Precursory off-fault deformation to slip along healed preexisting faults in restraining and releasing step overs: Insights from discrete element method models

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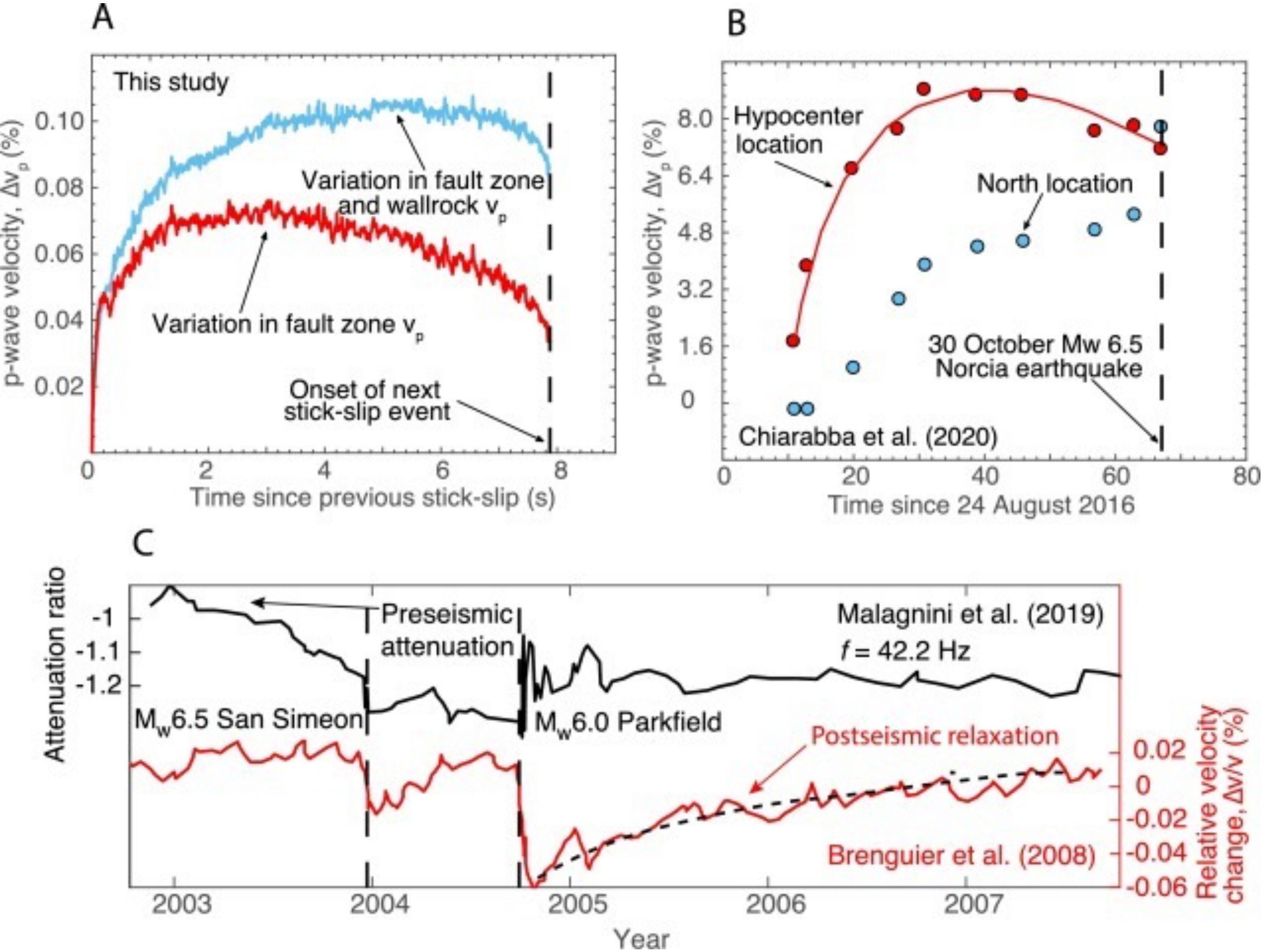


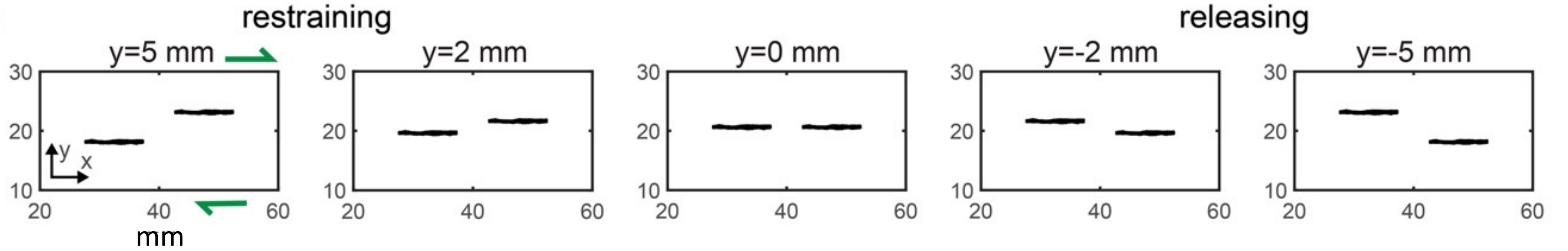
Question 1: Where does precursory deformation occur?

Question 2: What is the style of precursory deformation (displacement and strain)?

Precursory changes in the lab and crust (Shreedharan et al., 2021)

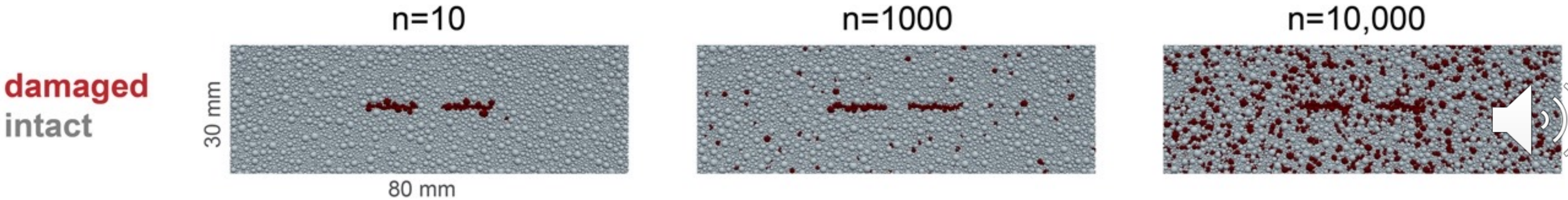
Influence of fault configuration on off-fault deformation

