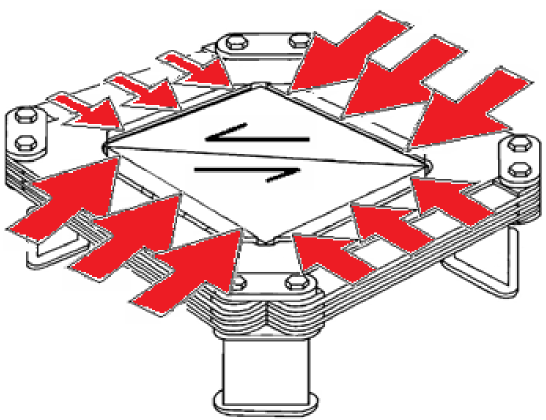
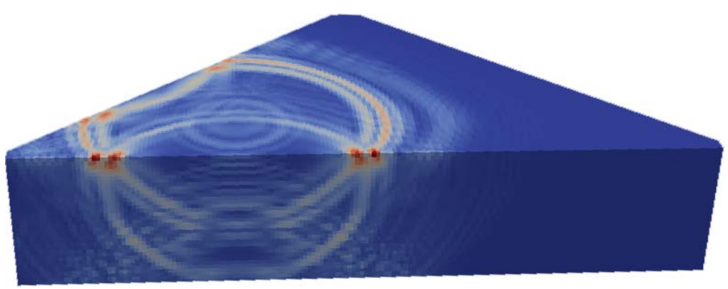
The nucleation of a laboratory earthquake: Implications for foreshocks and minimum earthquake size

