Click to see animation of elastic thrust simulation

Click to see animation of elastic-plastic thrust simulation

Click to see animation of elastic-plastic-damage thrust simulation

Numerical Simulation of Reservoir Structures, Part III: Folding of a Layered Rock Sequence in a Ramp System*

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Search and Discovery Article #40485 (2010)
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*Adapted from oral presentation at AAPG Convention, Denver, Colorado, June 7-10, 2009. Please refer to closely related articles by Seth Busetti and Ze'ev Reches: Numerical Simulation of Reservoir Structures, Part I: Rheology of Reservoir Rocks, Search and Discovery article #40483 (2010), and Numerical Simulation of Reservoir Structures, Part II: Propagation of a Pressurized Fracture in Rock Layers with Damage Rheology, Search and Discovery article #40484 (2010).

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Abstract

We present a 2D numerical model of a flat-ramp-flat thrust system that includes mechanical stratigraphy and inter-layer friction to investigate the effects of rheology, friction and ramp angle on the geometry of ramp associated folds. This work is part of our study on structural processes in reservoir rocks by numerical simulations with Abaqus finite element code. Part I discusses rock rheology and benchmark simulations, and Part II investigates fracture propagation into a sequence of damaged rock layers.

Analysis and restoration of fault-fold systems requires understanding of the mechanical processes associated with their development. In our calculations we use in-situ conditions including relevant dimensions, gravity, deformation rates, inter-layer friction, and rock properties of Berea Sandstone, as a realistic elastic-plastic-damage rheology (Part I, Busetti et al.). The thrust fault-zone is modeled by a weak layer (representing salt or clay) with a visco-plastic rheology calibrated with experimental results of rock salt (Carter et al., 1993).

In a typical model, we consider a system of a flat thrust, 60-80 km long, with a 5-45 degrees ramp in its center. The sedimentary hanging wall is up to 14 km thick with individual alternating layers 1-2.5 km thick each. The footwall consists of a 5 km thick competent, elastic basement. In the simulations, the hanging wall is transported horizontally up to 16 km over the basement ramp in a quasi-static mode.

The structural geometry and the associated patterns of stress, strain and damage are explored as a function of basal friction (of the thrust fault-zone), inter-layer friction and fault ramp angle. The main results show that (1) large inter-layer friction significantly reduces the fold amplitude leading to a flat crest above the ramp-flat transition; (2) high basal friction leads to asymmetric folding, whereas low basal friction leads to symmetric folding; (3) high amplitude folds occur for ramp angles that are 10 to 30 degrees; (4) steep front limbs develop for ramp angle > 30 degrees.

Acknowledgement

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Stein, R.S., and G. Ekstrom, 1992, Seismicity and geometry of a 110-km-long blind thrust fault, 2, Synthesis of the 1982–1985 earthquake sequence: Journal of Geophysical Research, v. 97, p. 4865–4884.

Suppe, J., 1983. Geometry and kinematics of fault-bend folding: American Journal of Science, v. 283, p. 684-721.

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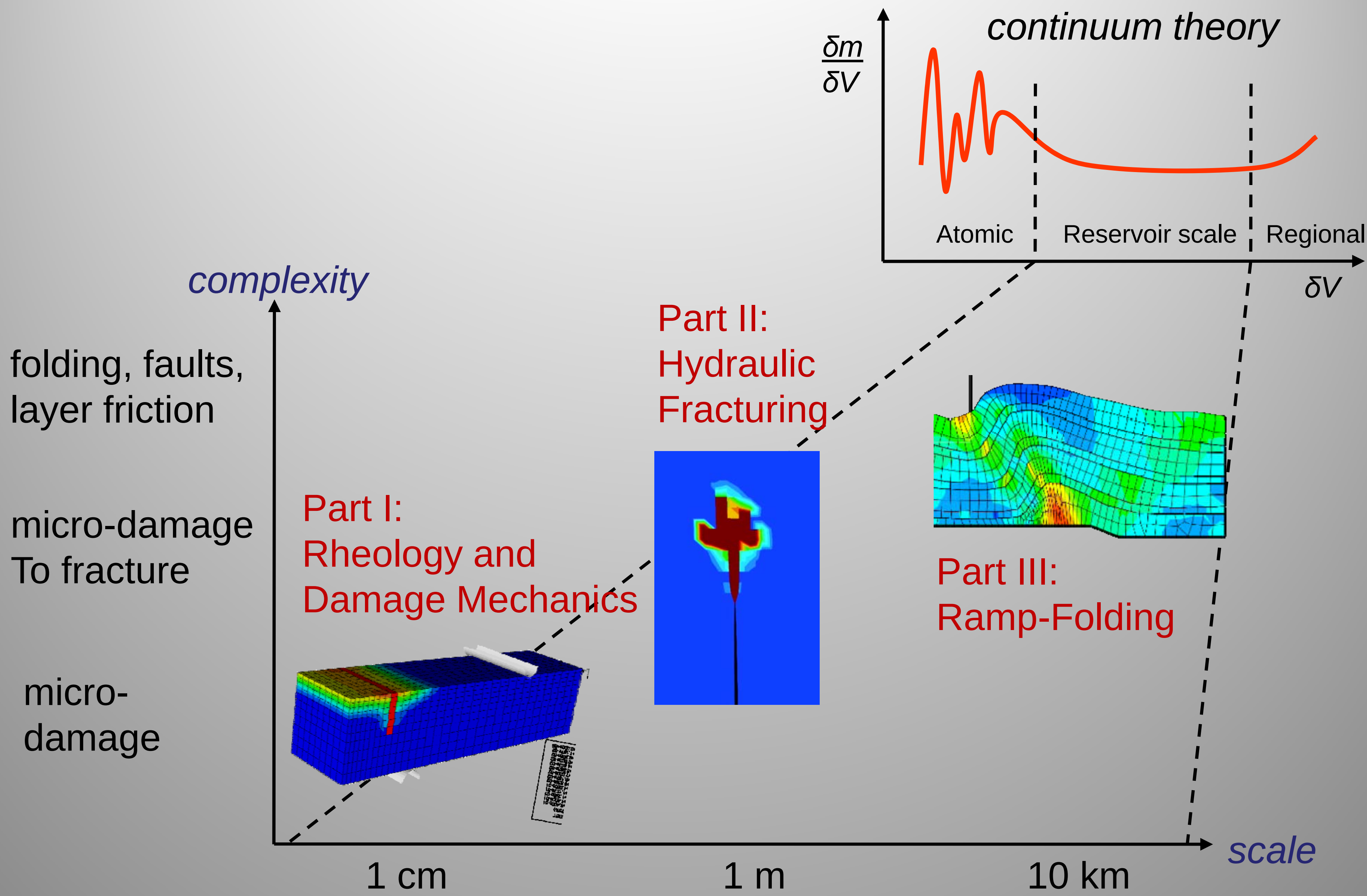
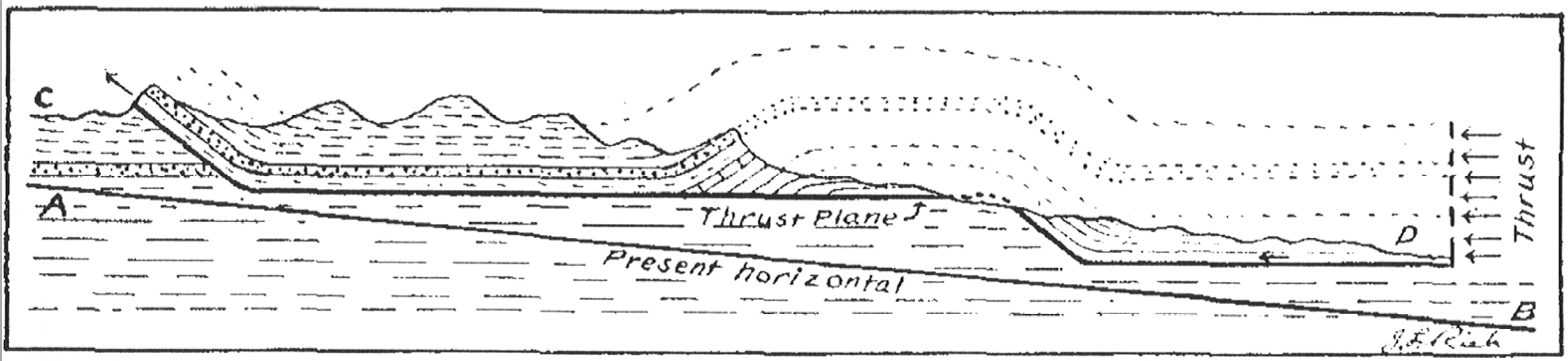
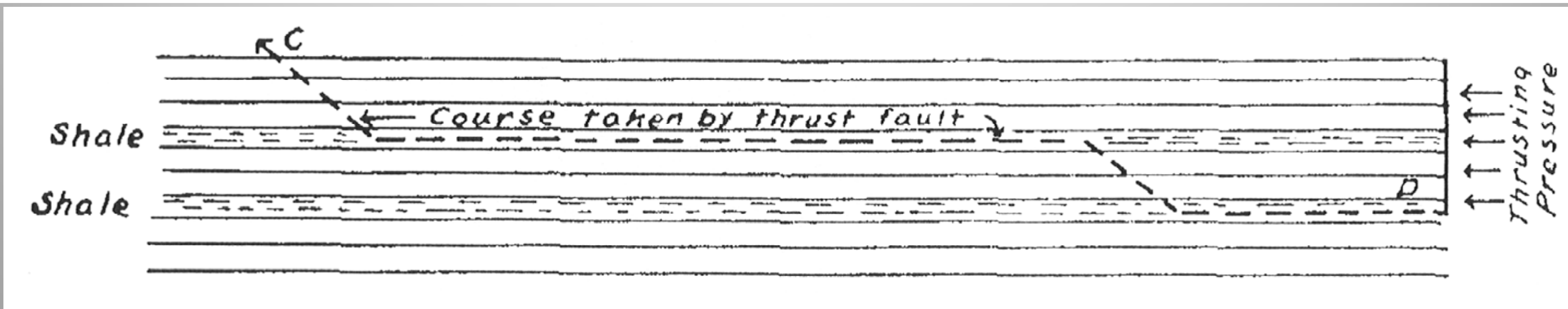
ConocoPhillips
SCHOOL OF GEOLOGY & GEOPHYSICS
The University of Oklahoma