- More off-fault deformation near more complex fault geometries (e.g., *Oskin et al*., 2007; *Scott et al*., 2018; *Wechsler et al*., 2009; *DeLong et al*., 2010; *Lindsey et al*., 2014; *Dolan & Haravitch*, 2014; *Teran et al*., 2015; *Milliner et al*., 2015, 2016)
- Vary the spacing between the step overs to capture the influence of fault zone



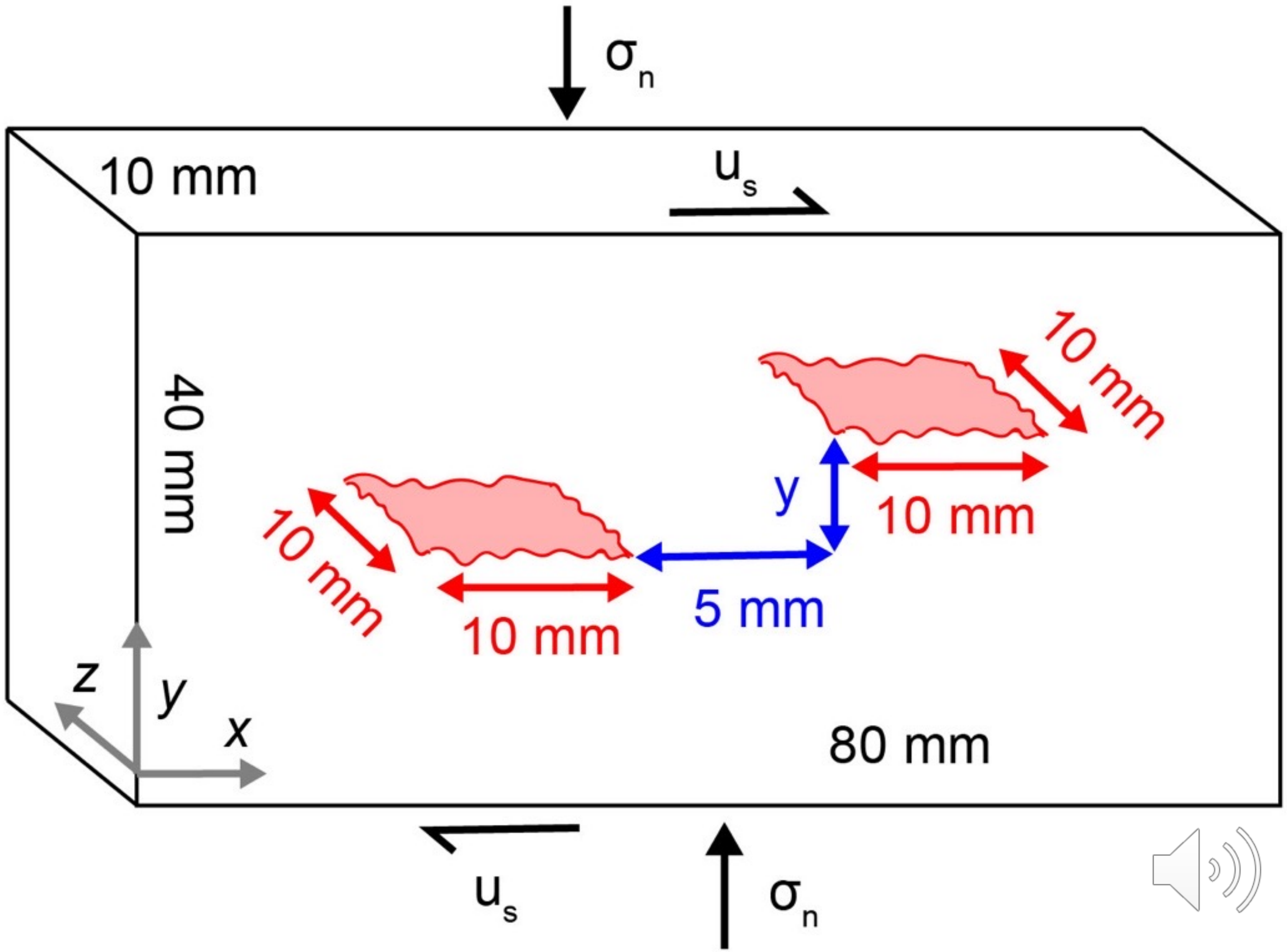
Influence of host rock damage on off-fault deformation

- More off-fault deformation in weaker materials (sediments) (e.g., *Rockwell et al*., 2002; *Titus et al*., 2011; *Zinke et al*., 2014; *Milliner et al*., 2015)
- Vary the preexisting host rock damage to capture the influence of ratio of strength of fault to host rock