Greg McLaskey

USGS Menlo Park

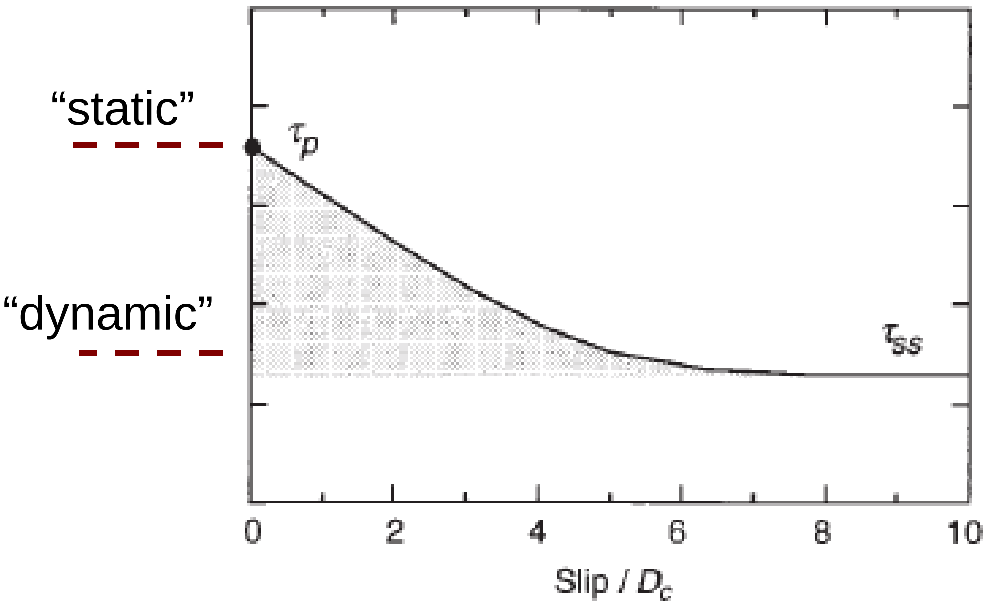
June 22, 2012



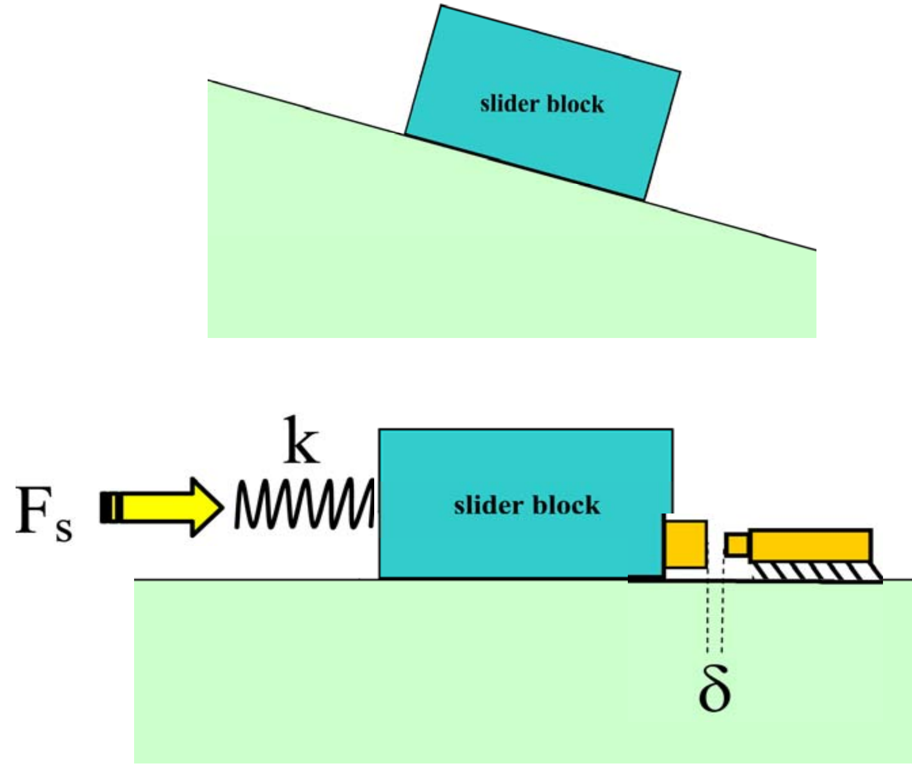


Brian Kilgore, Nick Beeler, Dave Lockner

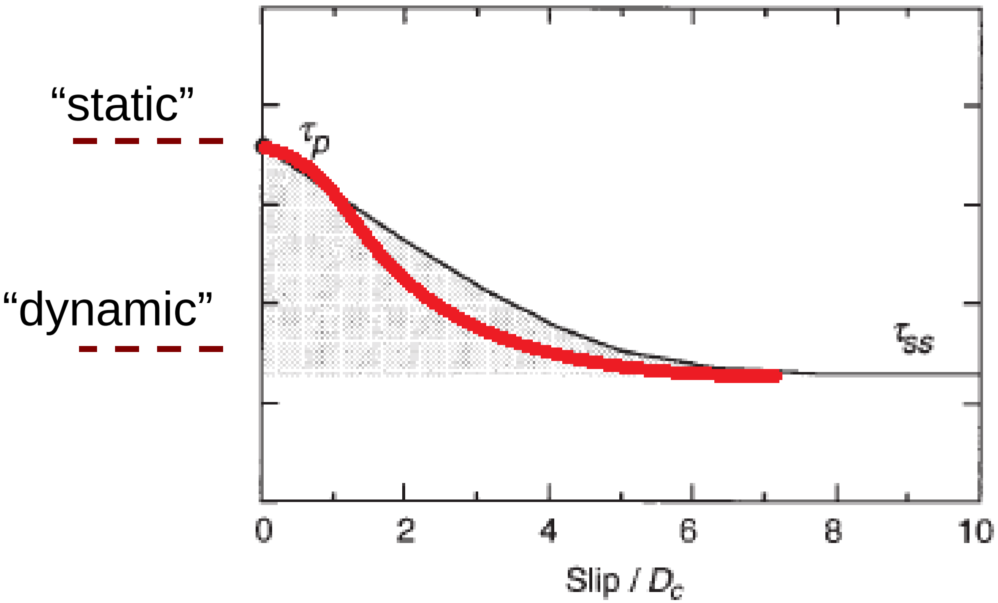
Slip weakening and stability

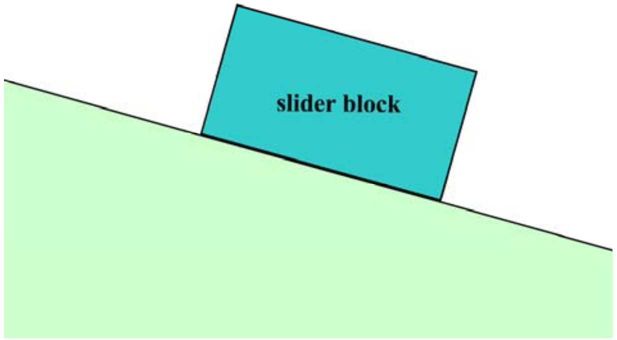


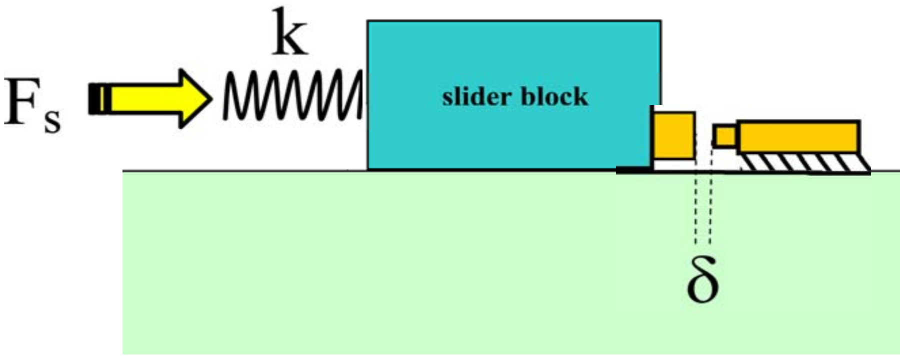
Dieterich and Kilgore 1996



