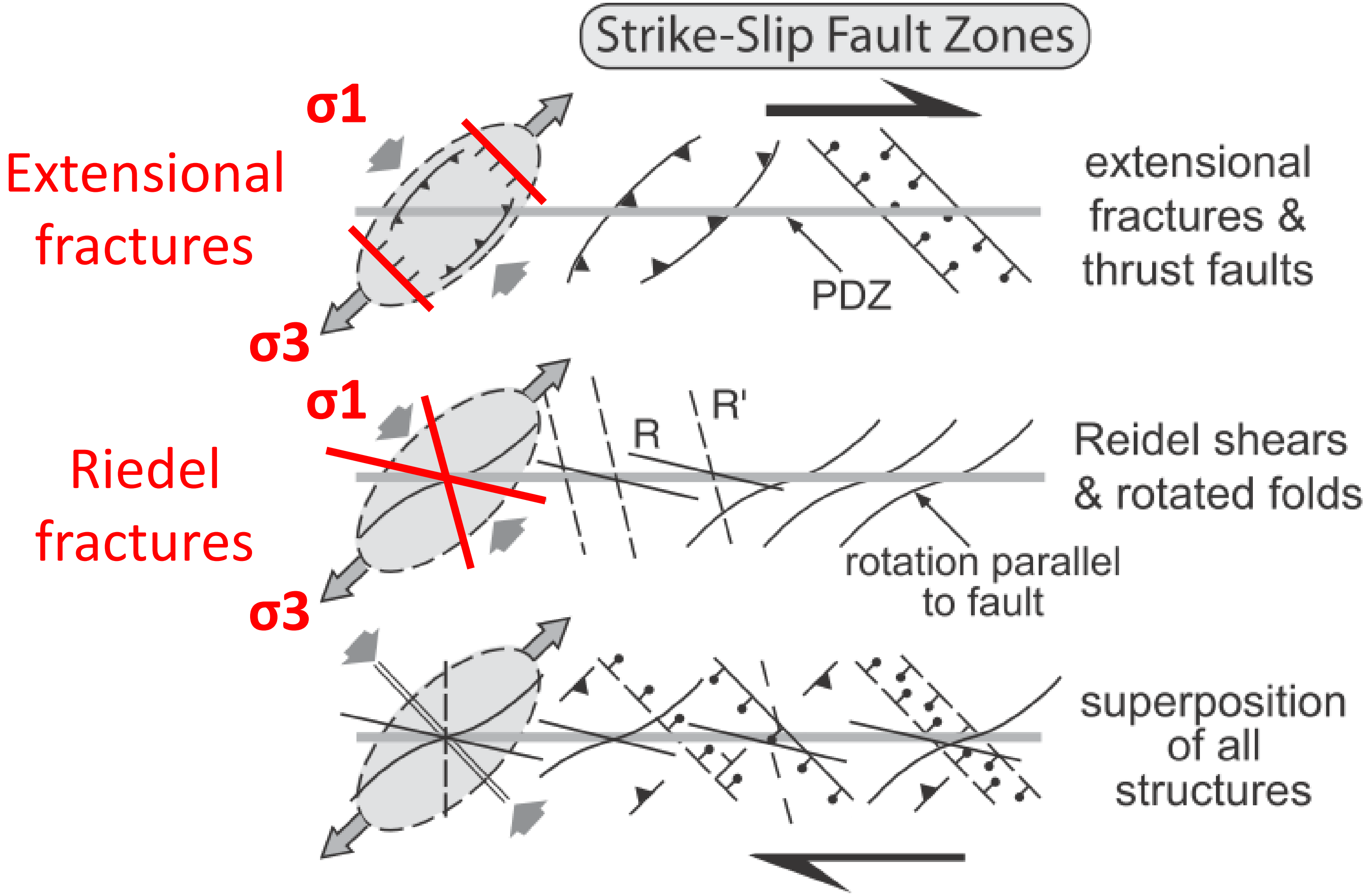
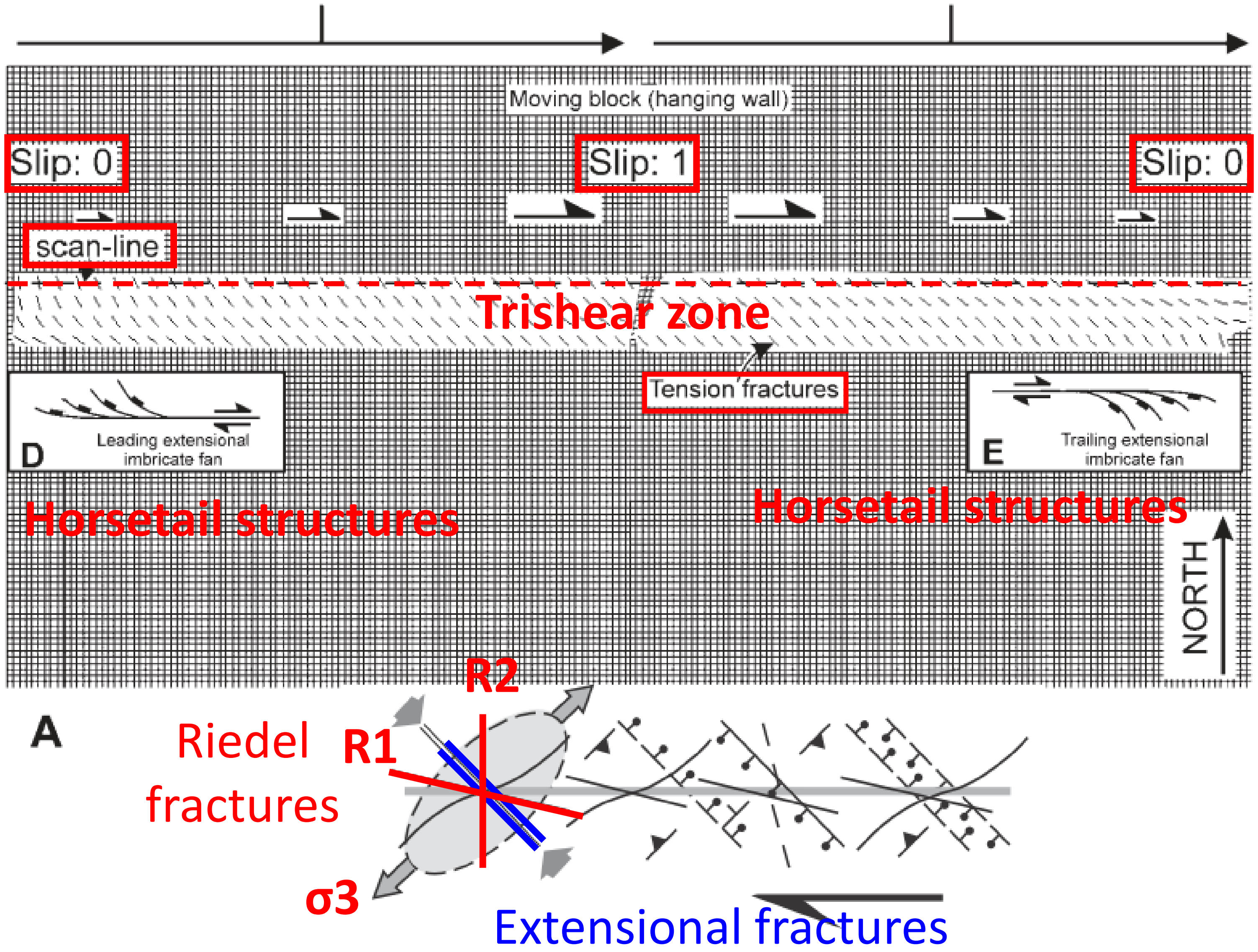