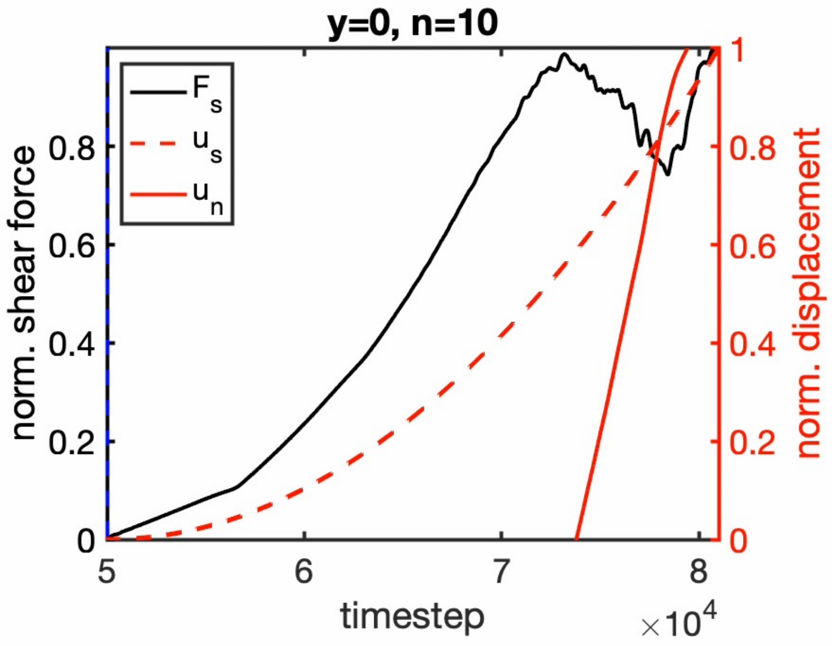


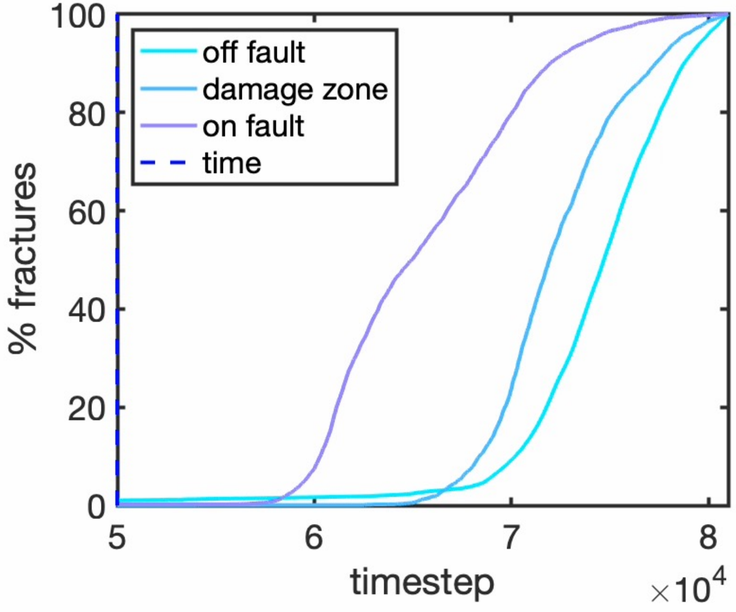
Model set up: Loading conditions

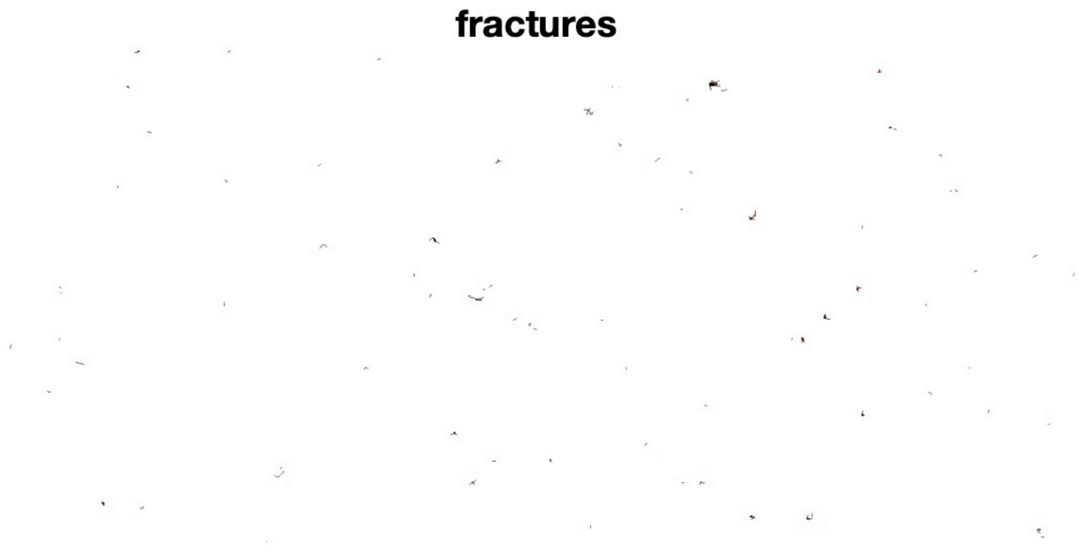
- ESyS-Particle discrete element method models
- 3D models
- Underlapping faults separated by one half fault length
- Varying step length, y
- Faults with roughness parameters of natural faults (Hurst exponents and roughness amplitude)
- Constant normal stress
- Constant shear velocity loading



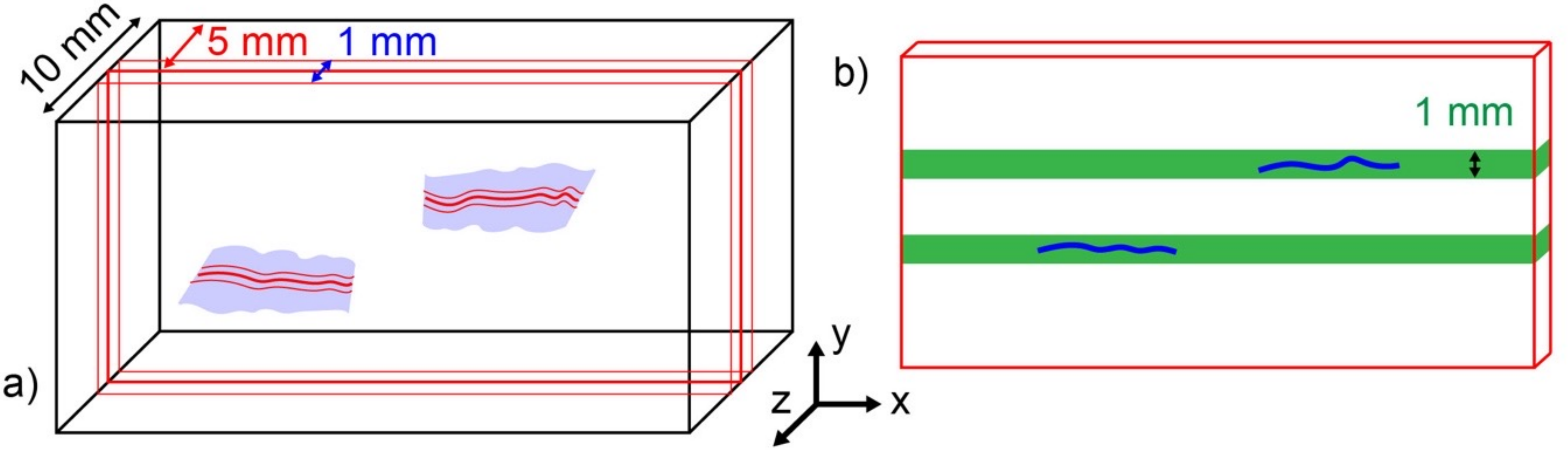
Fault network development
Coplanar, low damage