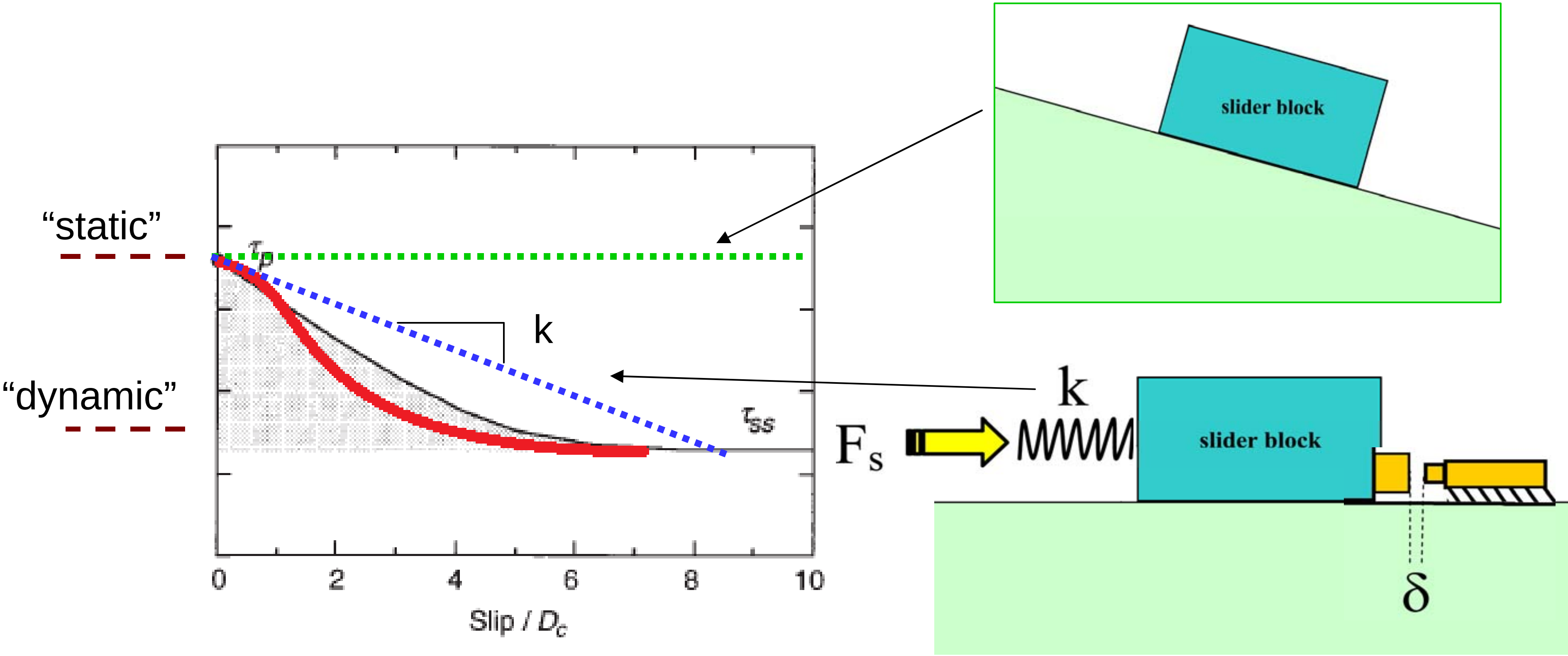
Slip weakening and stability



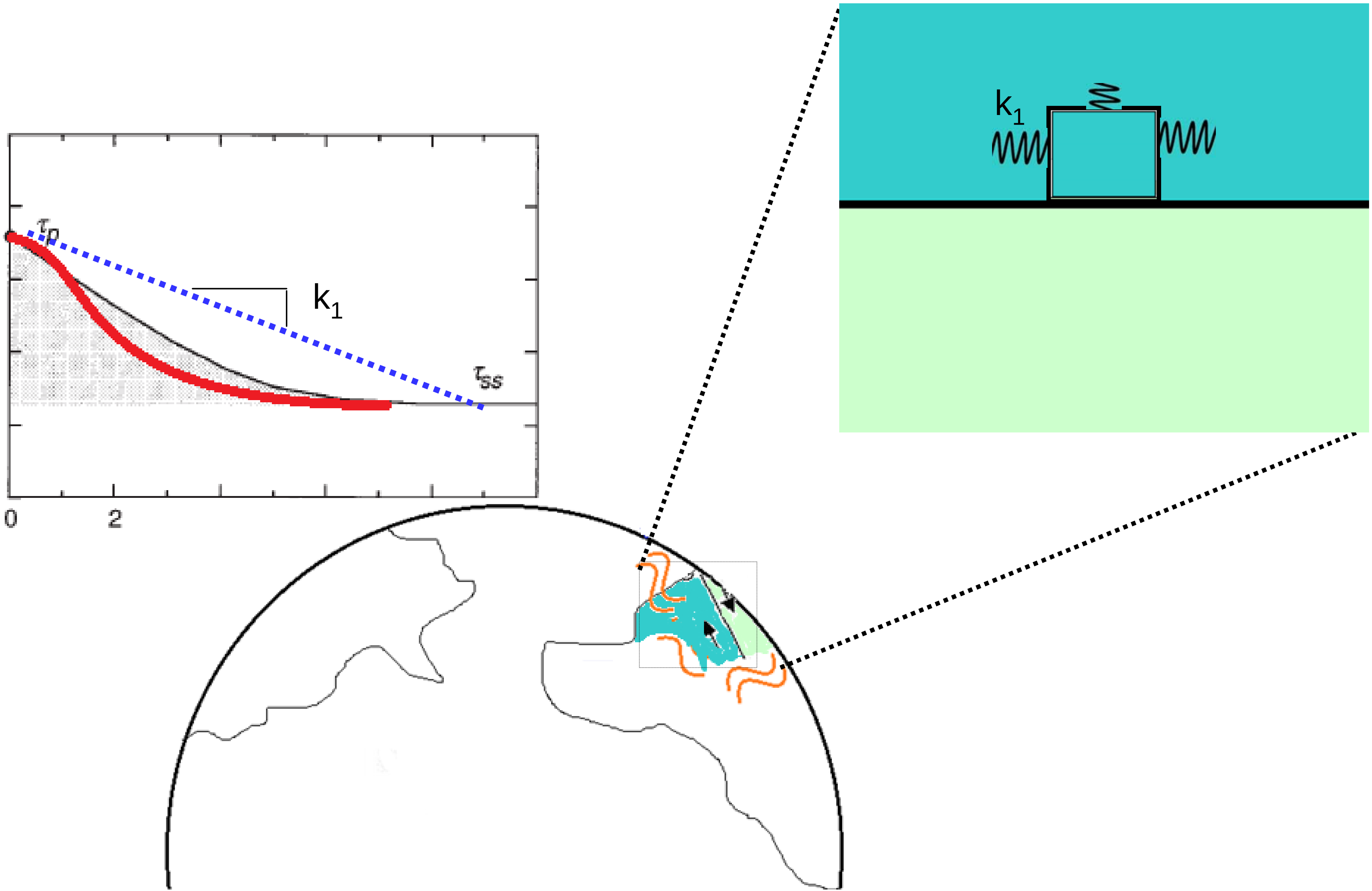




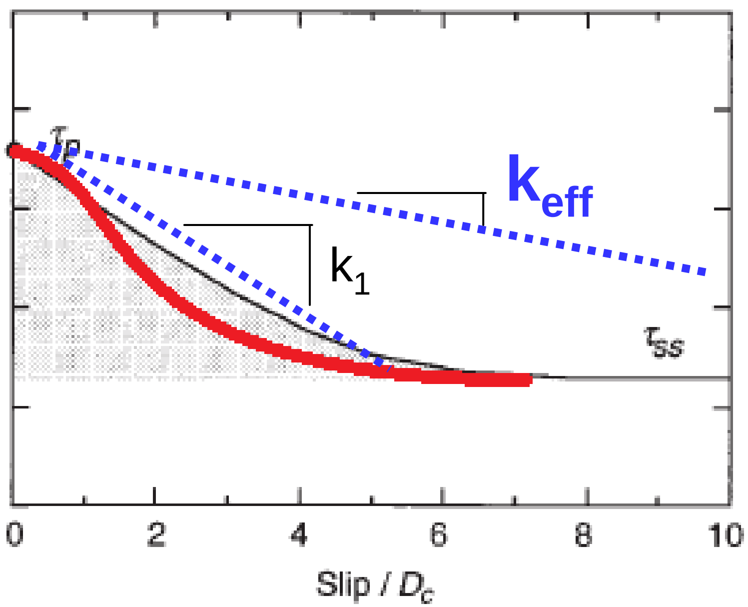
Slip weakening vs. unloading curve

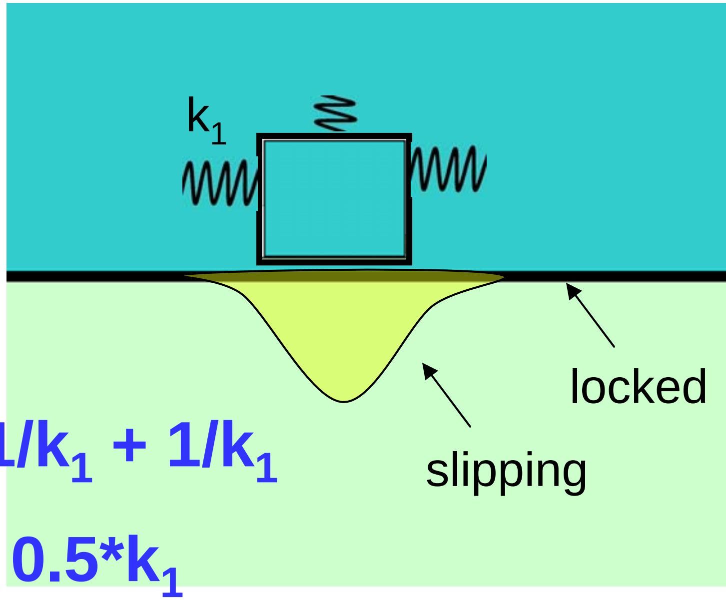


Who cares about slider blocks?



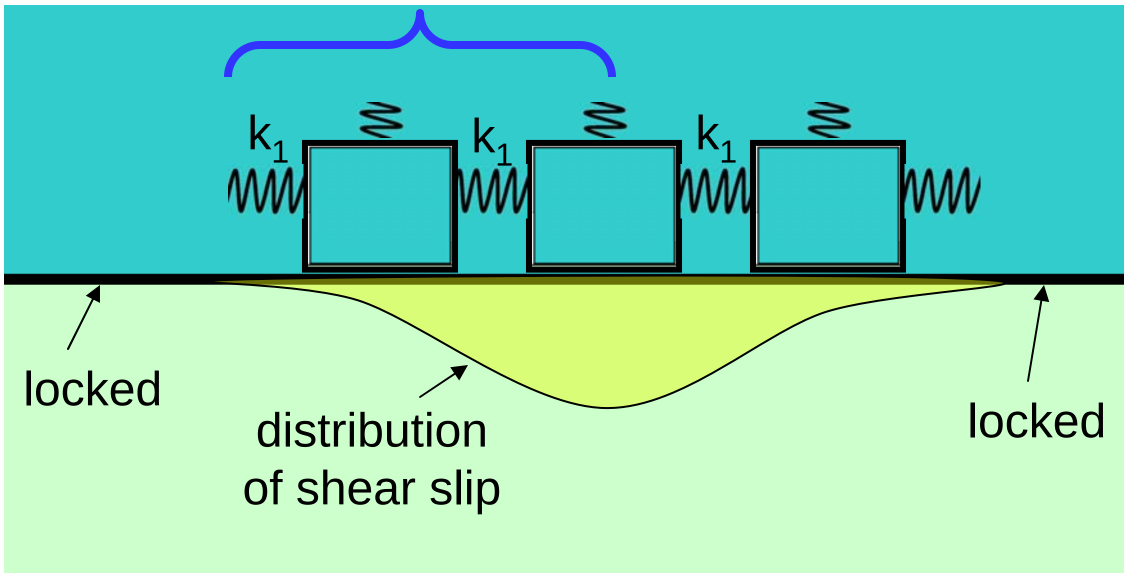
Stability of a slipping region in an elastic space