Simulating Deformation – Multi-scale Approach



Ramp system (Rich 1934)





Solutions:

1) <u>Kinematic</u>: Balanced cross-sections
Suppe (1983)

2) <u>Elastic</u>: Boundary element model
Stein and Ekstrom (1992)

3) <u>Viscous</u>*:* Folding of viscous layers
Johnson and Fletcher (1994); Erickson & Jamison (1993)

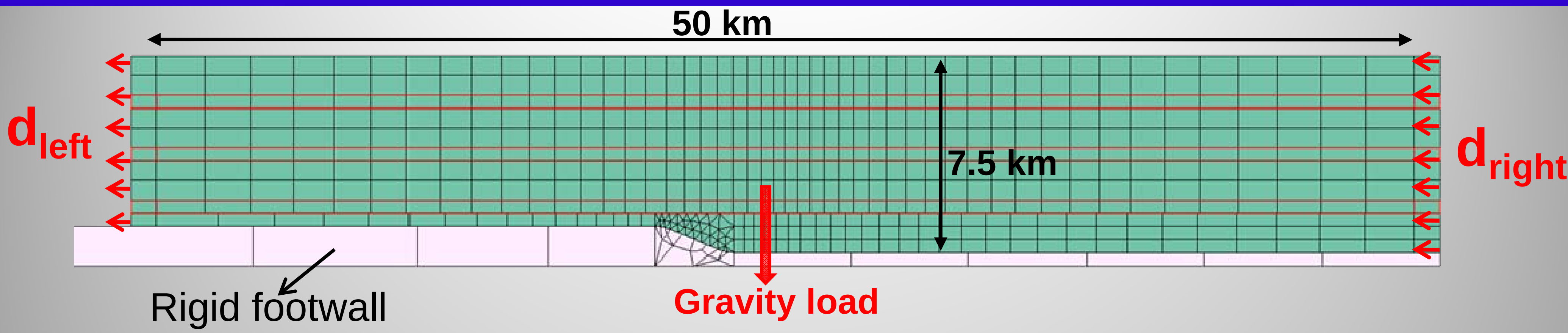
Current study:

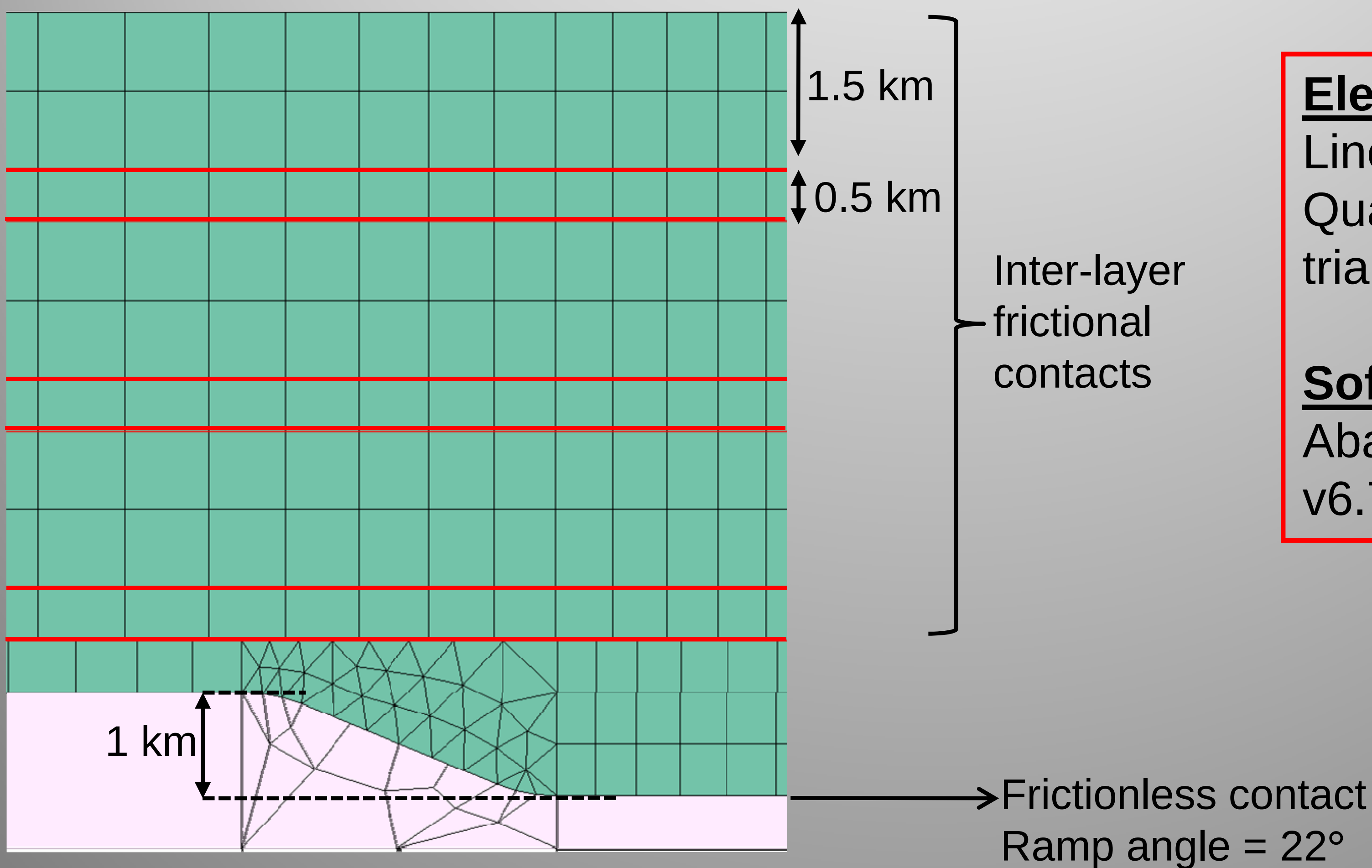
2D FEM analysis to investigate the effect of:

-Inter-layer friction

-Rheology

Present ramp model





Elements:
Linear Plane Strain Quadrilateral and triangular

Software:
Abaqus Student Edition v6.7-2 Explicit

Present ramp model

Range of rheology:

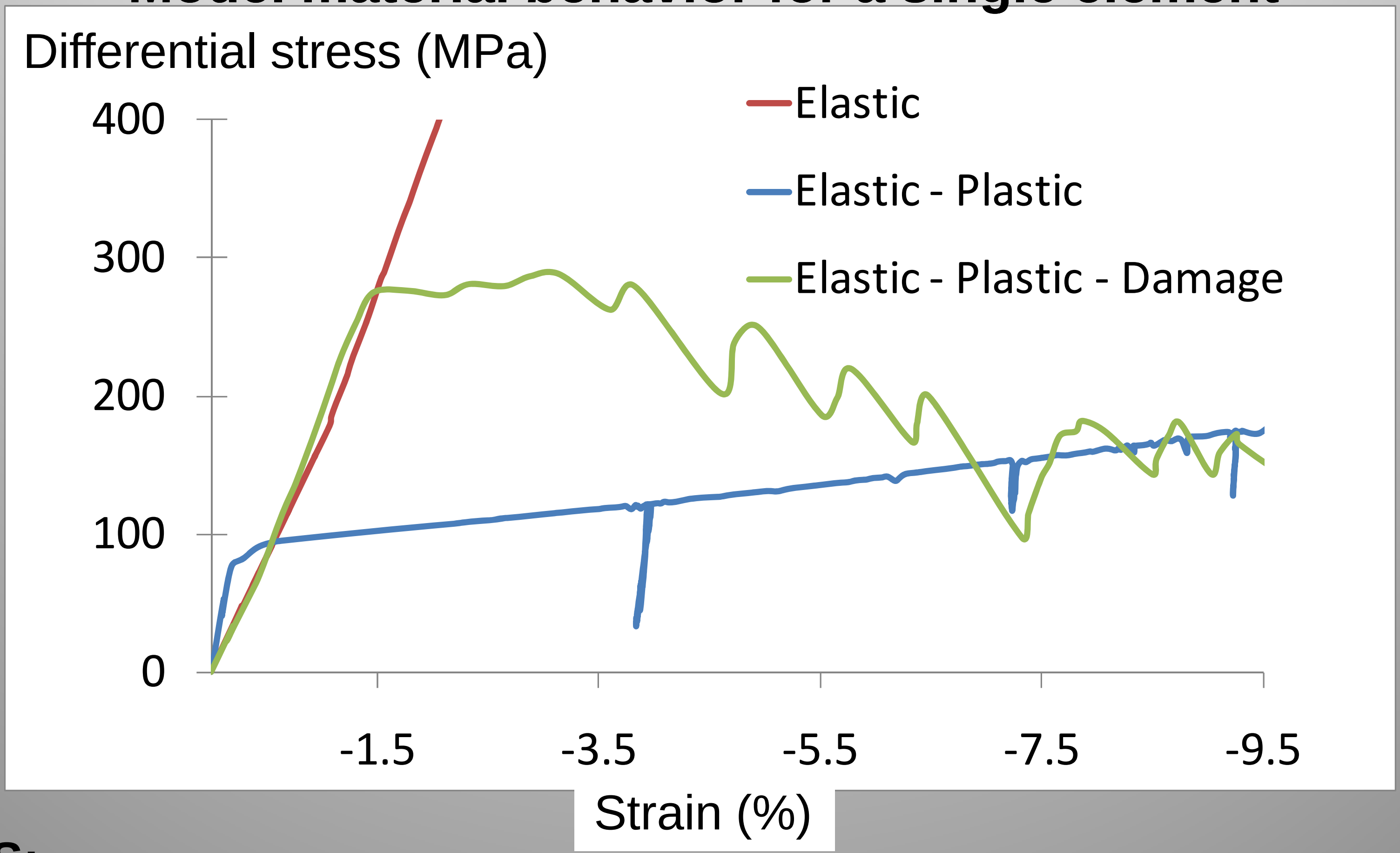
Linear Elastic (generic)

Elastic – Plastic (generic)

Elastic – Plastic – Damage (Berea Sandstone from rock mechanics experiments)

(Busetti et al., Part I)

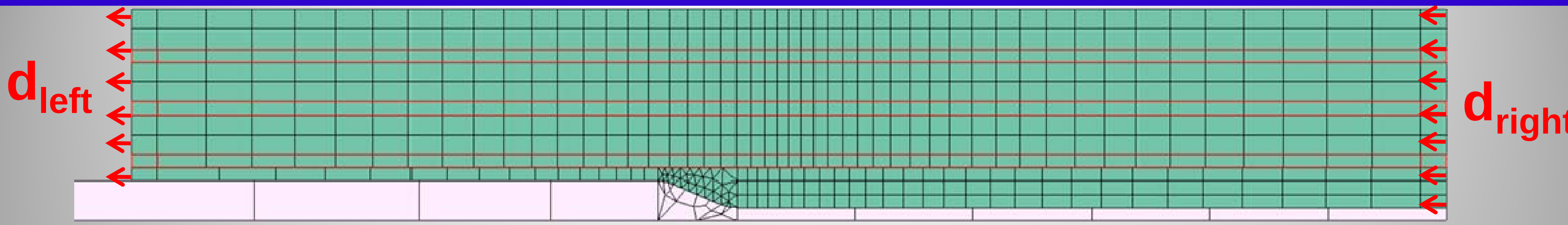
Model material behavior for a single element



Berea SS:

Non-linear, brittle (**hardening** and **softening** in ***tension*** and ***compression***)

Model Conditions



d_{right} = 20 km; μ_{fault} = 0

Rheology	Boundary conditions	Inter-layer friction (μ_{layer})
Elastic	$d_{left} = d_{right}$	0
Elastic – Plastic	$d_{left} = ½\, d_{right}$	0.4
E-P-Damage	$d_{left} = 0$	0.8

3 movies for illustration

Total of 27 models

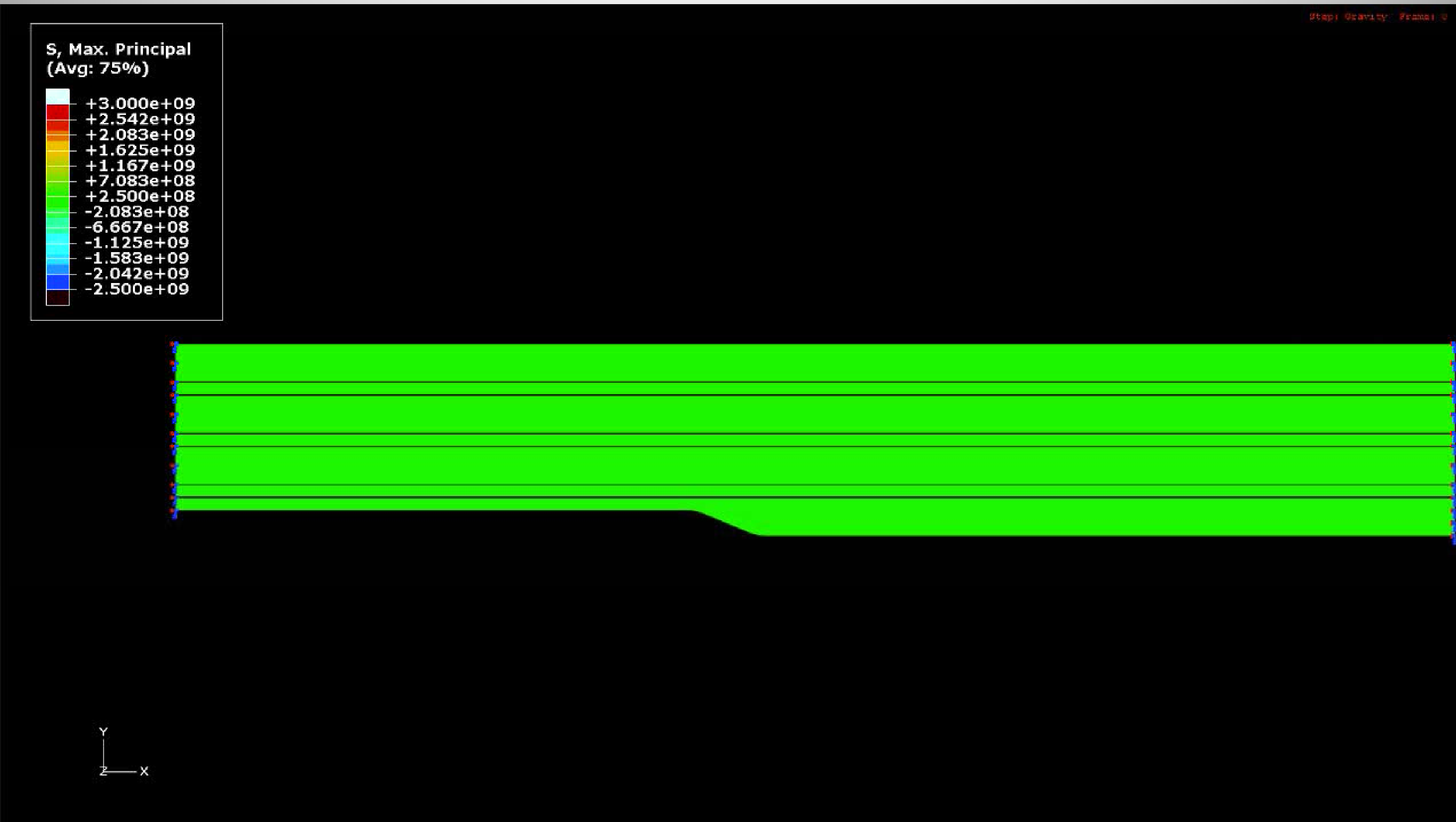
Results:

1) Structural geometry of the fold
2) Fold – fault position
3) Volumetric strain

Elastic

$U_{layer} = 0.4$

$d_{left} = ½ \, d_{right}$



Elastic - Plastic

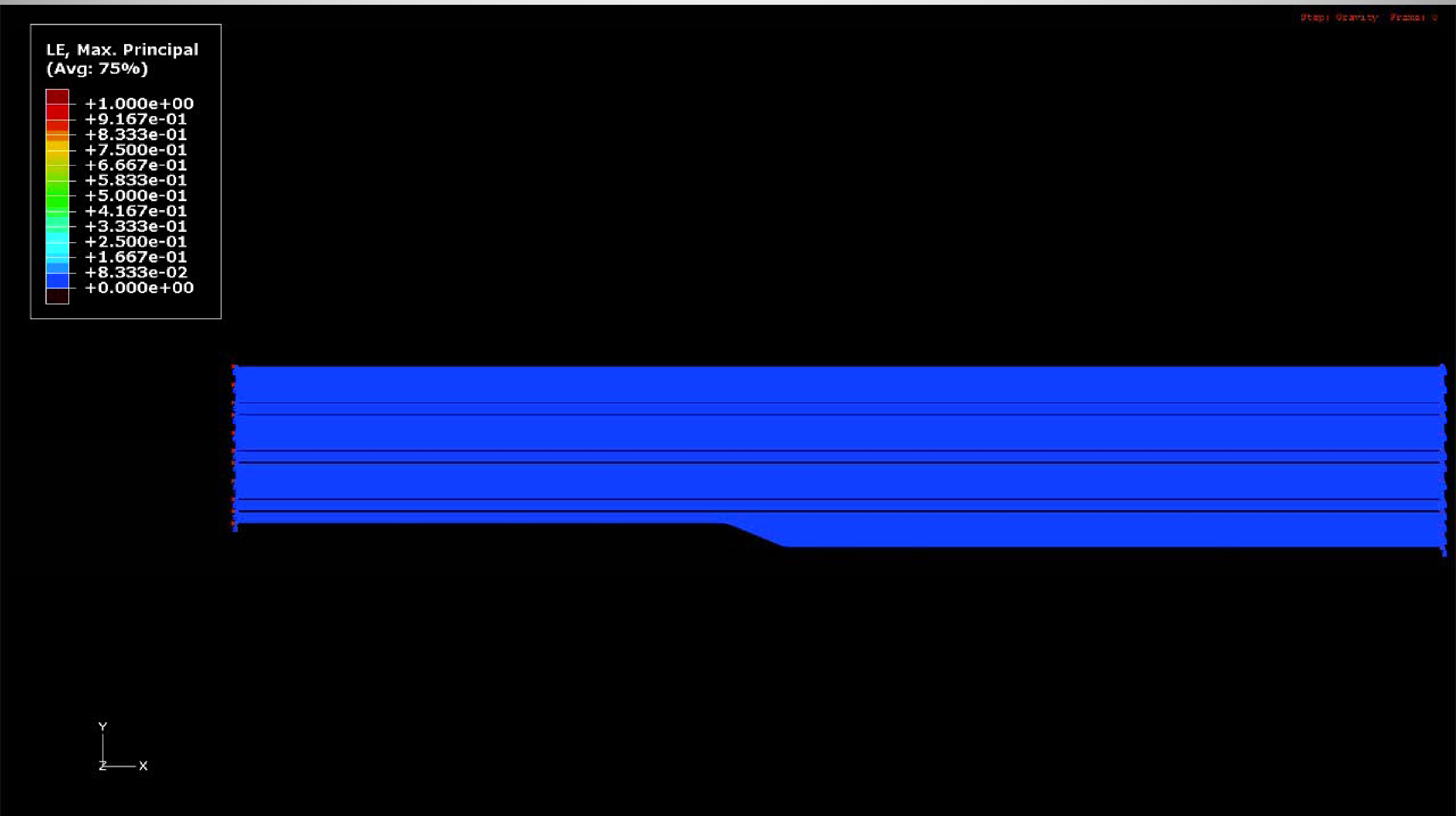
$U_{layer} = 0.4$

$d_{left} = ½\ d_{right}$

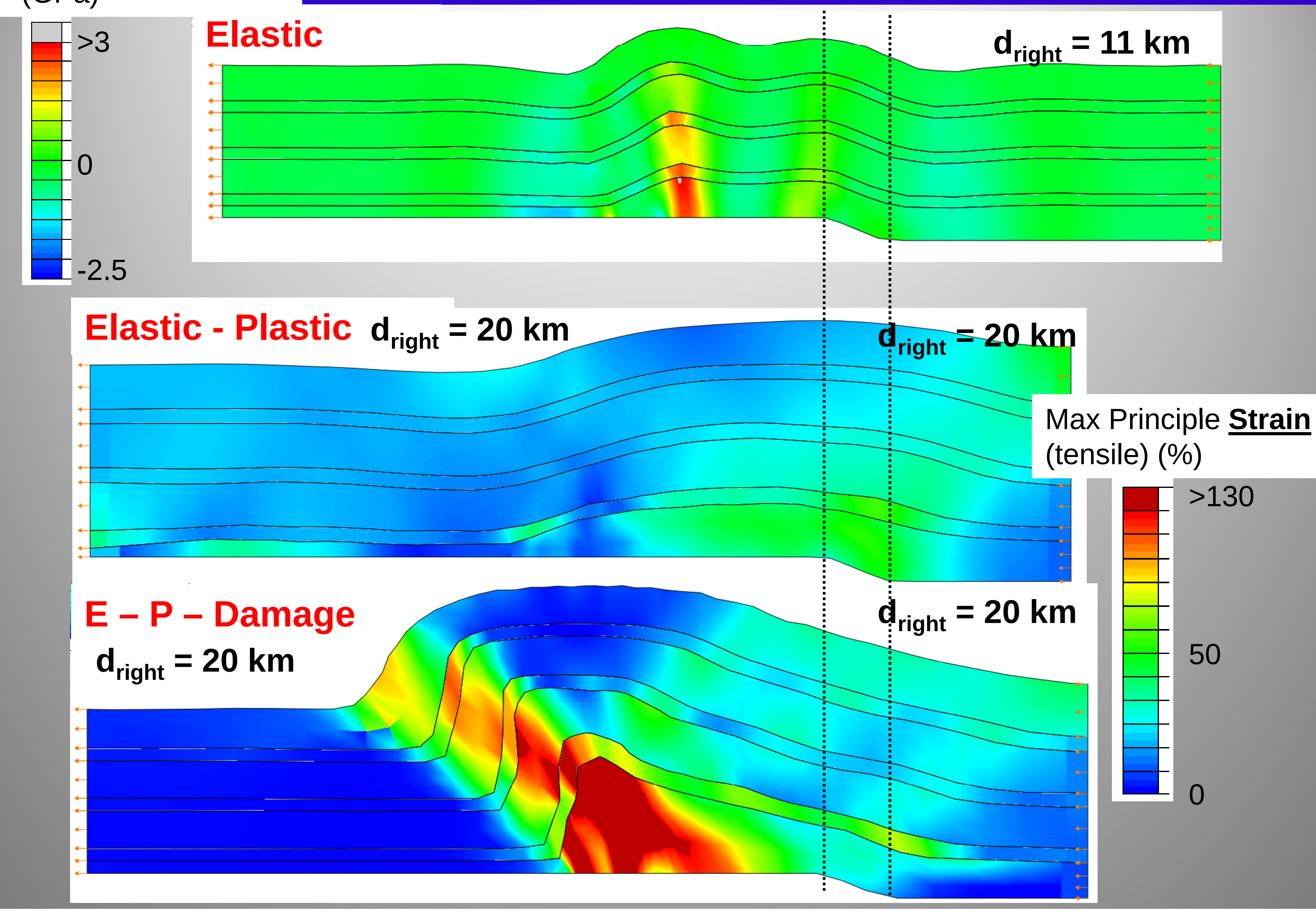
Elastic – Plastic – Damage