Extracting off-fault deformation preceding slip on healed faults

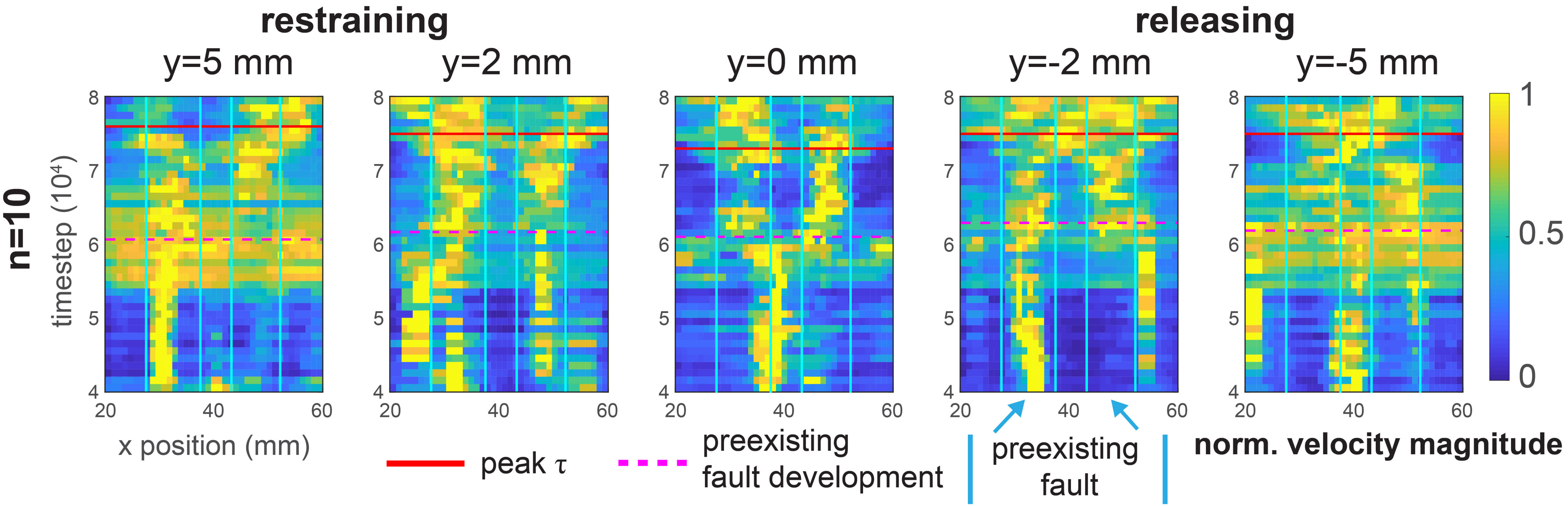


Extraction of the velocity field

- take a 1 mm wide two-dimensional slice of the velocity field at the center of the model at *z*=5 mm, throughout the *x*-*y* plane
- take one-dimensional transects that are 1 mm wide of the velocity field along the *y*-position of the preexisting faults (green)
- sum the velocity components from the two transects at each *x*-position

Time series of normalized velocity magnitude transects

- Step overs with coplanar faults host elevated deformation between the preexisting faults.
- Step overs with larger steps, y=±5 mm, produce pervasive elevated deformation across the width of the model prior to slip along the preexisting faults.

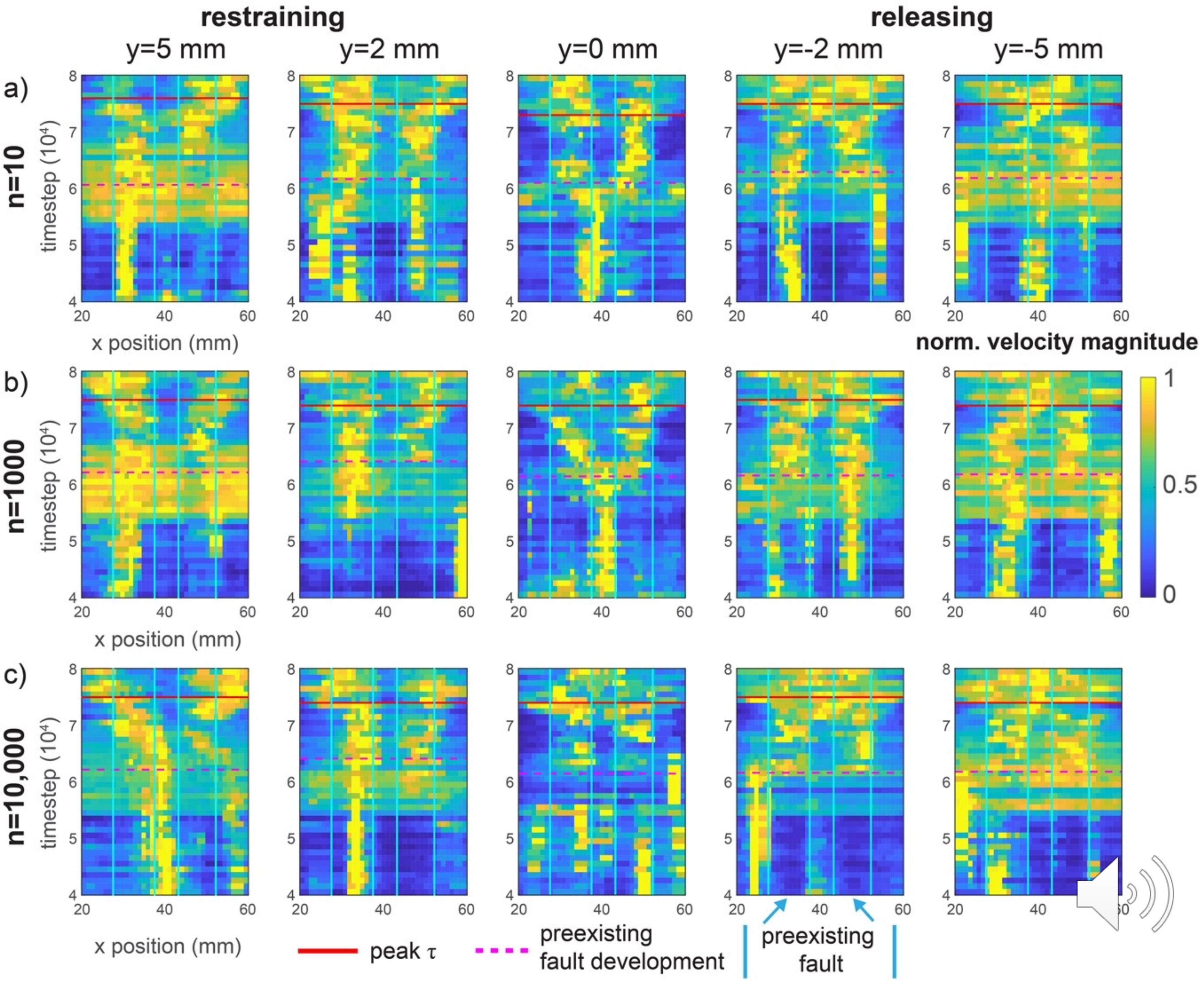


Low diffuse host rock damage, n=10

Timeseries of normalized velocity magnitude transects

- But, increasing damage, n, suppresses the pattern of higher velocities for y=5 mm
- And removes the pattern of higher velocities between the coplanar faults, y=0