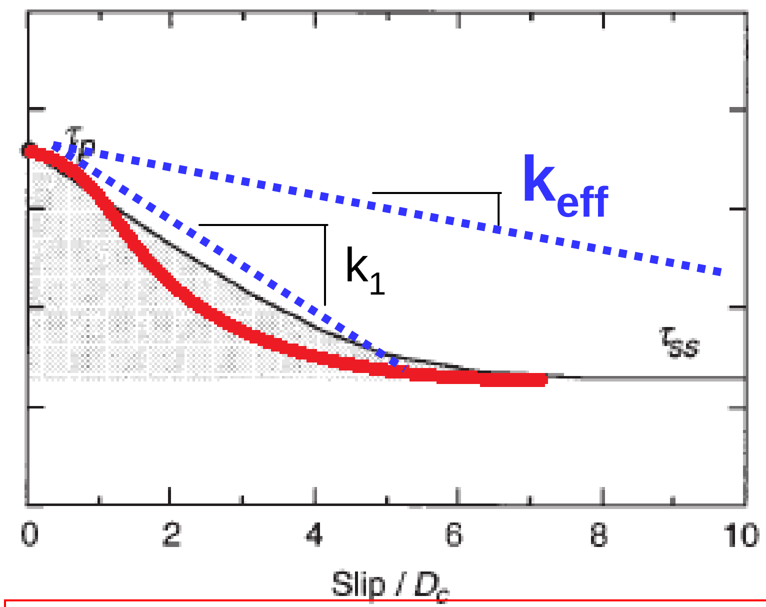


$$1/k_{eff} = 1/k_1 + 1/k_1$$

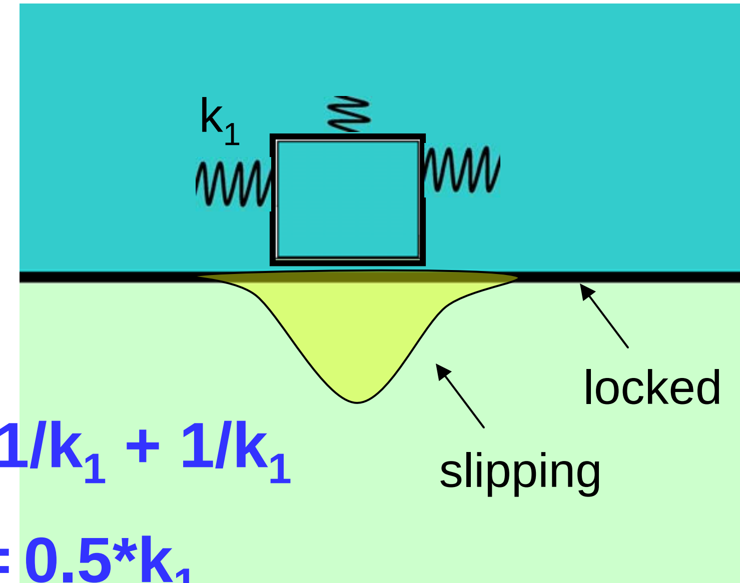
$$k_{eff} = 0.5*k_1$$



Stability of a slipping region in an elastic space

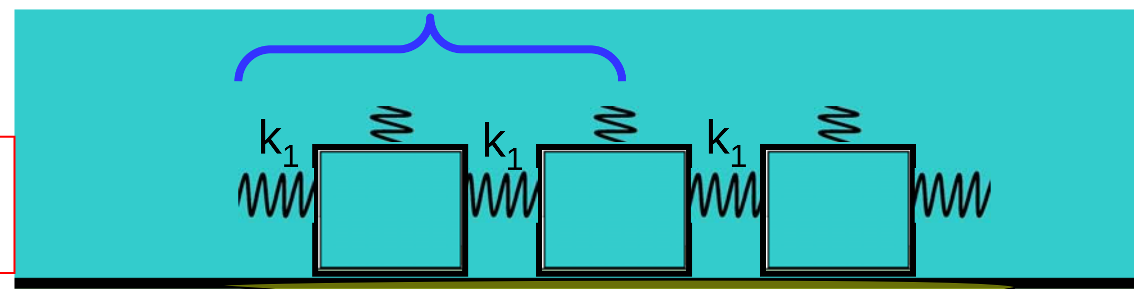


Assumption: fault strength is slip weakening with no discontinuities.



$1/k_{eff} = 1/k_1 + 1/k_1$

$k_{eff} = 0.5*k_1$



1) there must be a minimum size of slipping patch below which slip is stable
2) even for patches that are large enough to host unstable slip, slip accelerates

Motivating questions

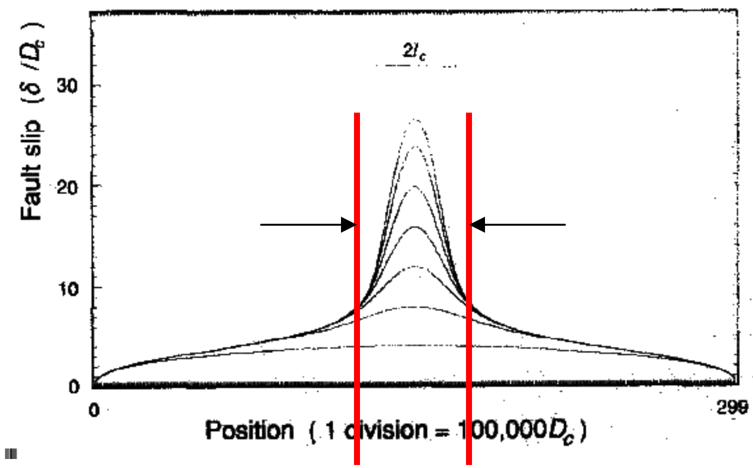
- Better understand this transition from aseismic to seismic
  - More effective use of initial P-waves can be more efficiently utilized for earthquake early warning systems
- Better physical interpretation of microseismicity
  - Intelligently interpret observations of small earthquakes for short-term earthquake forecasting
  - Are small earthquakes indicators of the nucleation of a larger and potentially-damaging earthquake?

Earthquake nucleation models

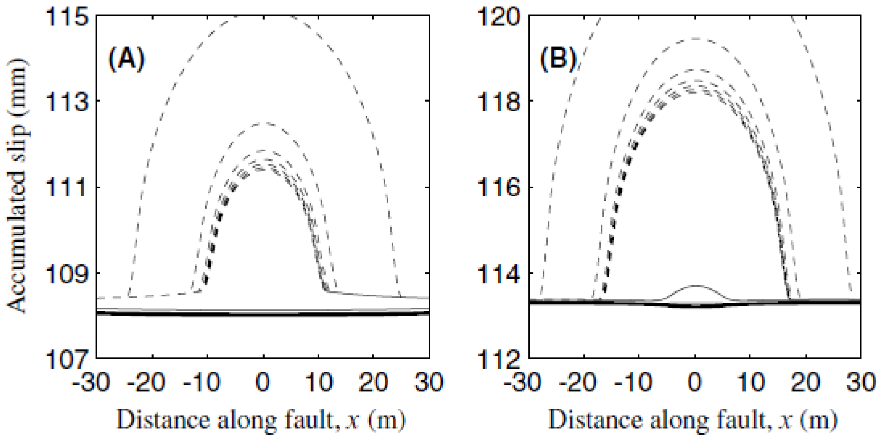
Rapid slip is ALWAYS preceded by slow and accelerating slip in a nucleation zone