$U_{layer} = 0.4$

$d_{left} = \frac{1}{2} d_{right}$

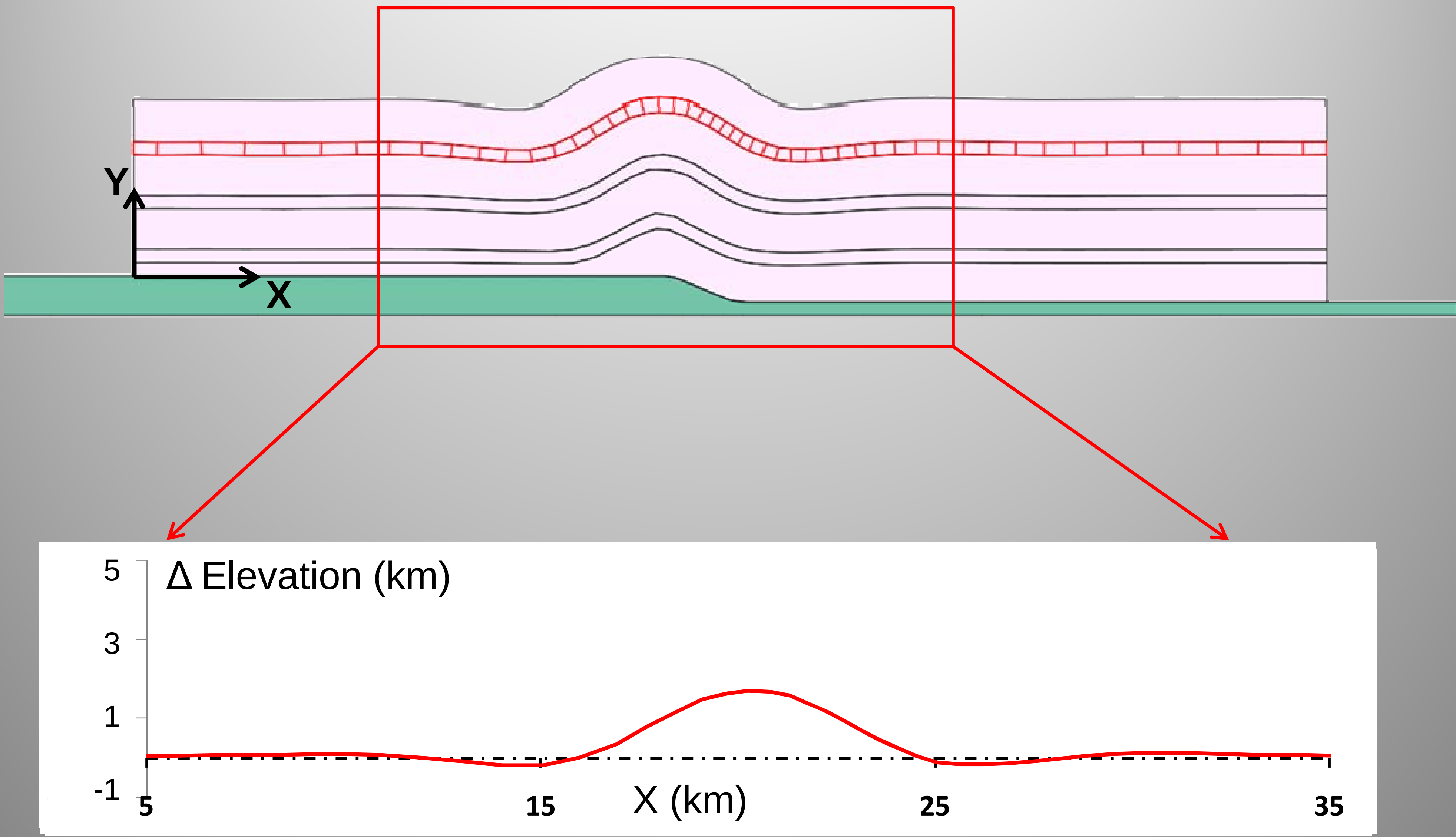


Movies



Max Principle **Stress** (GPa)
>3
0
-2.5
Elastic
d_{right} = 11 km
Elastic - Plastic
d_{right} = 20 km
d_{right} = 20 km
Max Principle **Strain** (tensile) (%)
>130
50
0
E – P – Damage
d_{right} = 20 km
d_{right} = 20 km