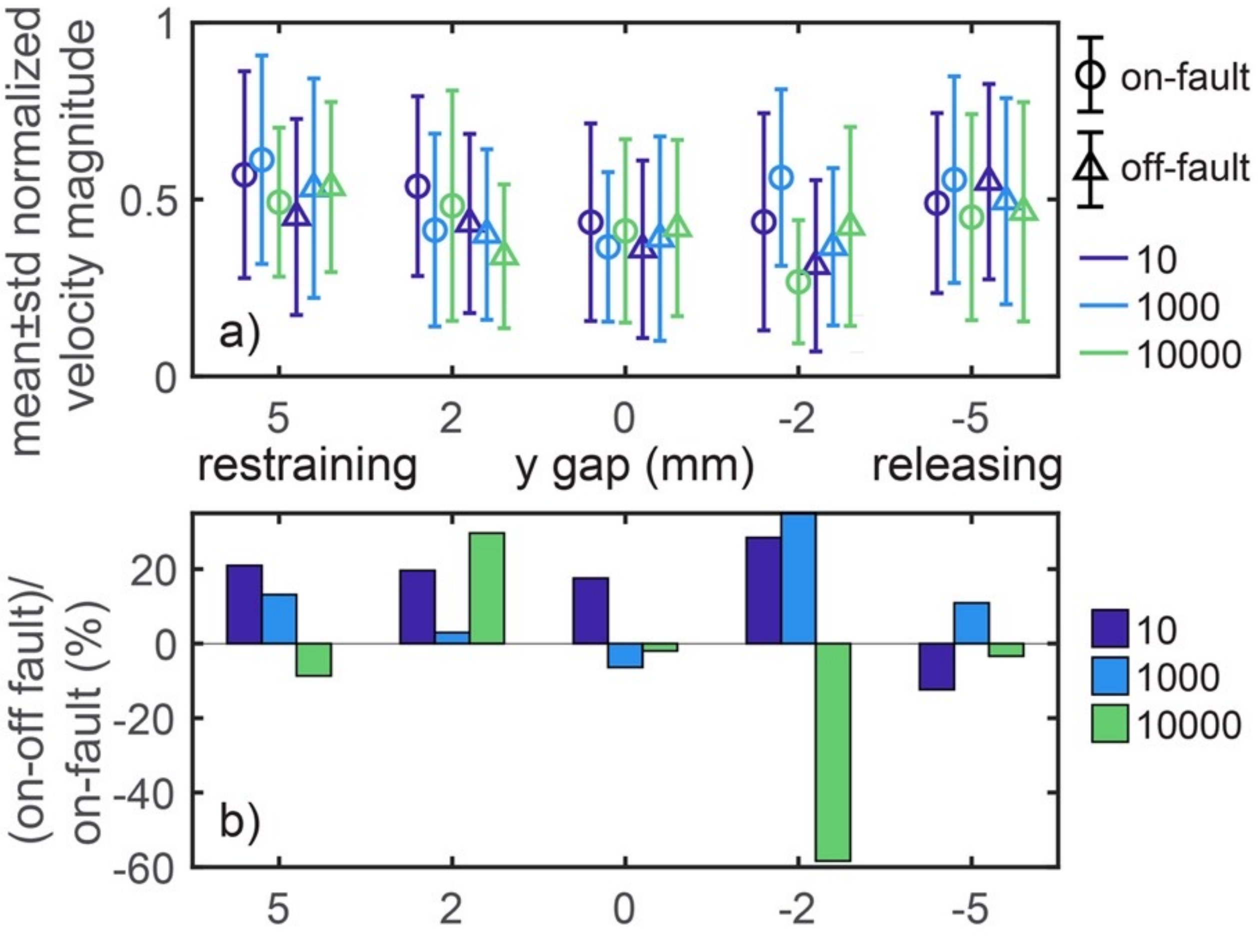
- Both host rock damage and fault configuration influence the amount of identifiable precursors on- and off-fault



Comparing on-fault and off-fault deformation *preceding* slip on healed faults

- **Question 1: Where does the precursory deformation occur?**

- May expect higher velocities in the region that the preexisting faults develop.
- Instead, the difference in the mean on- and off-fault velocity <30% for all the models, and negative in some cases



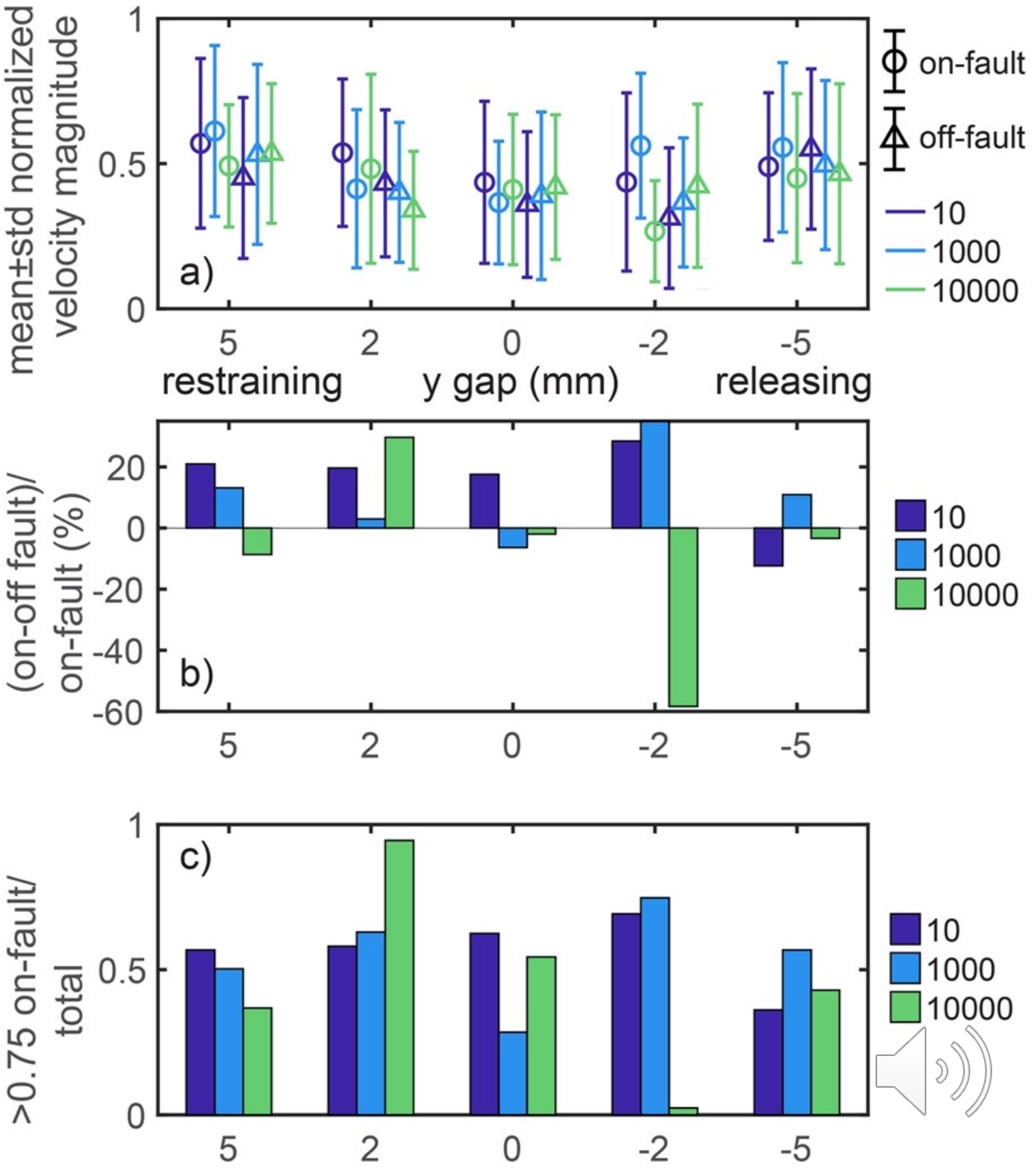
Comparing on-fault and off-fault deformation *preceding* slip on healed faults