This nucleation zone is ~ 1m – 10m ? depending on parameters

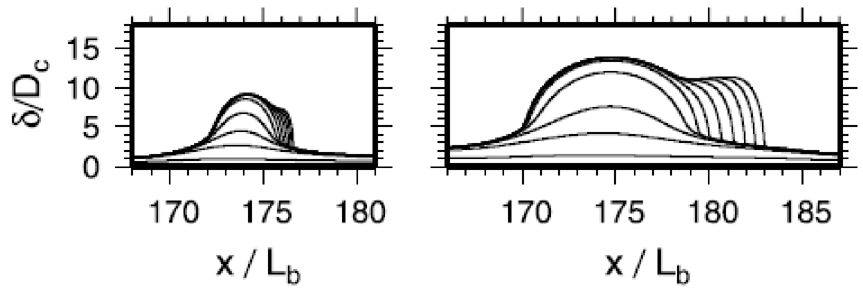
Dieterich 1992



Kaneko and Lapusta 2008

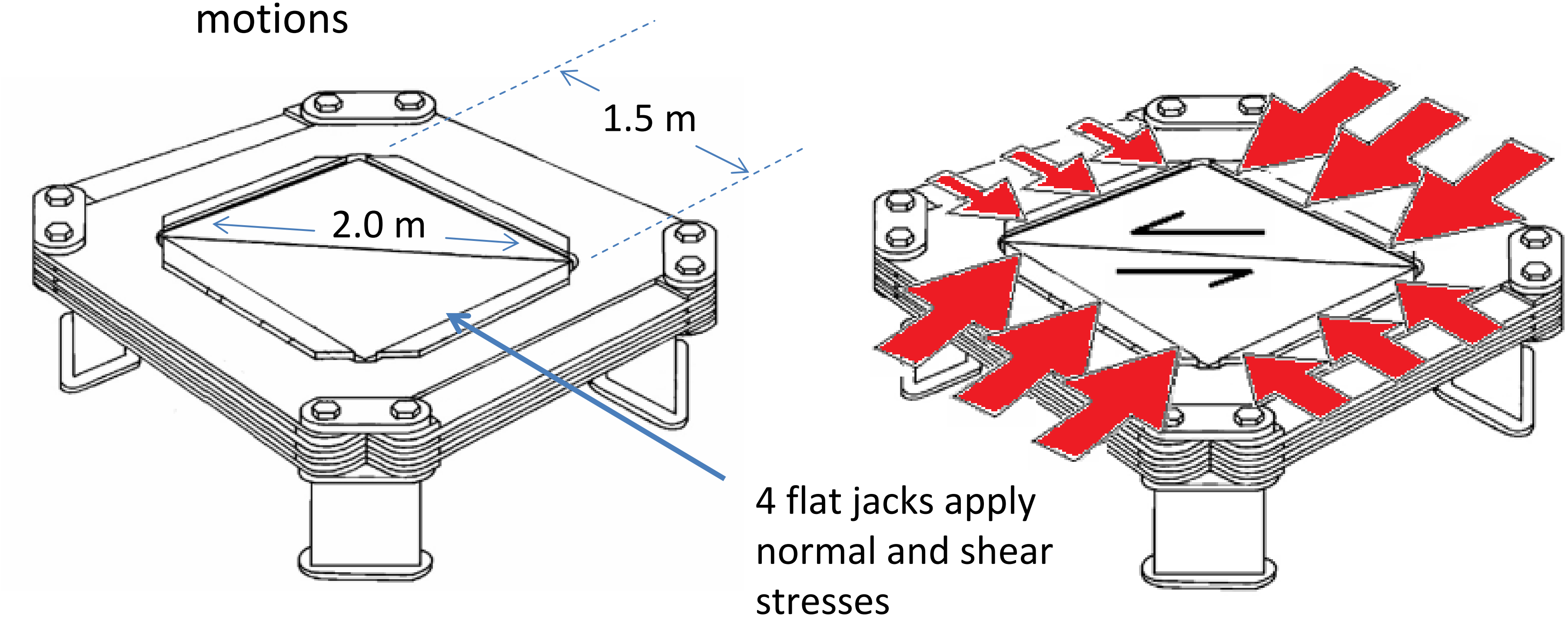


Ampuero and Rubin 2008

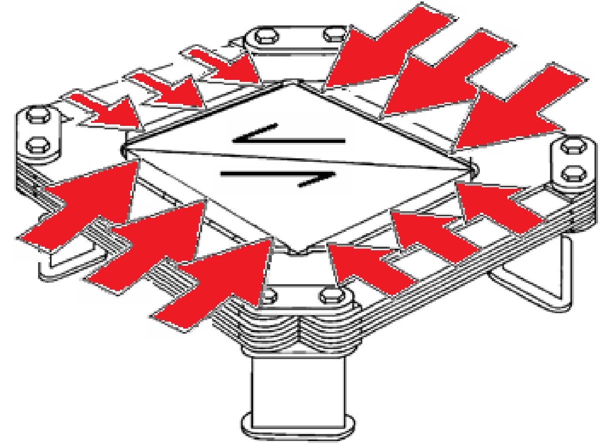


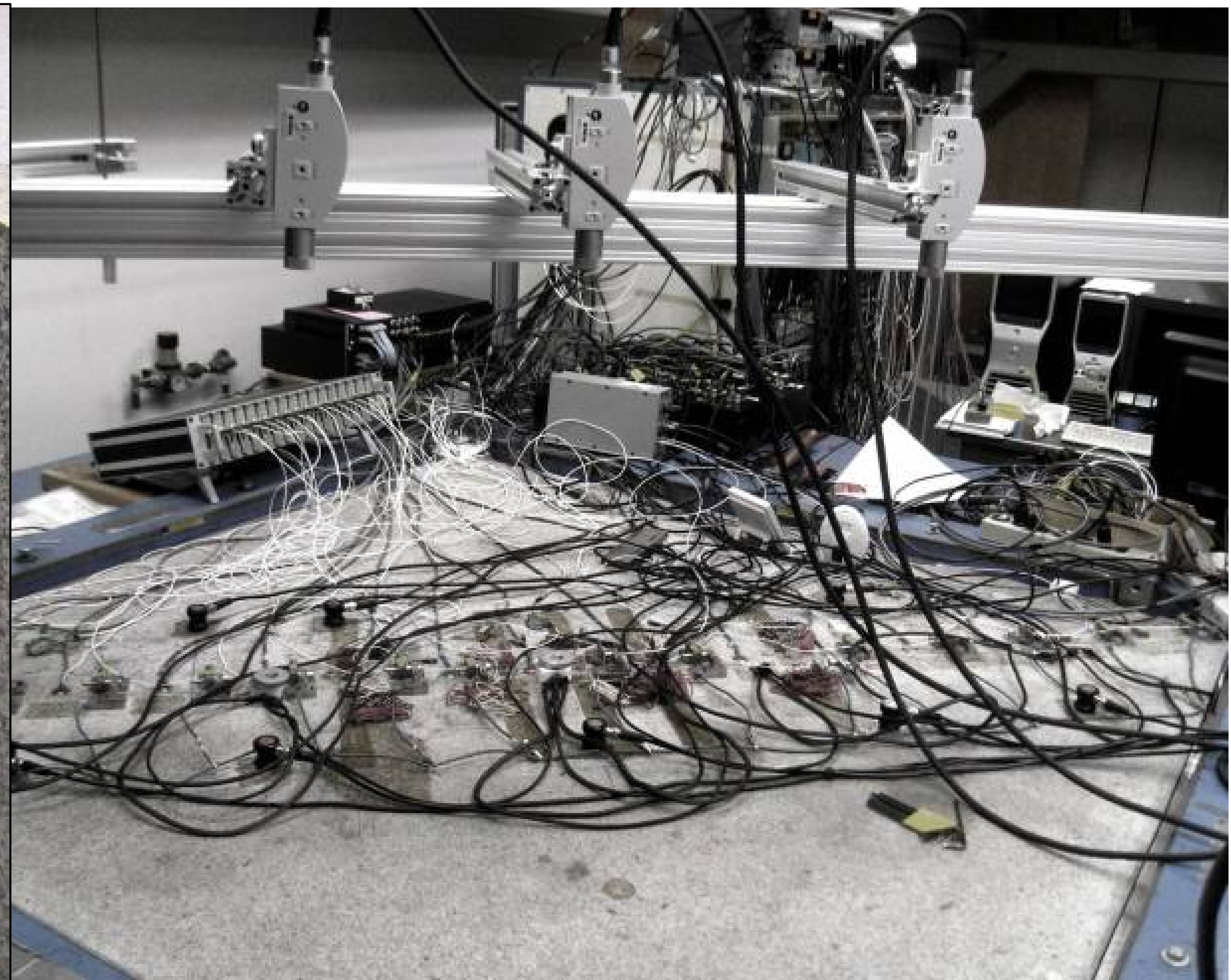
Laboratory Earthquakes

- 2 meter biaxial press
- Fault is large enough that one part of it can slip while another part remains locked
  - We can nucleate earthquakes, measure local stress state along the fault, observe dynamic rupture, and measure high frequency ground motions