Fig. 4.18 Orientation of structural features formed in response to strike-slip shear couple. Normal and thrust faults, folds (some rotated near the shear zone), Reidel shears and conjugate shears (R′) form at predictable angles with the principal displacement zone (PDZ). Modified after Sylvester (1988).

Burbank & Anderson, 2012

Testing different slip along fault strike

Similar pattern of strike slip cracks



Right lateral strike-slip fault

Fault angle = 90°

Rake ≠ 90°

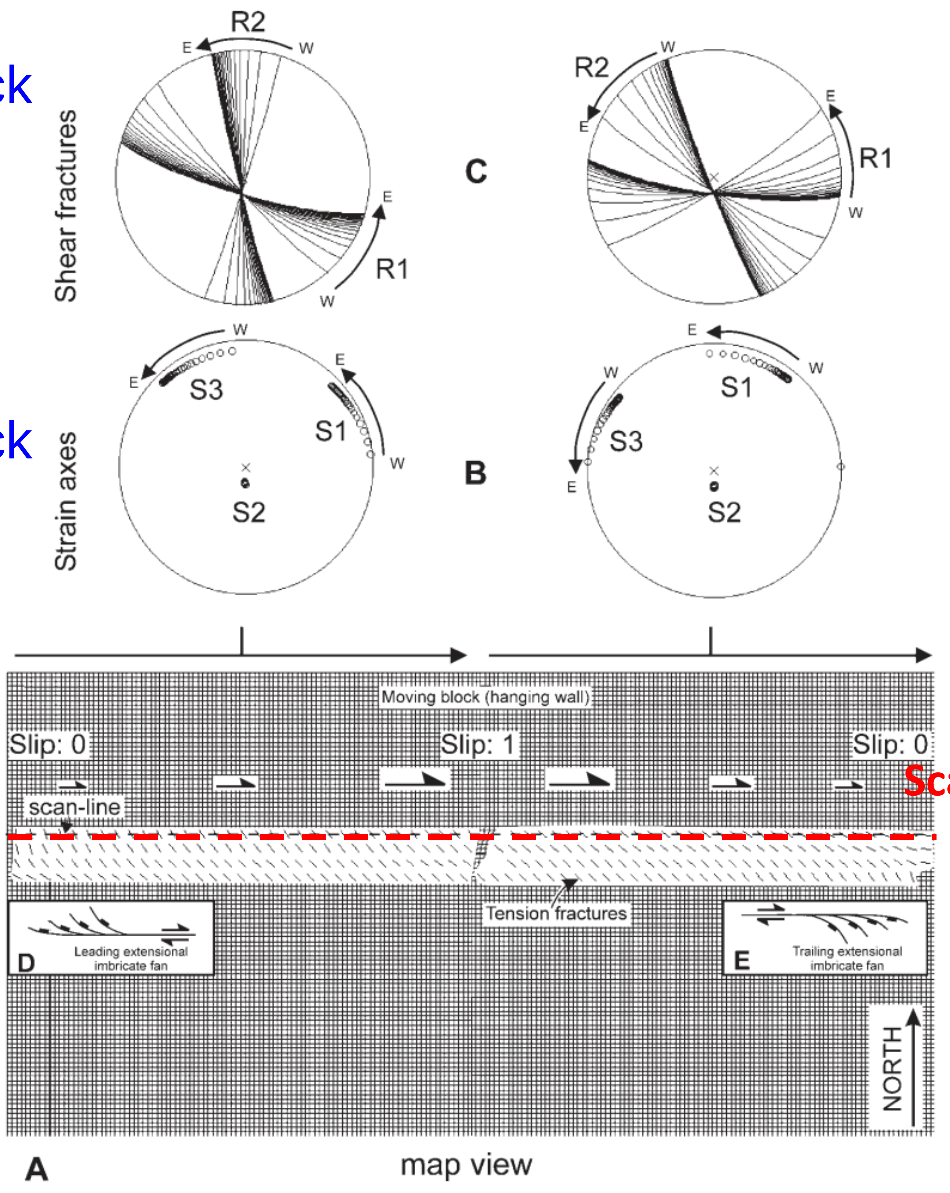
Mohr- Coulomb failure criterion

internal friction angle: 30°

Testing different slip along fault strike

Counterclock
-wise

Counterclock
-wise



Scan line

W

E

Rotation of Riedel Shear and shear strain

Detailed deformation feature/information

maximum and minimum axes (S1 and S3) will **rotate** near the horizontal plane. This rotation is faster near **the west and east** fault terminations than in the middle of the model. Likewise, the orientations of the Riedel fractures (R1 and R2) are almost constant in the middle of the model but **change very abruptly in both extremes.**

Trishear-Angle (apical) Variation

Ex: Sedimentary facies change
→ different lateral thickness
→ Different Trishear angles along fault strike