- **Question 1: Where does the precursory deformation occur?**

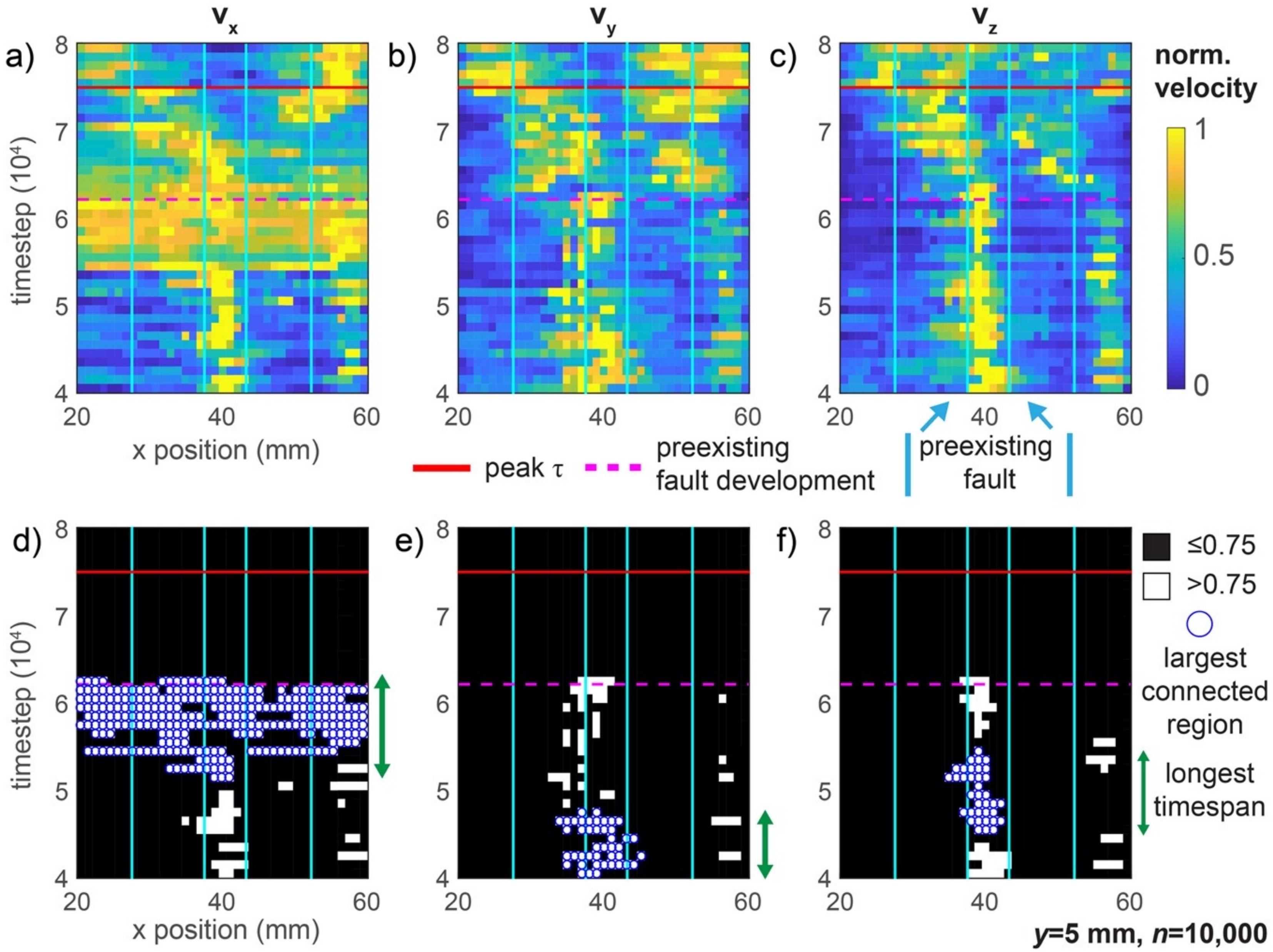
- May expect higher velocities in the region that the preexisting faults develop.
- Instead, the difference in the mean on- and off-fault velocity <20% for all the models, and negative in some cases.

- Similarly, the regions of the transect that host the greatest deformation (>0.75) are generally equally split between the on- and off-fault zones.

- Highlights importance of crustal monitoring efforts away from the main fault(s)



Which velocity component dominates deformation *preceding* slip?