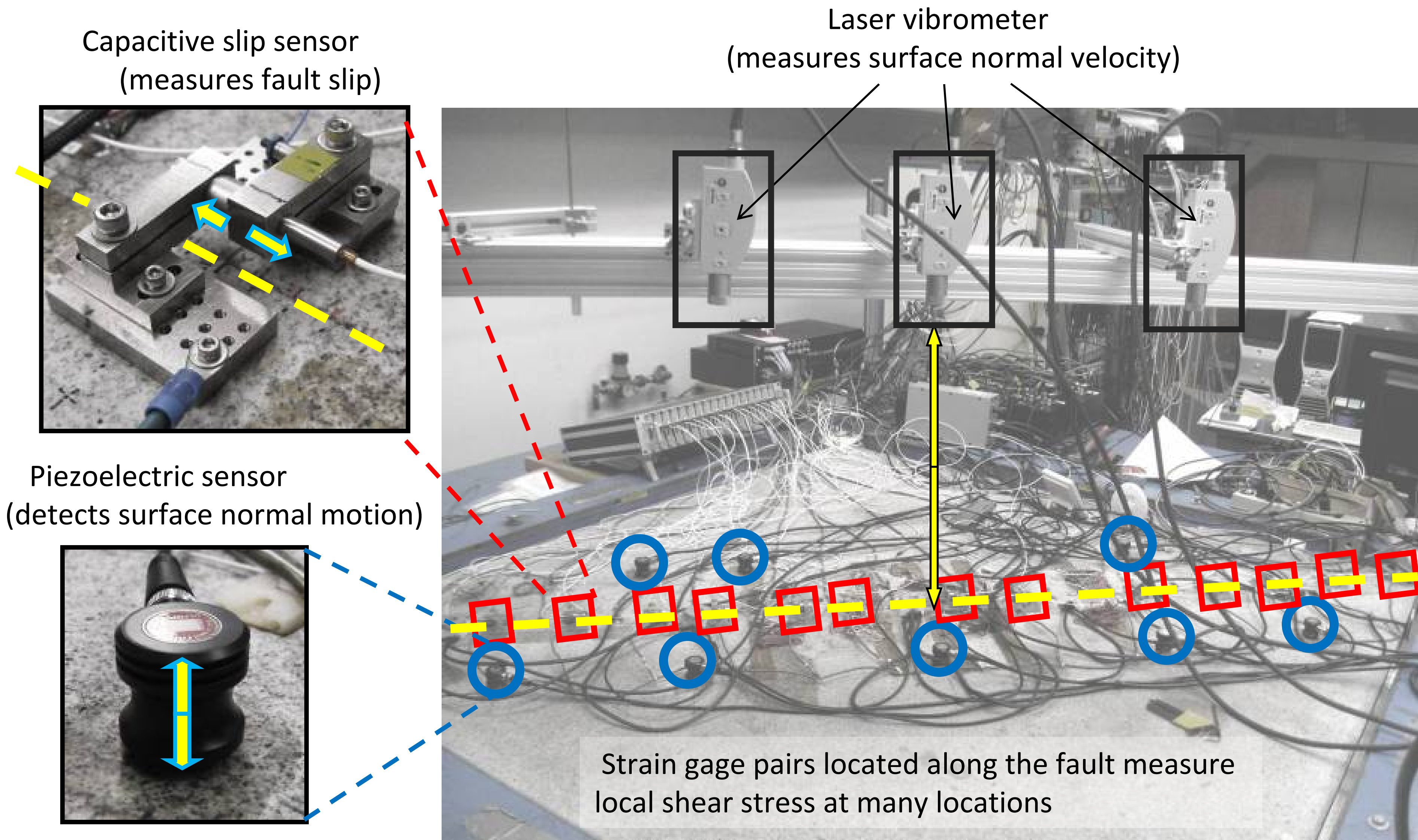


2 meter biaxial press

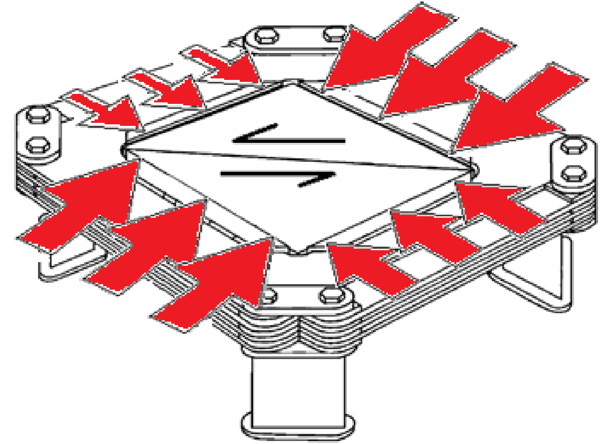


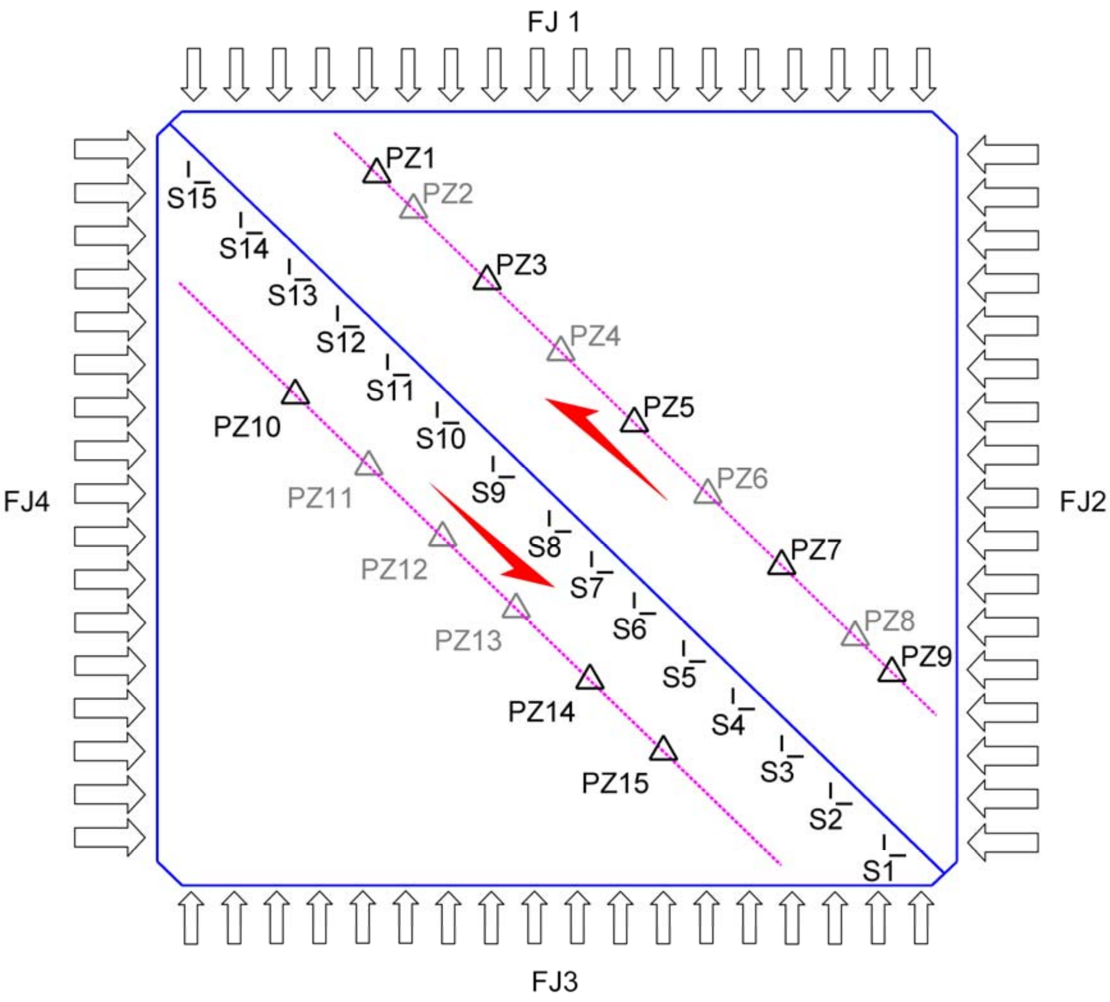


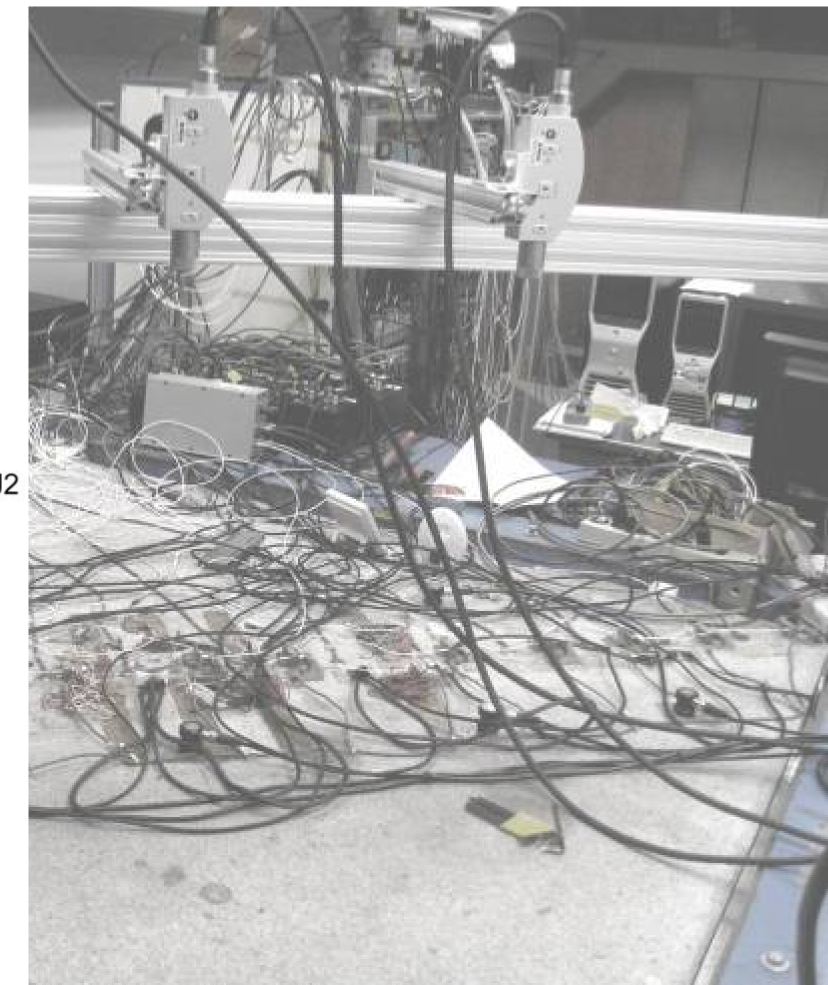