Geometrical Analysis

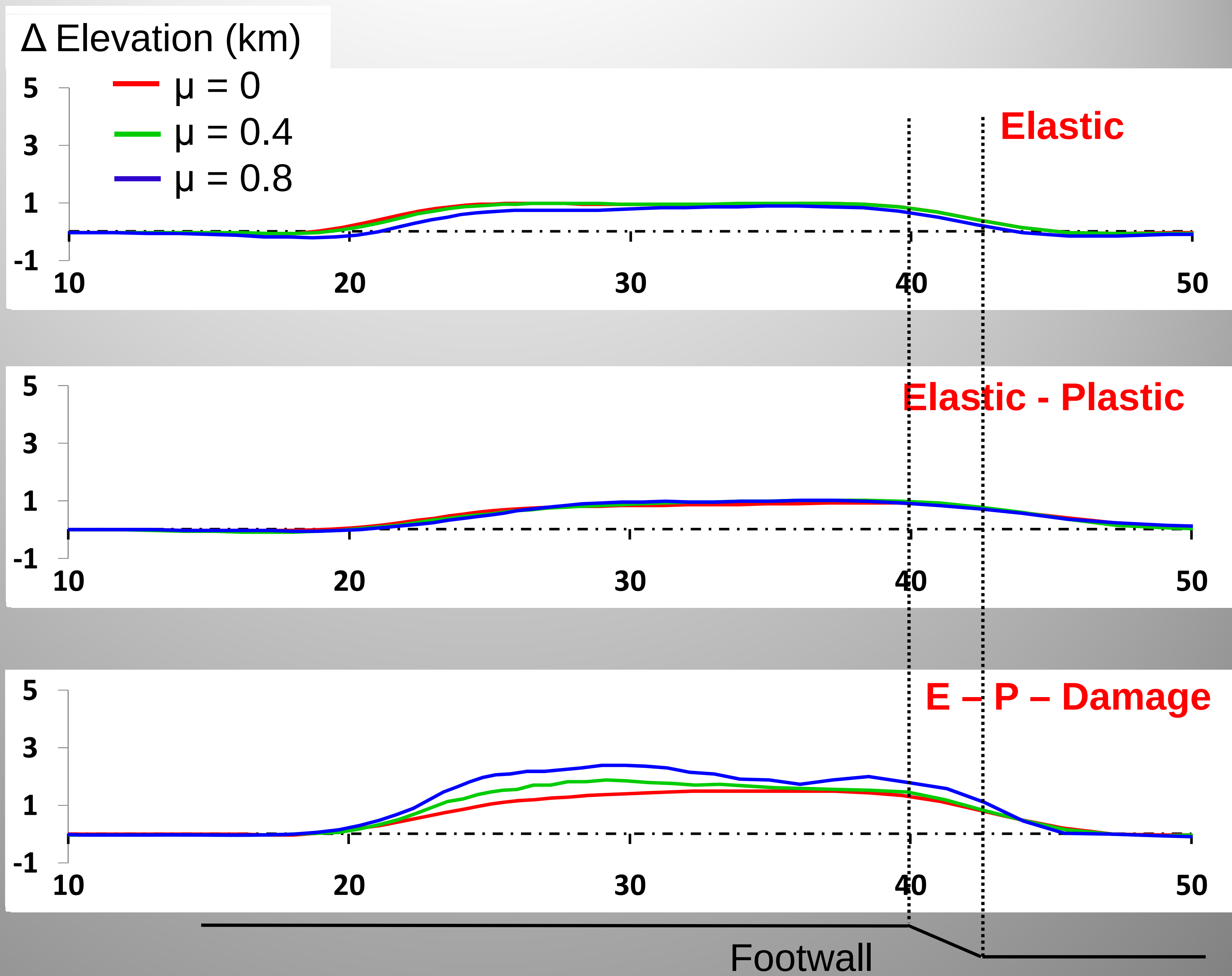


Results

d_{right} = 20 km
d_{left} = d_{right}

d_{right} = 20 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = 0 km

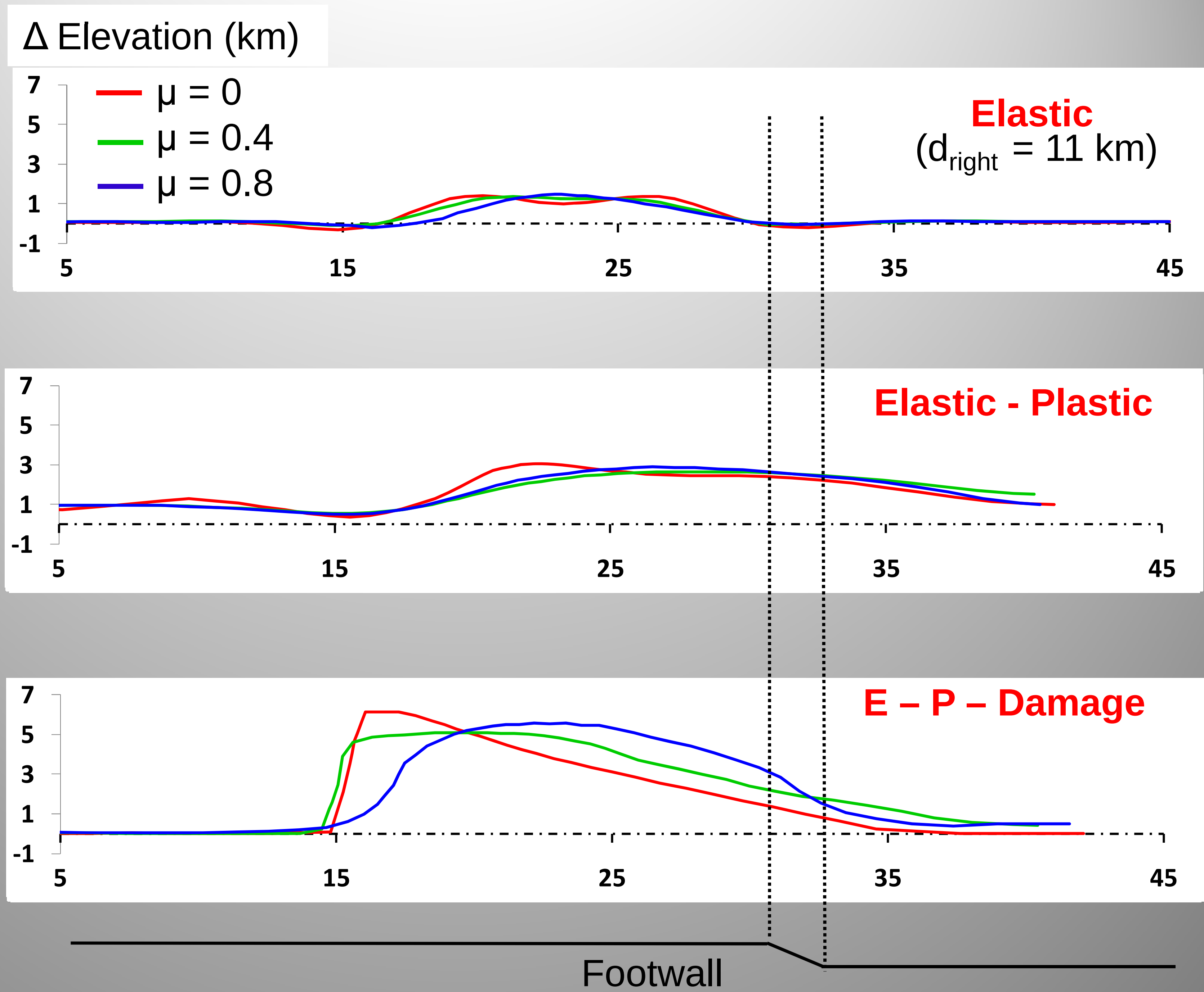


Results

d_{right} = 20 km
d_{left} = 0 km

d_{right} = 20 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = d_{right}

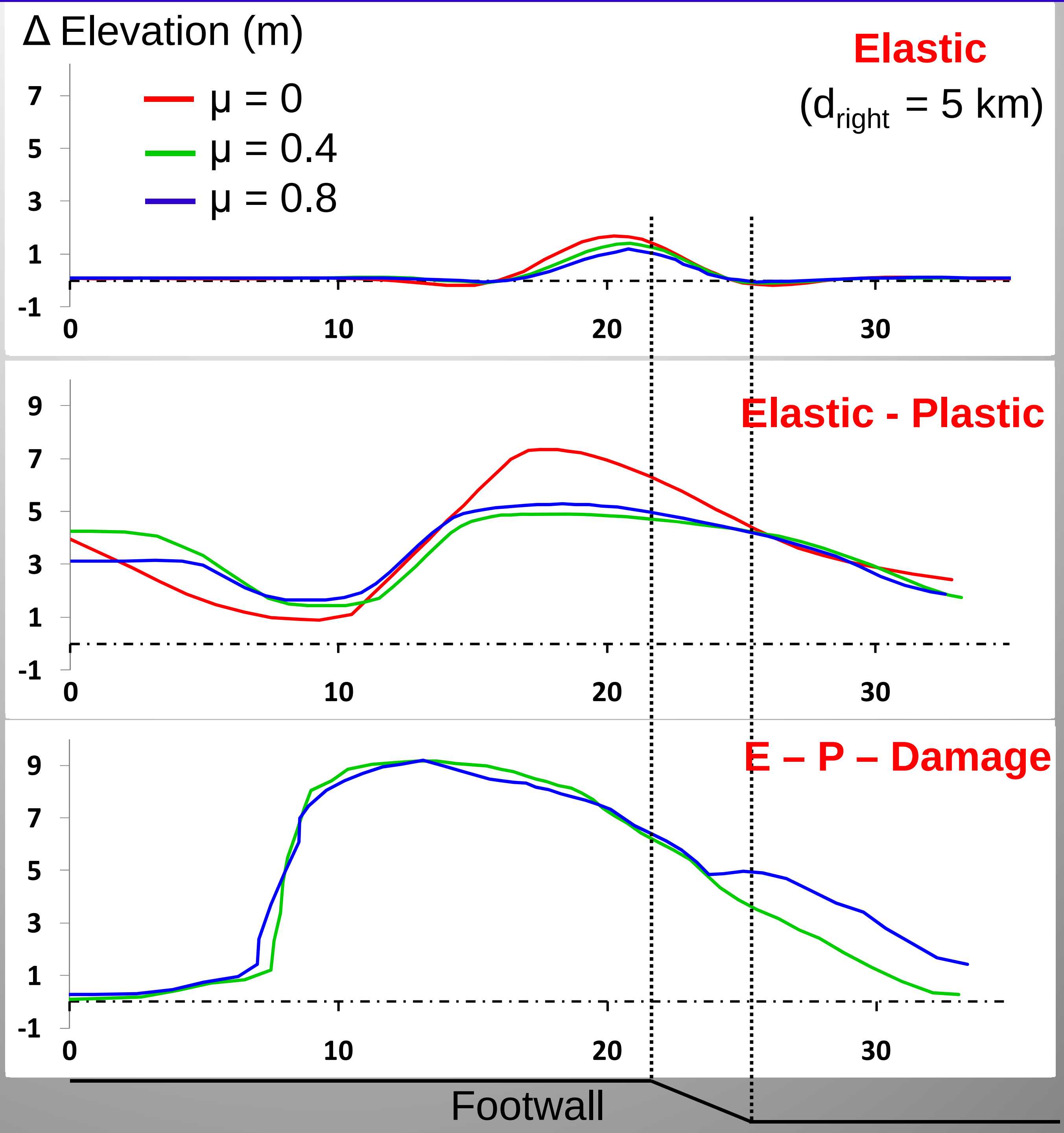


Results

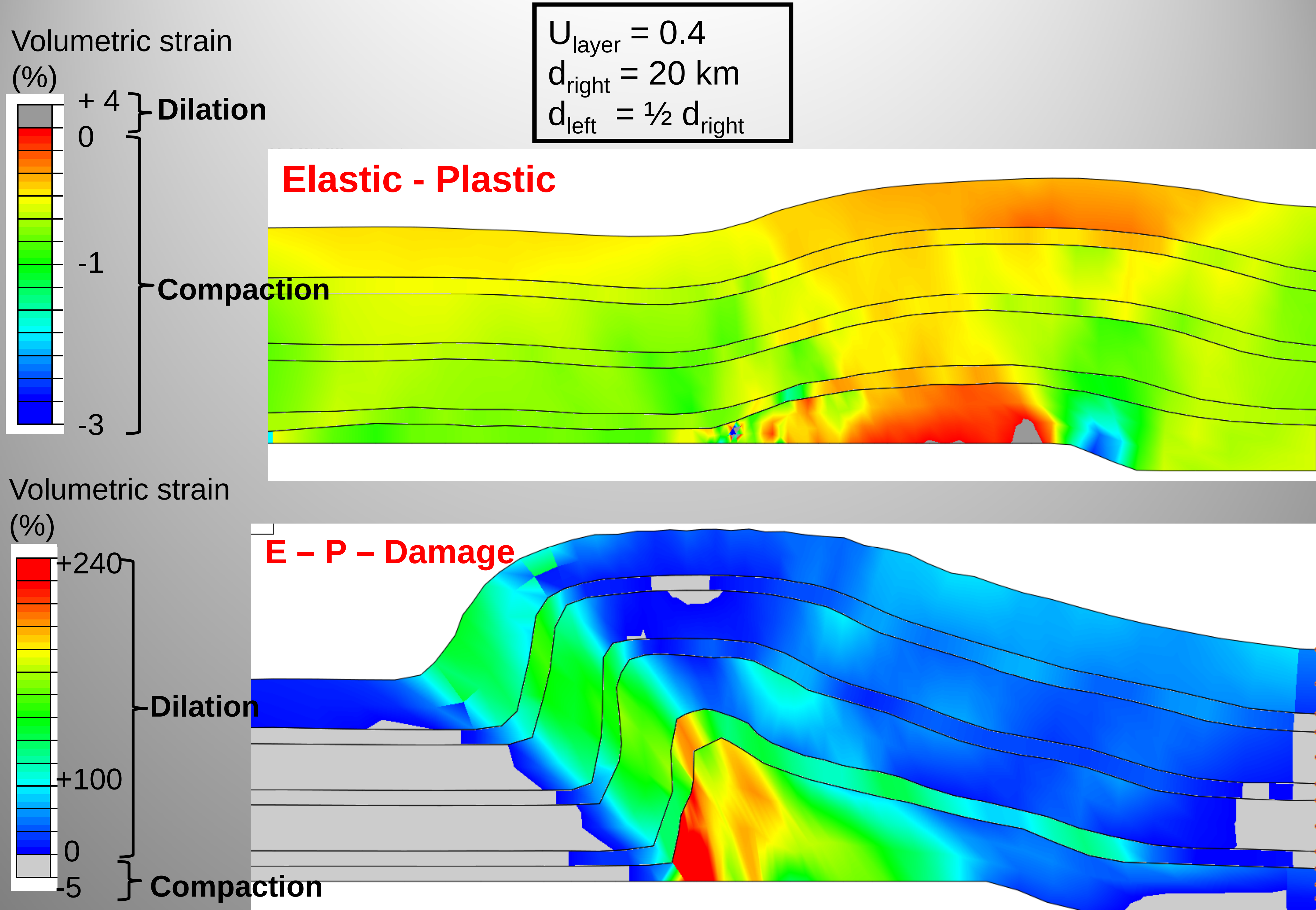
d_{right} = 20 km
d_{left} = d_{right}

d_{right} = 20 km
d_{left} = ½ d_{right}

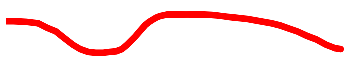
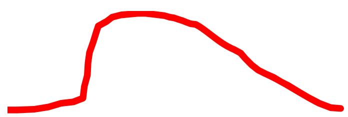
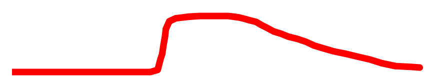
d_{right} = 20 km
d_{left} = 0 km



Volume changes