Reasonable cracks prediction

trishear angle: 10°

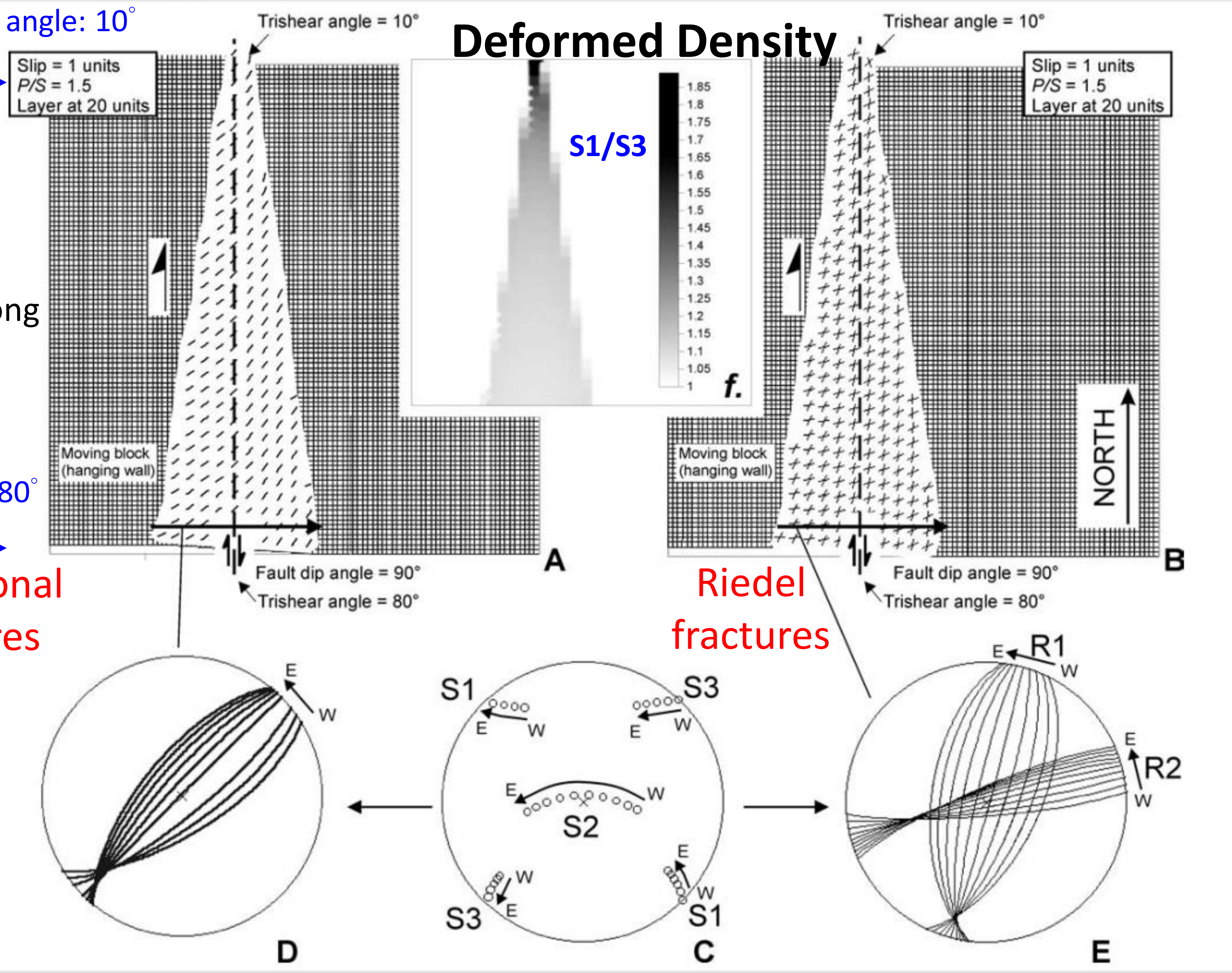
trishear angle: 80°

Extensional fractures

Riedel fractures

Deformed Density

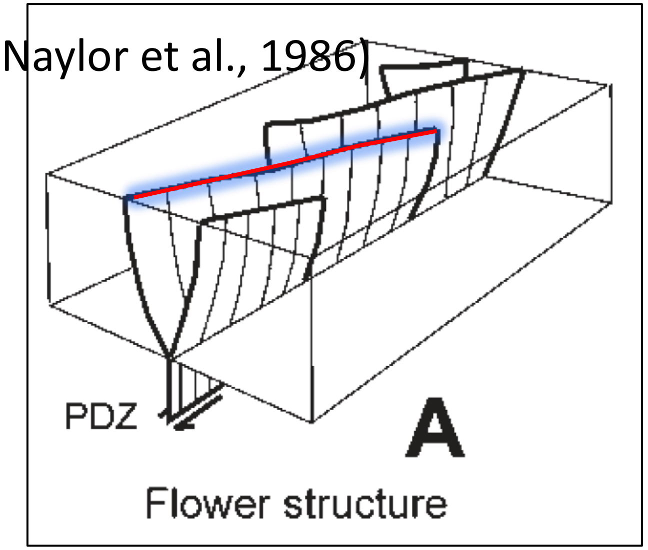
S1/S3

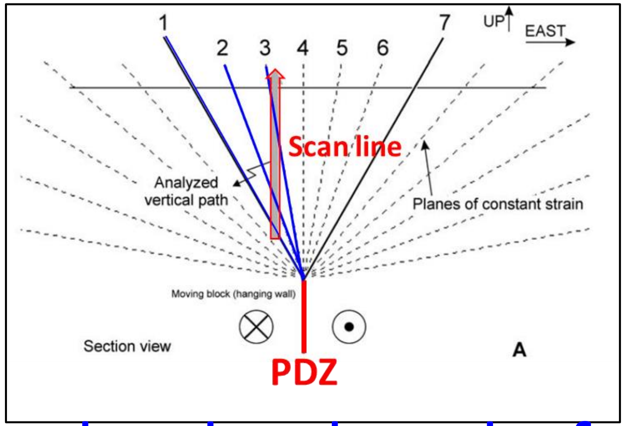


vertical,
strike-slip fault

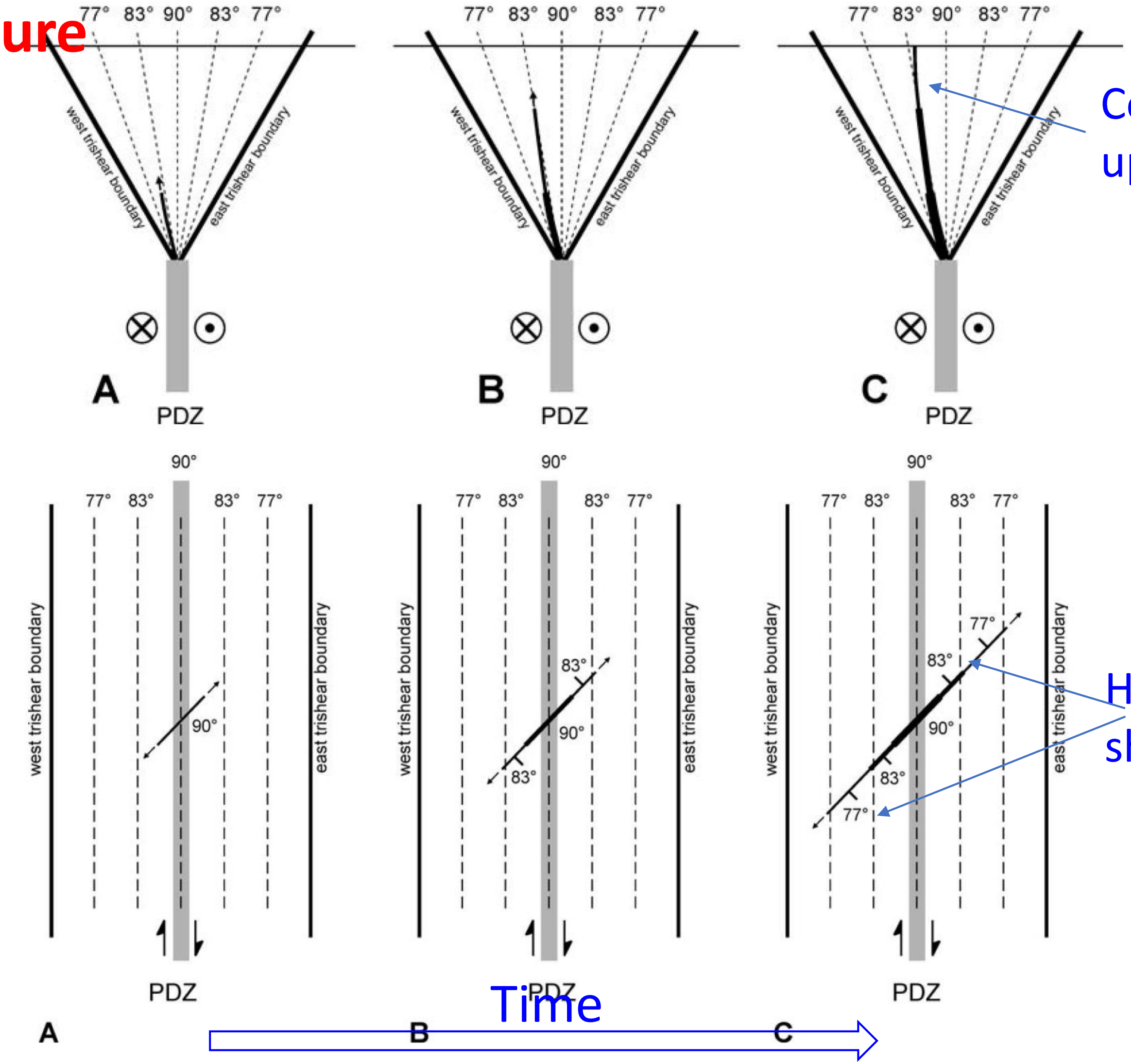