2 meter biaxial press: instrumentation



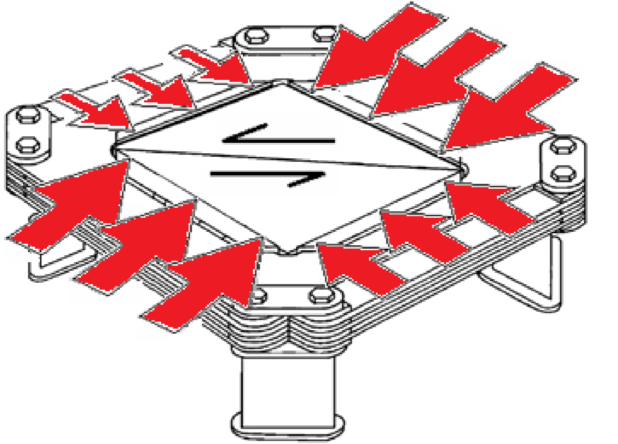
2 meter biaxial press: instrumentation

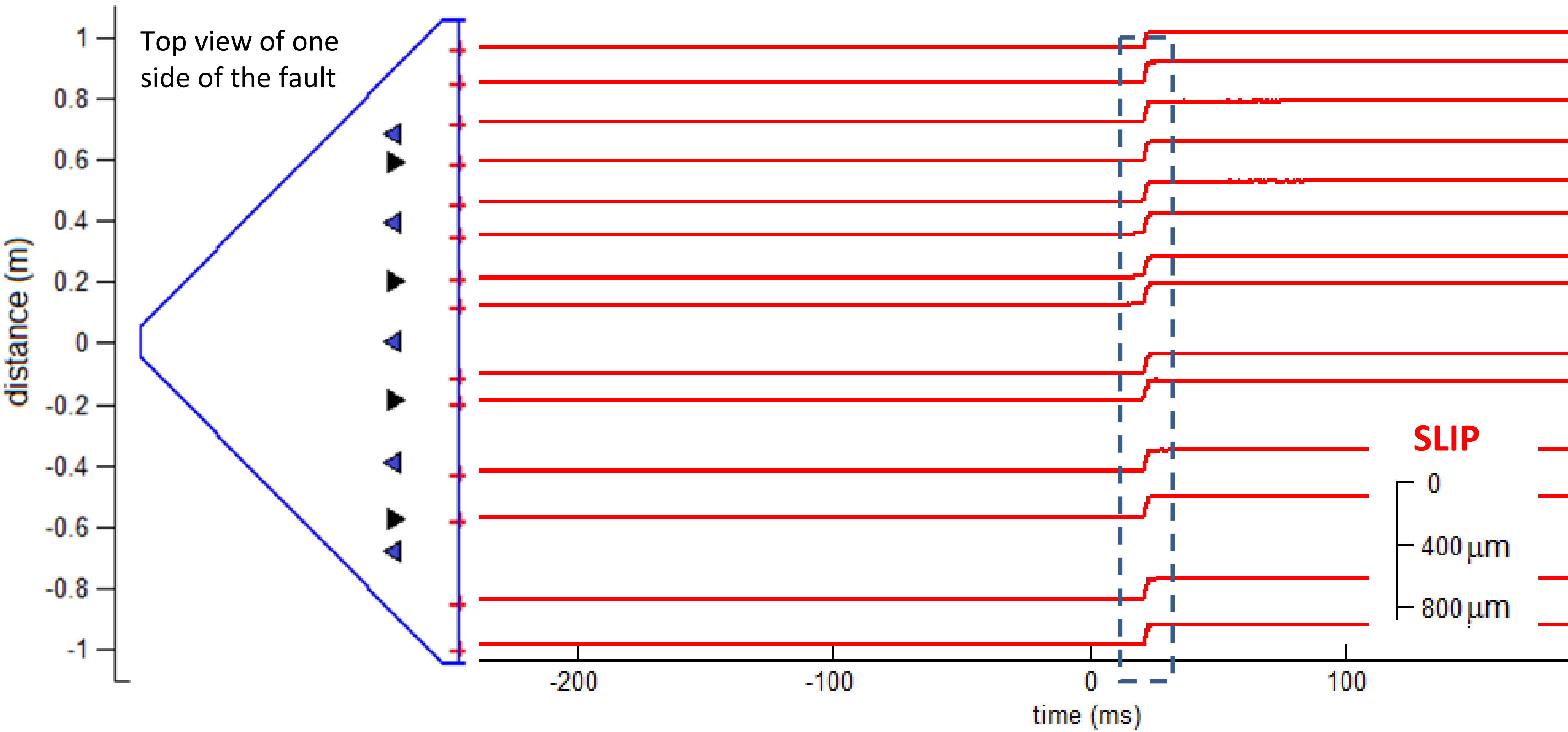






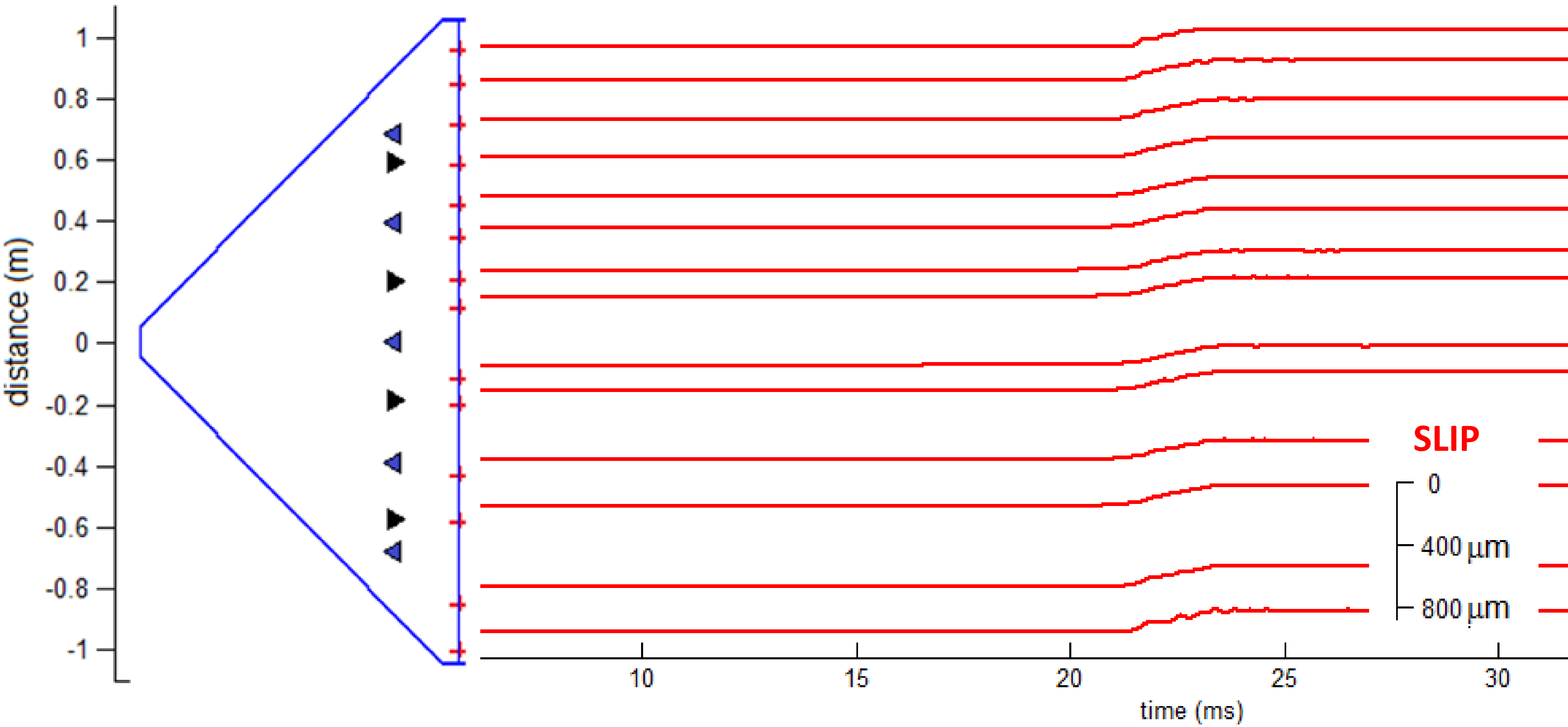