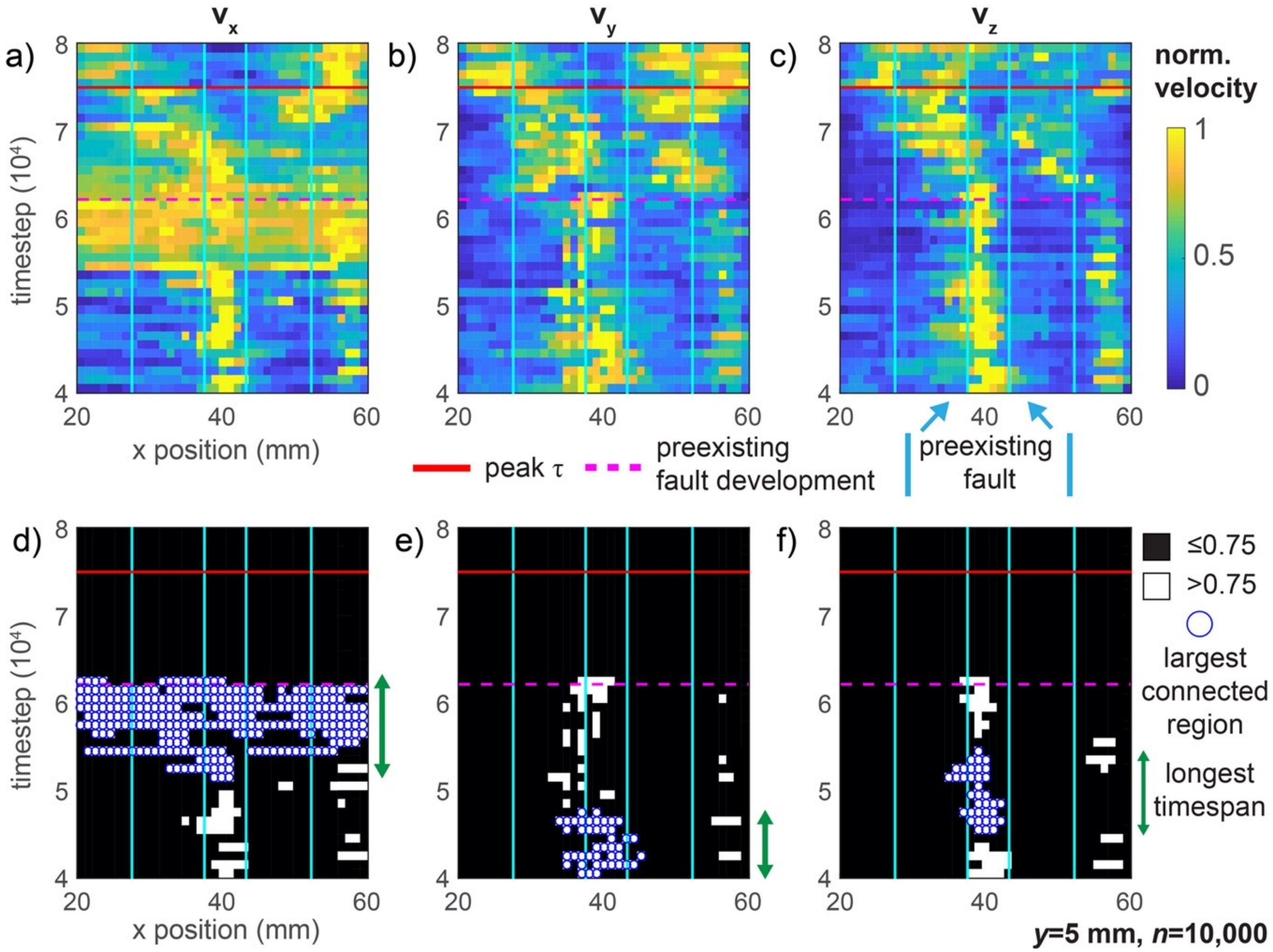


Question 2: What is the style of precursory deformation?

Identify continuous regions of elevated deformation

- use the normalized velocity transect timeseries (a-c) to produce a binary field in which ones represent where the normalized velocity components are >0.75 (d-f)
- Identify the connected components in this field using 8-fold connectivity
- Identify the cluster of high velocities that has the largest area (blue circles), and the longest length in the time dimension (green line).

Which velocity component dominates deformation *preceding* slip?



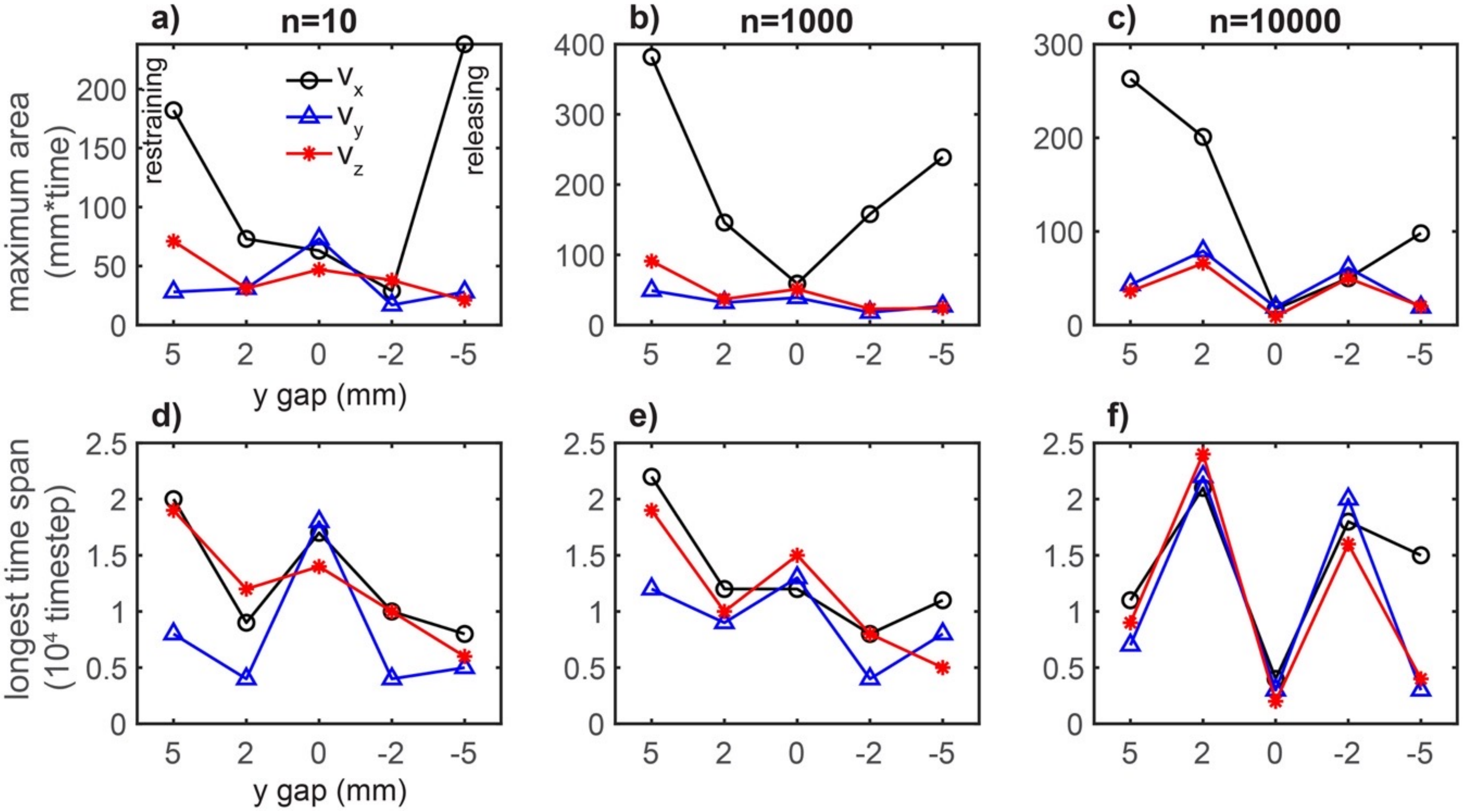
Question 2: What is the style of precursory deformation?