Simulate flower structure

(Naylor et al., 1986)





crack developed from principal displacement zone (PDZ) fits the flower structures



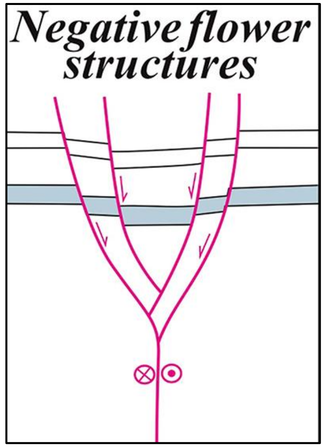
Concave upward

Helicoidal shape

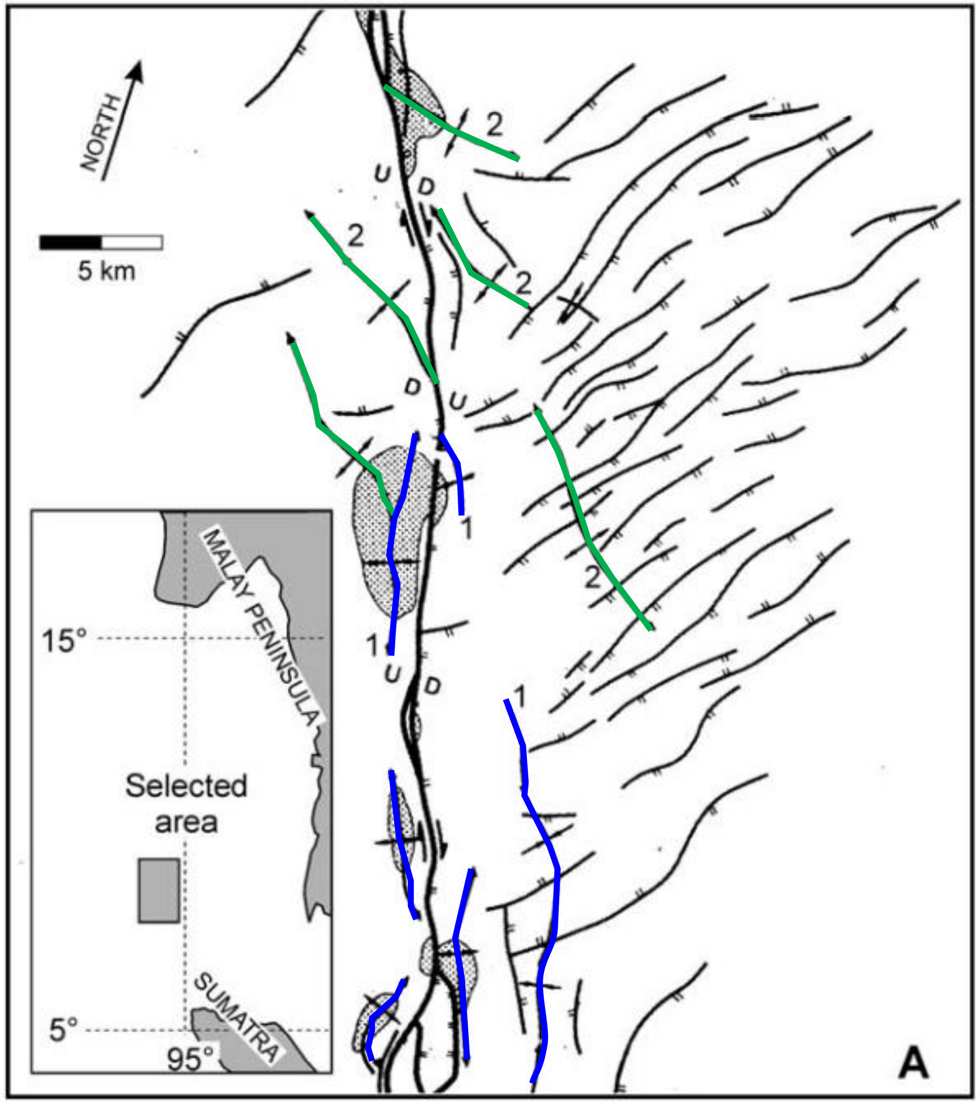
Time

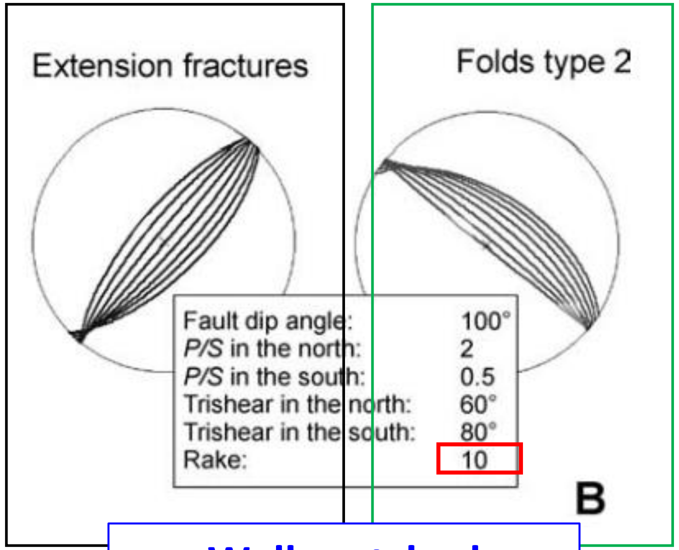
Natural Example 2: negative flower structures