Conclusions

μ_{layer} = 0.4	d_{left} = 0	d_{left} = ½ d_{right}	d_{left} = d_{right} (Rich model)
E			
E-P			
E-P-D			

Material softening

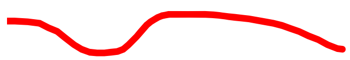
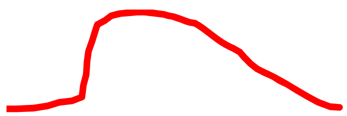
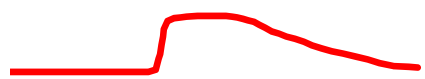
Amplitude
Front limb syncline
Distance from ramp
Dilation

Asymmetry
Amplitude
Front limb steepness
Distance from ramp
Dilation

<u>Inter-layer friction</u>

↑ μ_{layer} = ↓ fold amplitude

Conclusions

μ_{layer}= 0.4	d_{left} = 0	d_{left} = ½ d_{right}	d_{left} = d_{right} (Rich model)
E			
E-P			
E-P-D			

Material softening

Amplit
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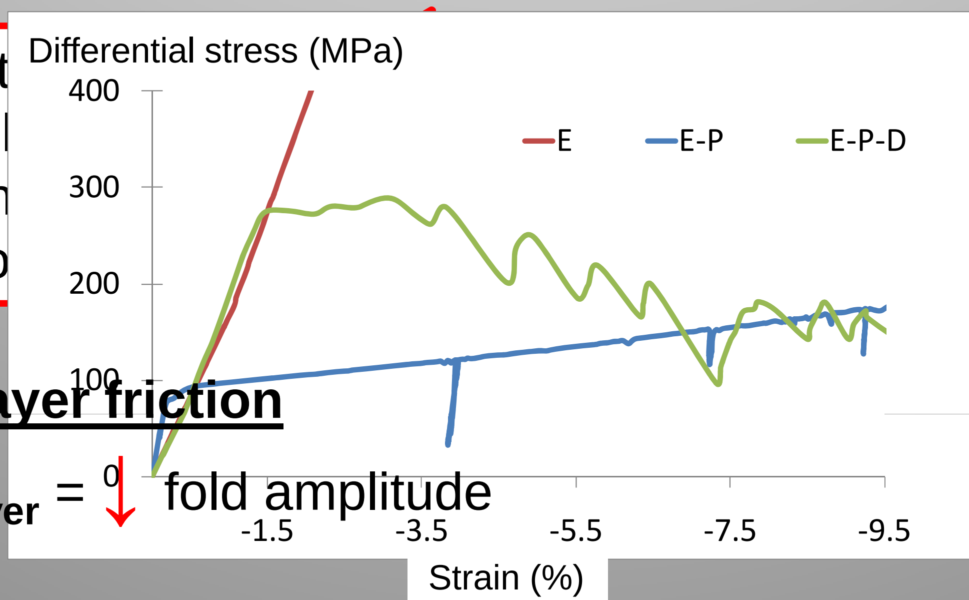