Larger areas indicate components with larger continuous regions of elevated deformation, in both the space and time dimensions.

Longer time spans indicate components with more persistent locations of elevated deformation, in only the time dimension.

We assume that the component with the largest area of continuous higher velocities or strain, and the longest time span, suggests which component can provide the most detectable precursory activity

Which velocity component dominates deformation *preceding* slip?

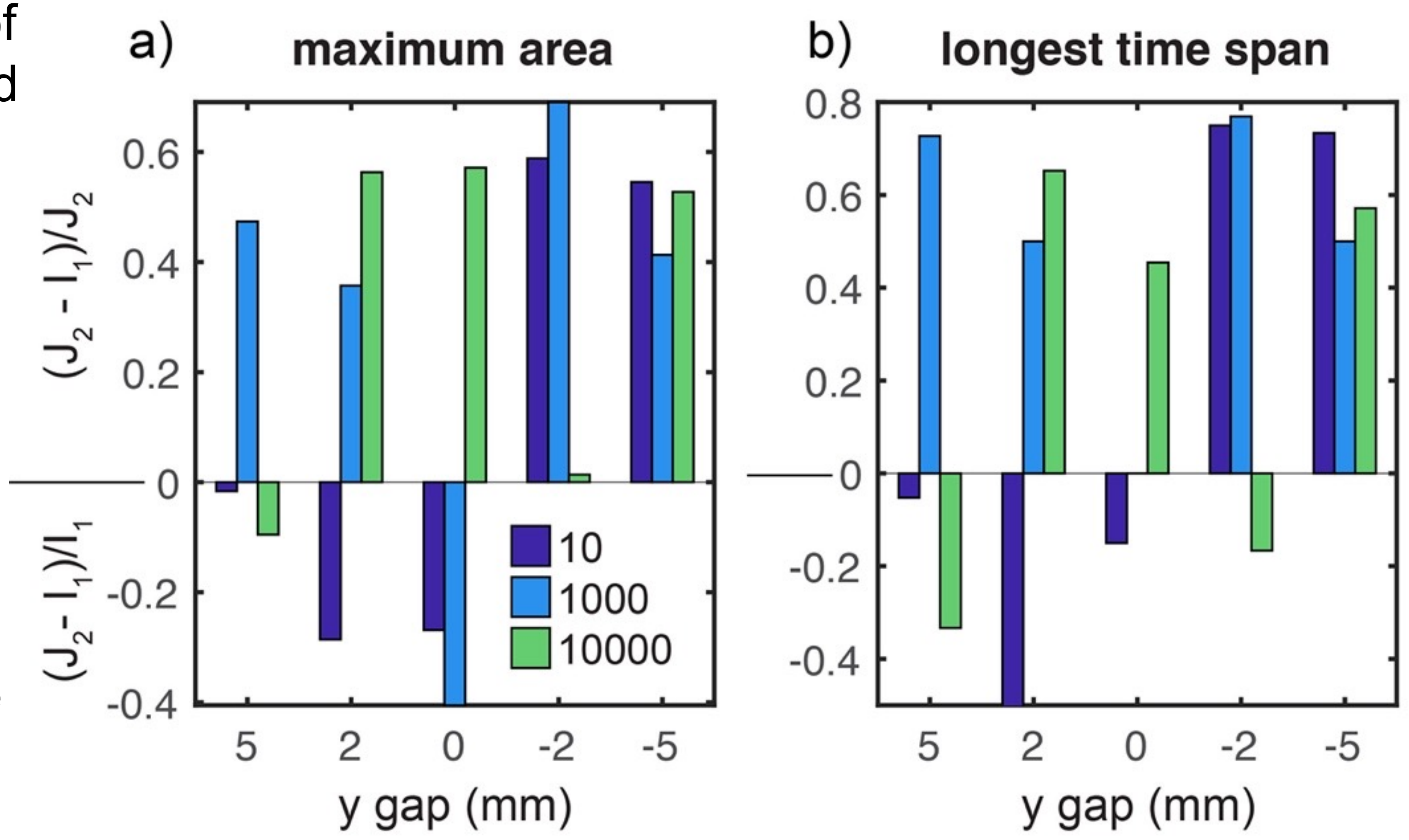


- Higher areas for v_x than other components for models with larger steps
- Similar maximum time spans for all three components
- Highlights that step overs host uplift/subsidence and fault perpendicular motion preceding slip

Identifying reliable precursors with the strain fields

- Calculate 3D strain fields from transect of velocity field, including I_1 (volumetric) and J_2 (shear).
- Shear strain fields generally host larger and more time continuous regions of elevated strain than the volumetric strain
- Shear strain fields may provide more useful information than the volumetric fields.

- Influence of volumetric strain could be stronger in systems with faults at oblique angle to loading direction.



$$I_1 = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

$$J_2 = \frac{1}{6}\left[\left(\varepsilon_{xx} - \varepsilon_{yy}\right)^2 + \left(\varepsilon_{yy} - \varepsilon_{zz}\right)^2 + \left(\varepsilon_{zz} - \varepsilon_{xx}\right)^2\right] + \varepsilon_{xy}^2 + \varepsilon_{yz}^2 + \varepsilon_{zx}^2$$

Question 1: Where does precursory deformation occur?

- Off-fault about 50% of the time, up to one fault length away
- Fault configuration complexity and amount of diffuse damage does not show a clear trend with amount of off-fault deformation *preceding* fault slip

Question 2: What is the style of precursory deformation?

- Larger areas of fault parallel velocity, but similar timespans
- Larger areas and timespans for the shear strain than the volumetric strain