- Principal wrench fault: north, northwest–striking
- Rake: 10°
- Trishear angles: 60° (north), 80° (south).
- P/S ratio: 2 ~ 0.5 (north to south)

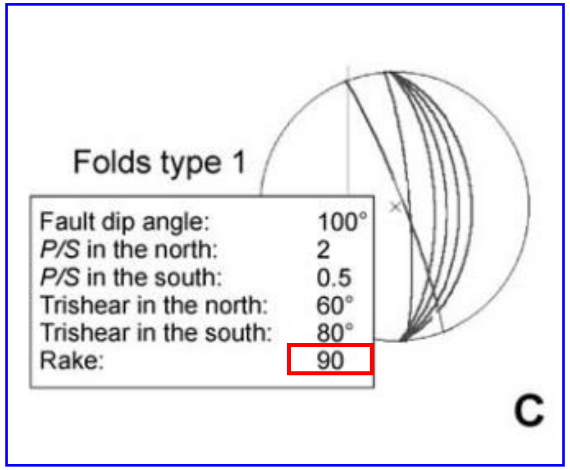


Tectonic map **Andaman Sea** ***3D-trishear predictions***





Well matched

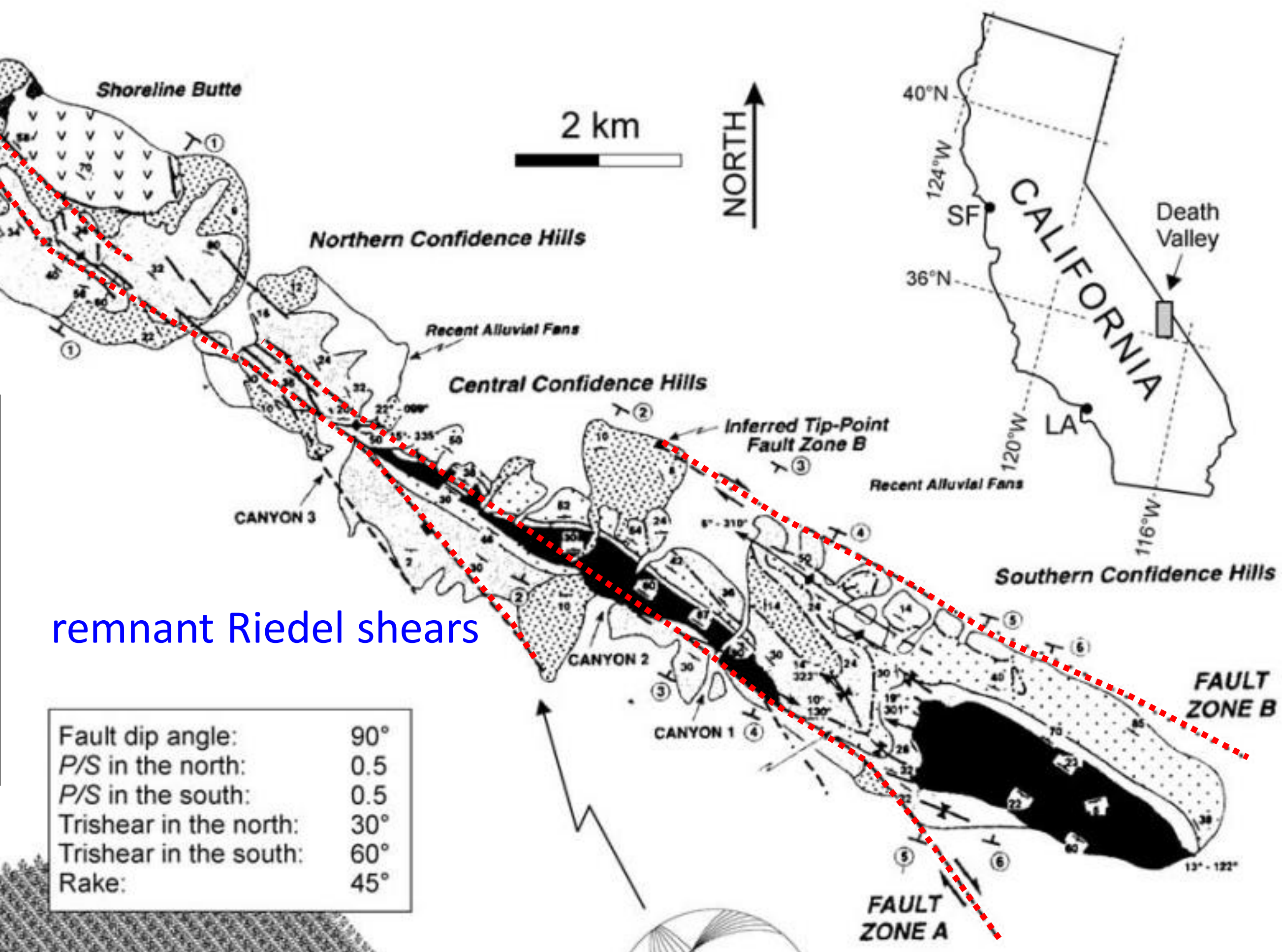


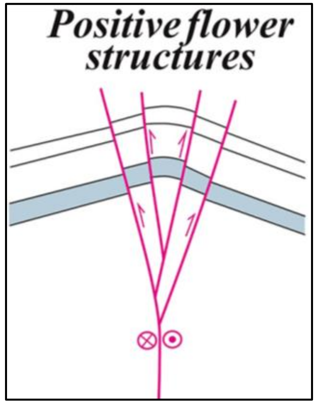
normal faults that flank the wrench fault and fold type 2 compare well with the predictions of a 10° rake three-dimensional trishear model. (C) To obtain fold type 1, it was necessary to construct a 90° rake model.