Asymmetry
Amplitude
Front limb steepness
Distance from ramp
Dilation

Inter-layer friction

↑ μ_{layer} = ↓ fold amplitude

Backup slides

Results

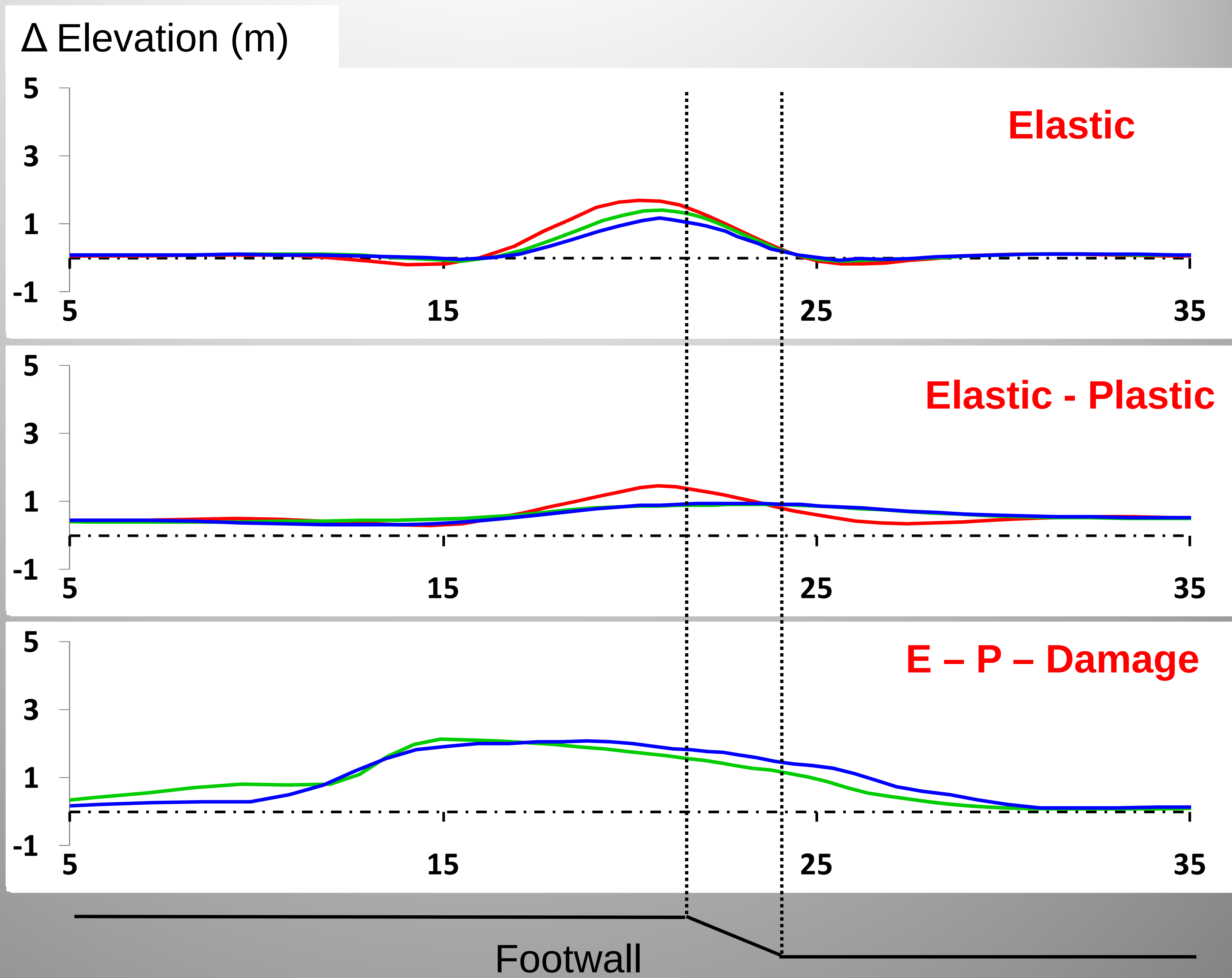
d_{right} = 5 km
d_{left} = 0 km

d_{right} = 20 km
d_{left} = 0 km

d_{right} = 11 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = 1 d_{right}



Results

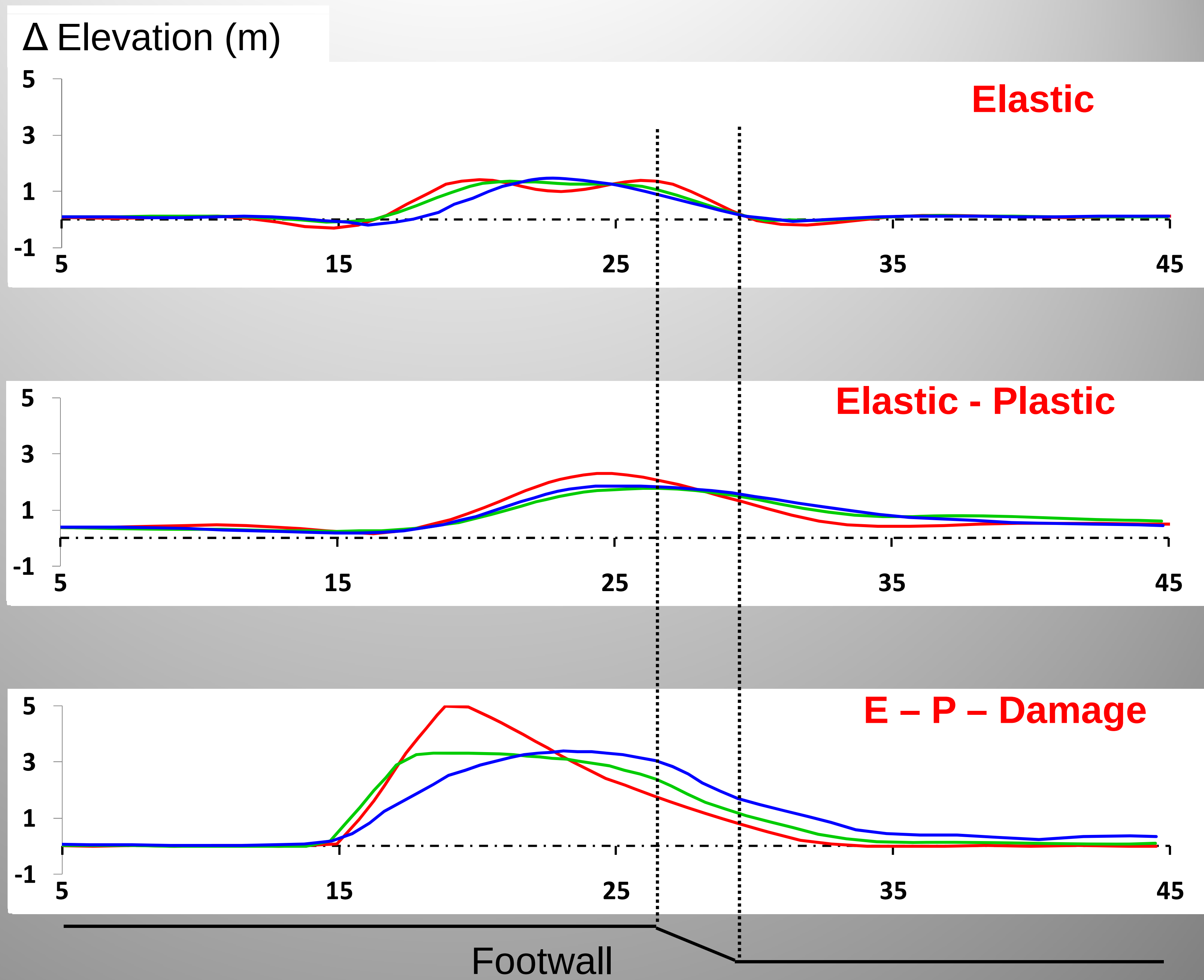
d_{right} = 5 km
d_{left} = 0 km

d_{right} = 20 km
d_{left} = 0 km

d_{right} = 11 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = ½ d_{right}

d_{right} = 20 km
d_{left} = 1 d_{right}



Conclusions

General observations

Rheology

1) Symmetric folding for elastic rheology
2) ↑ material softening = ↑ asymmetric folding = ↑ dilation
3) ↑ material softening = ↑ forelimb steepness
4) Max curvature away from the ramp for Berea SS

Inter-layer friction

1) ↑ friction = ↓ fold amplitude

Field application

If a final ramp related fold geometry is known we can predict:

- Associated boundary condition
- Area's of intense fracturing / faulting