Natural Example 3: positive flower structures

Confidence Hills, California, United States

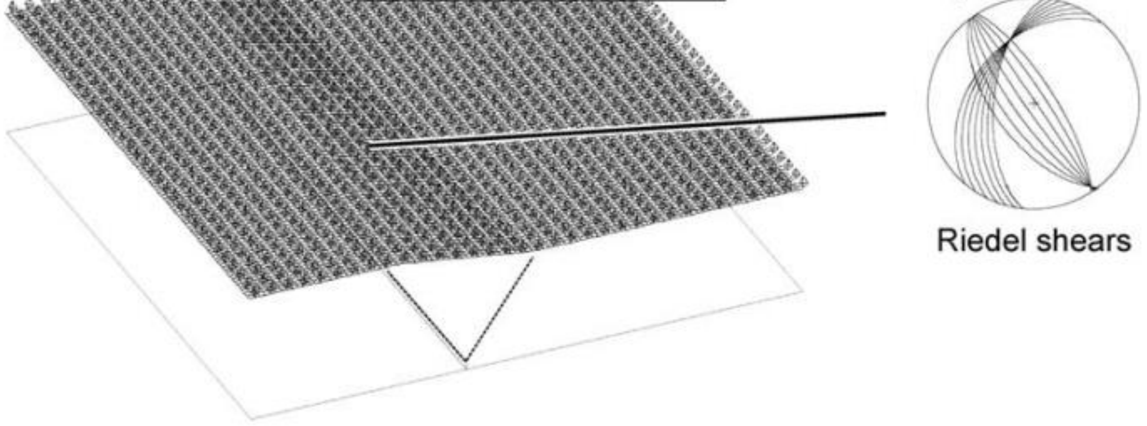
- 2 overlapping dextral strike-slip fault systems: northwest-striking
- Rake: 45°
- Trishear angle: 30° and 60°
- 1 of main faults are remnant Riedel shears





remnant Riedel shears

Fault dip angle:	90°
P/S in the north:	0.5
P/S in the south:	0.5
Trishear in the north:	30°
Trishear in the south:	60°
Rake:	45°



perfectly fit

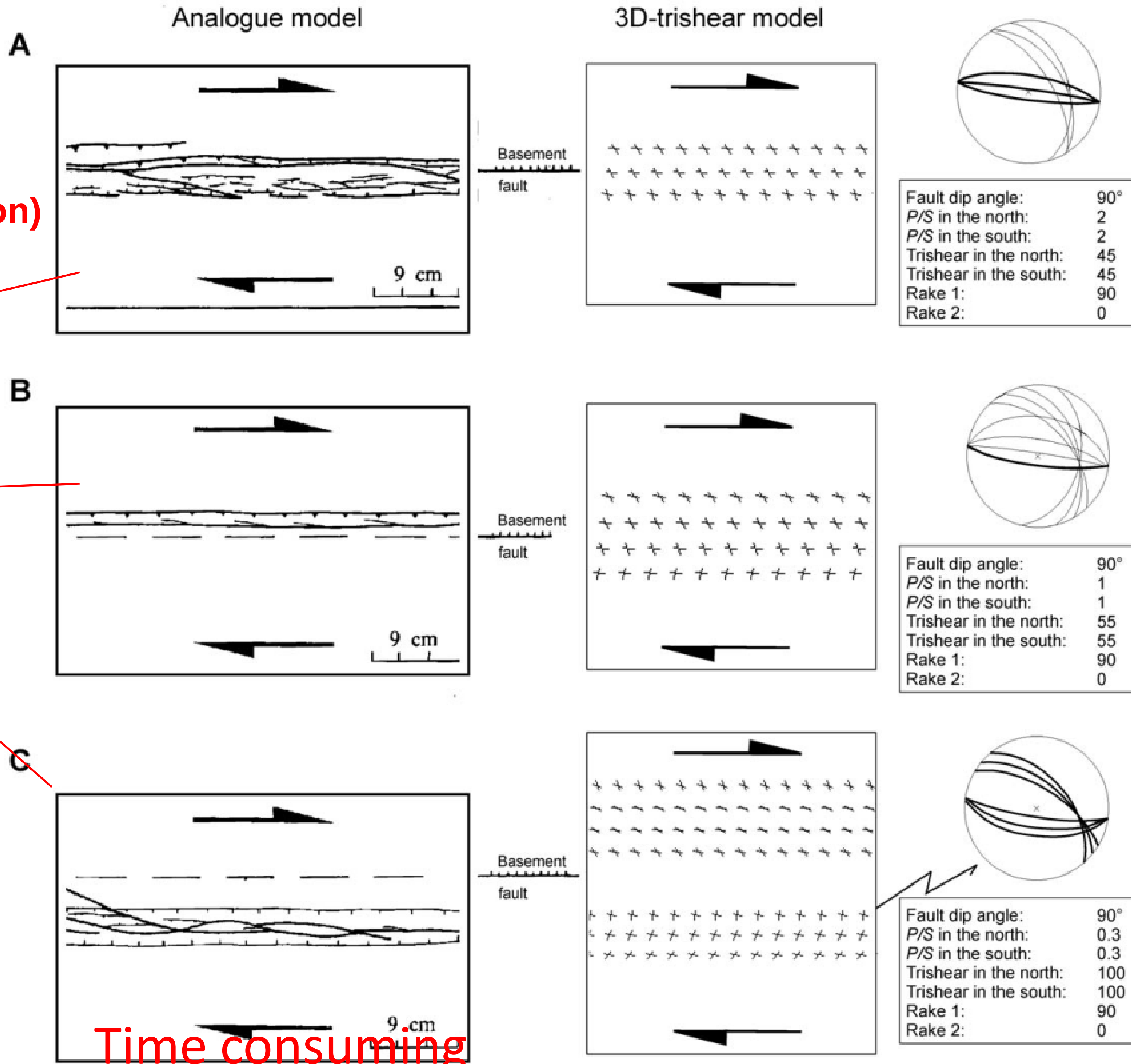
Analogue Experiment – Reactive Fault Dip 90˚

(1) Pure dip-slip displacement
(2) Pure right-lateral motion (reactivation)

Brittle faulting : pure sand layer
P/S=2

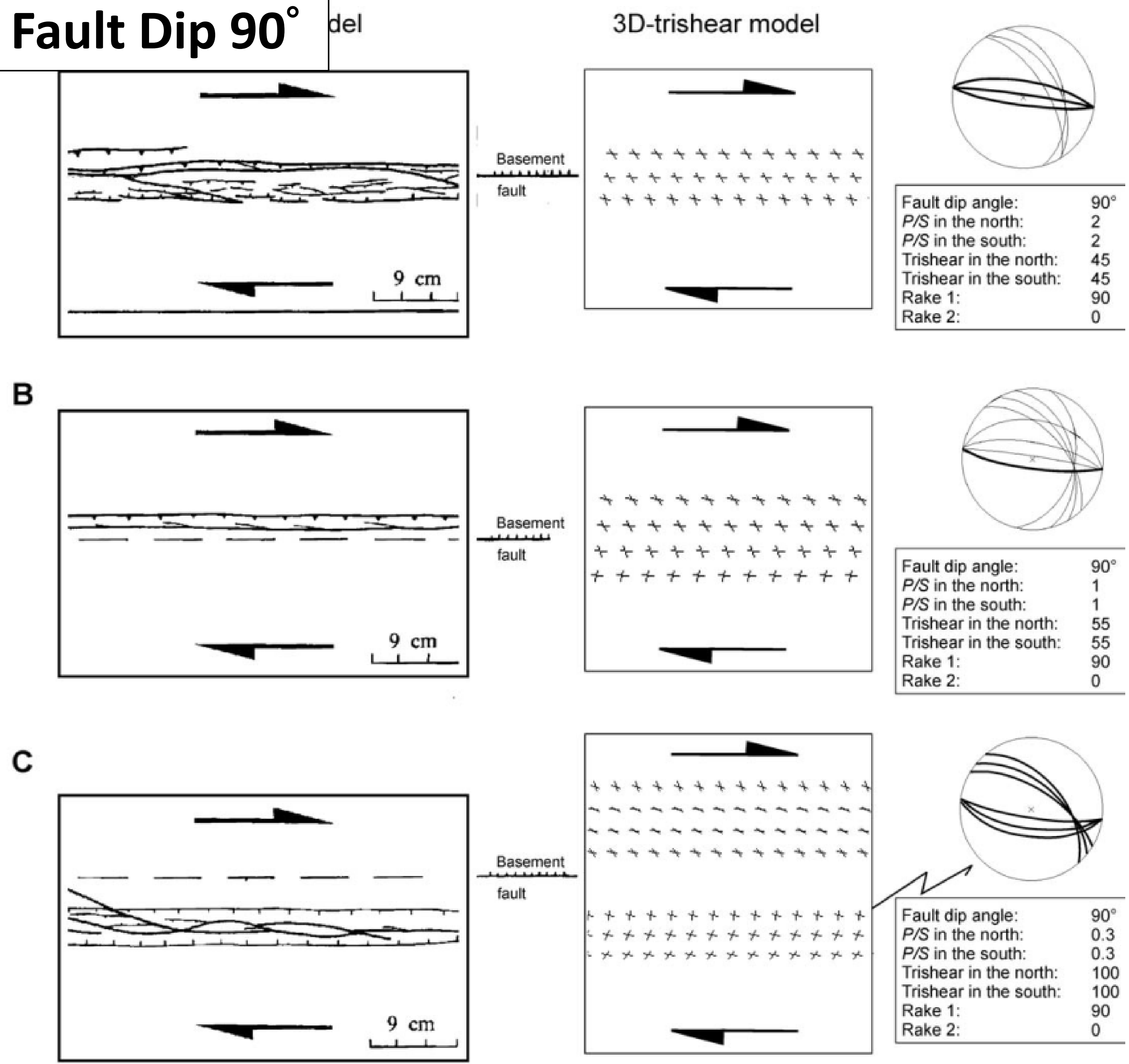
Ductile behavior: thick sand layer overlying thin silicone layer
P/S=1

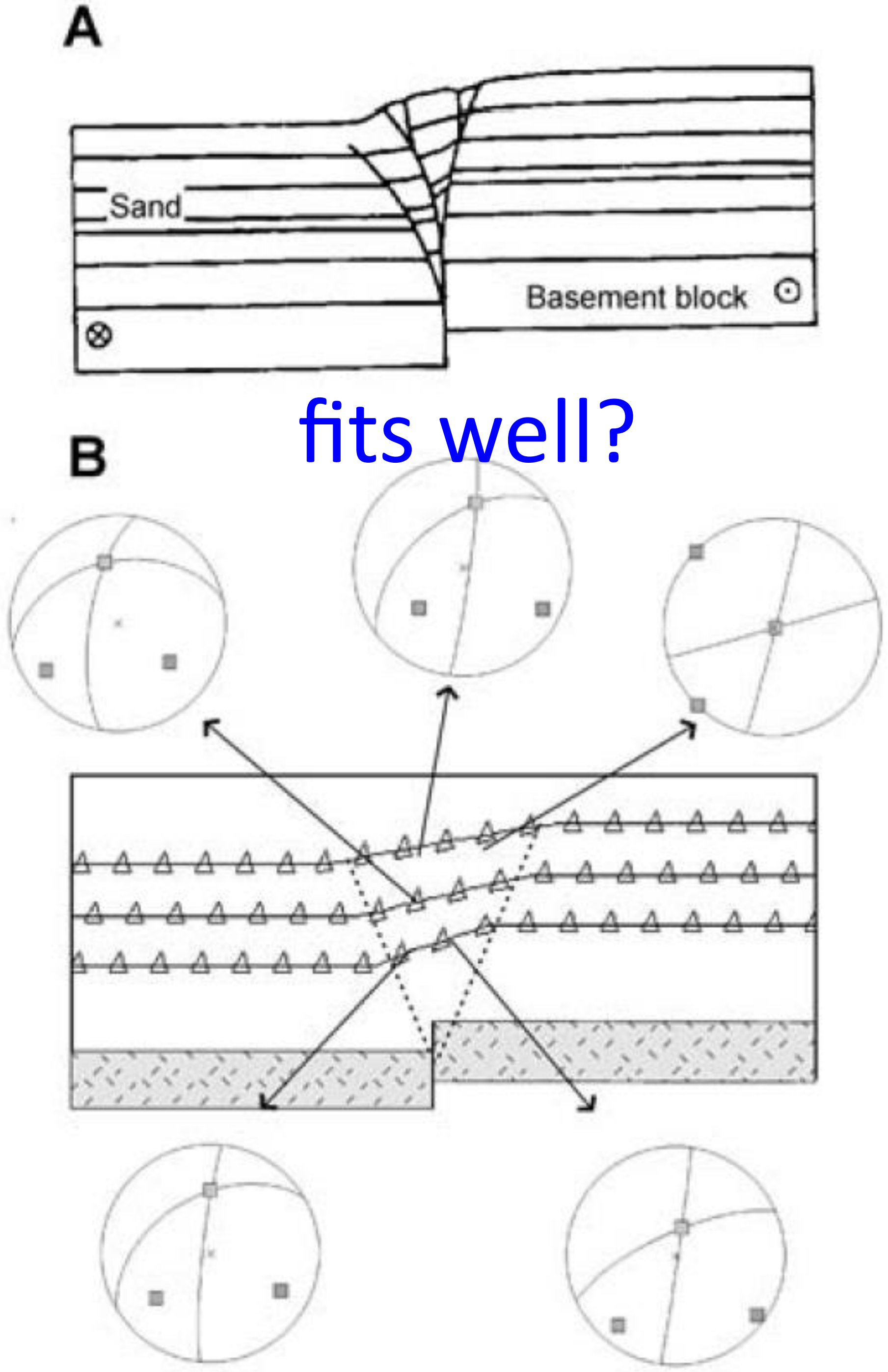
Ductile behavior: sand layer overlying thick silicone layer
P/S=0.3



Time consuming

Fault Dip 90°





fits well?

- Shortcoming:
  - True 3D is less versatile than pesupo-3D for dip slip (Cristallini and Allmendinger, 2001)
  - Time consuming for inverse method for 3D
  - Cardozo (2004): mathematical inconsistencies that result in considerable volume changes in dip-slip faults.

Trishear in 3D. Algorithms, implementation, and limitations

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Abstract

The algorithms and implementation of pseudo-3D and true-3D trishear models are explained, including a strategy to model lateral fault propagation. I show that the pseudo-3D algorithm is adequate and sufficient to model trishear in three-dimensions. Although ad-hoc, the pseudo-3D algorithm preserves volume in simulations without and with lateral fault propagation. A disadvantage of the pseudo-3D algorithm is that it produces very simple, and perhaps not realistic hanging wall geometries, specially in simulations in which the fault slip varies along strike. The true-3D algorithm has a more elaborate and richer kinematics that produces more realistic hanging wall geometries. However, the true-3D algorithm contains mathematical inconsistencies that result in considerable volume changes when the slip gradients along the tip line are high and the tip line is highly oblique to the slip vector and/or the fault strike. The volume changes occur to a large extent in the hanging wall, and to a minor extent in the forelimb and footwall areas.

Keywords: Trishear; 3D; Fault propagation folding

1. High slip gradients
2. Dip slip

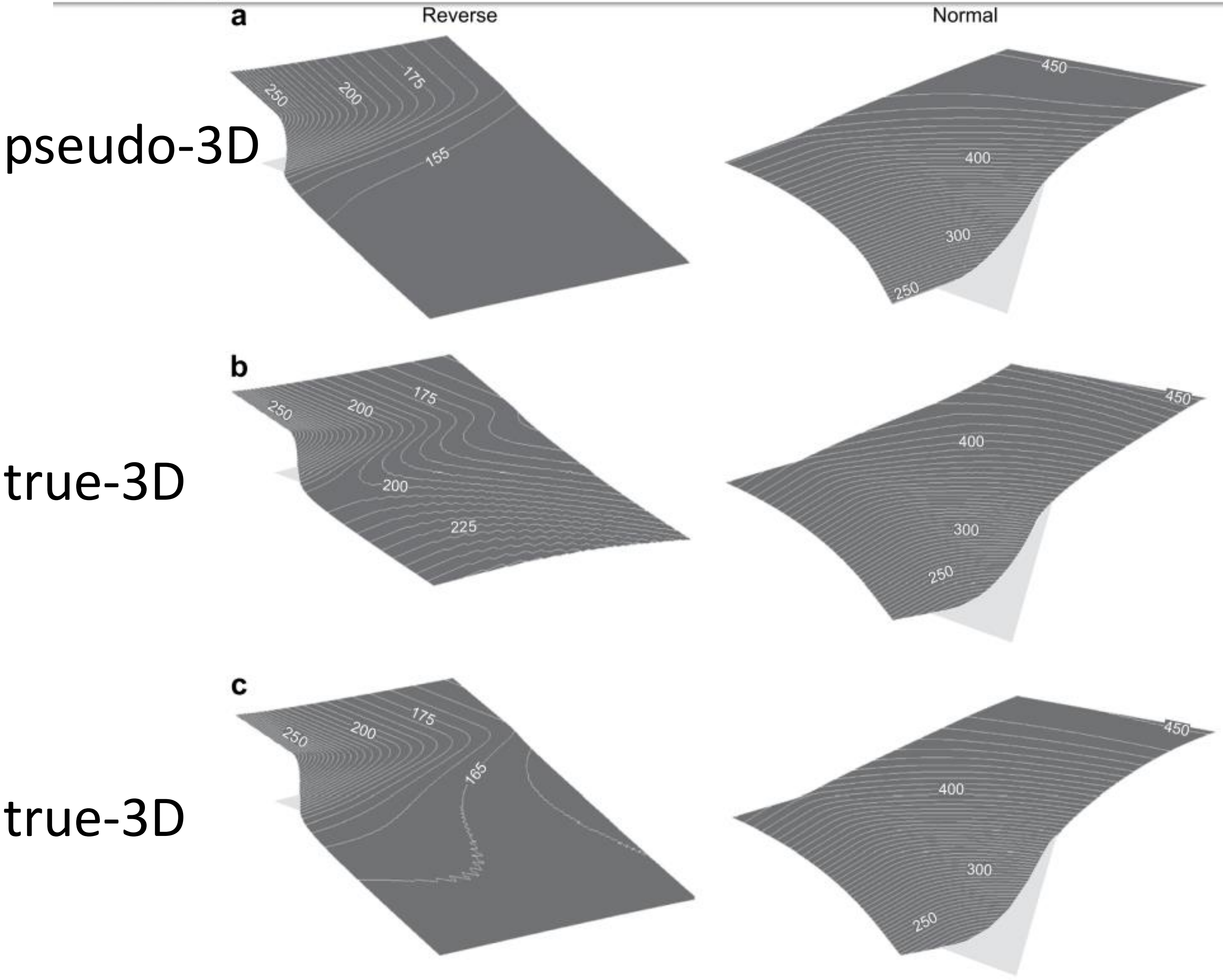

Fig. 6. 3D trishear models of laterally propagating, reverse (left side) and normal (right side) faults for (a) pseudo-3D, (b) true-3D using Eqs. (22) and (23), and (c) true-3D using Eqs. (24) and (25) models. White contours on the deformed bed are elevation.

CONCLUSIONS

1. Useful for analyzing oblique-slip/strike-slip systems:
   - Changing slip, P/S ratio, and trishear apical angle
   - allowed any obliquity of displacement
   - derived any point strain ellipsoid
   - Predict orientation of shear and extensional fractures.
2. A basic analysis of 3D trishear simulated helicoidal fractures in strike-slip–related structures.
3. More complex configurations with oblique slip and variations along strike can explain a wide range of minor structures.
4. Successful examples:
   - Natural strike-slip systems: positive and negative flower structure
   - Analogue models of fault reactivation in strike-slip mode

Caution to use in dip slip!

- Thank you very much!