Stick slip



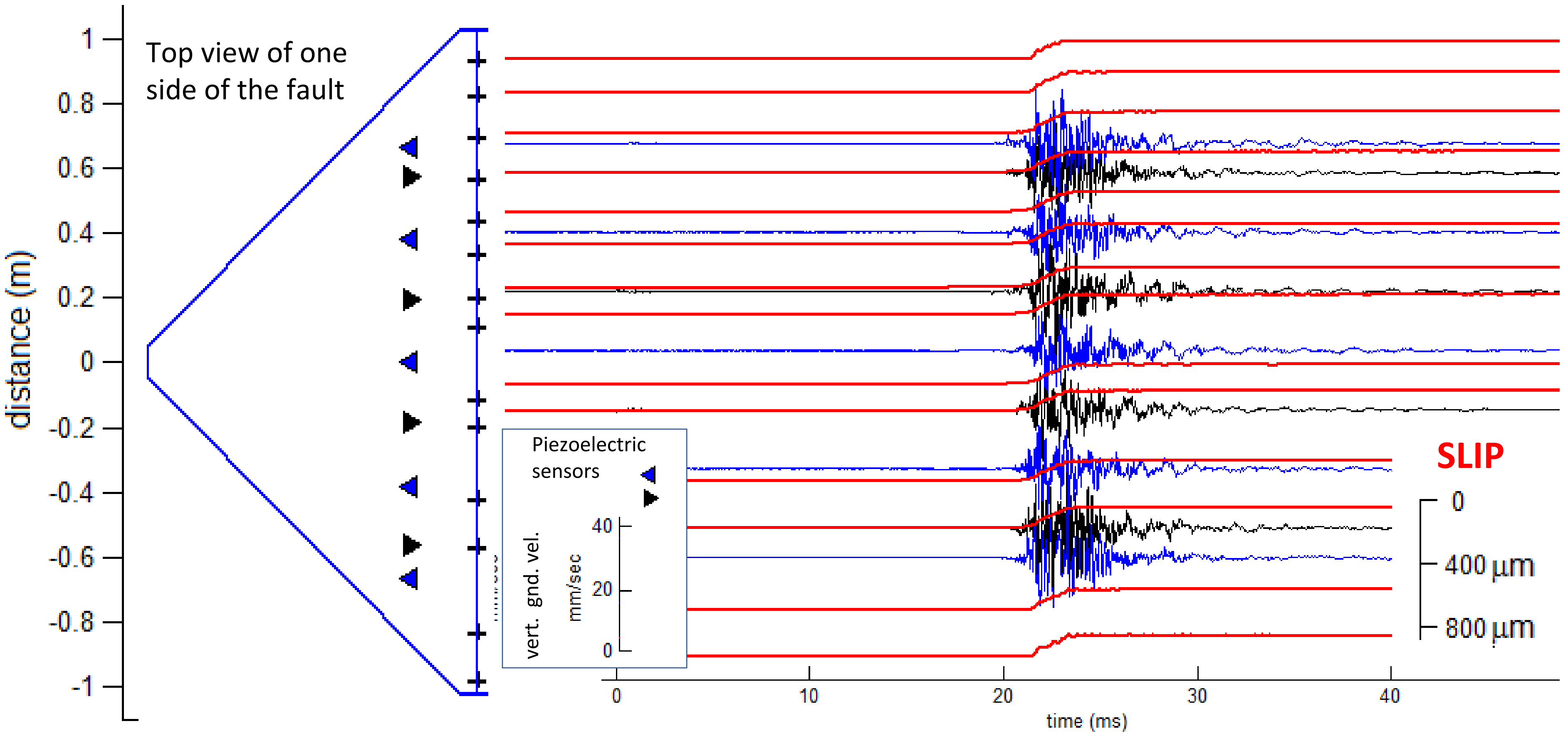


Top view of one side of the fault
distance (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-200
-100
0
100
time (ms)
SLIP
0
400 μm
800 μm

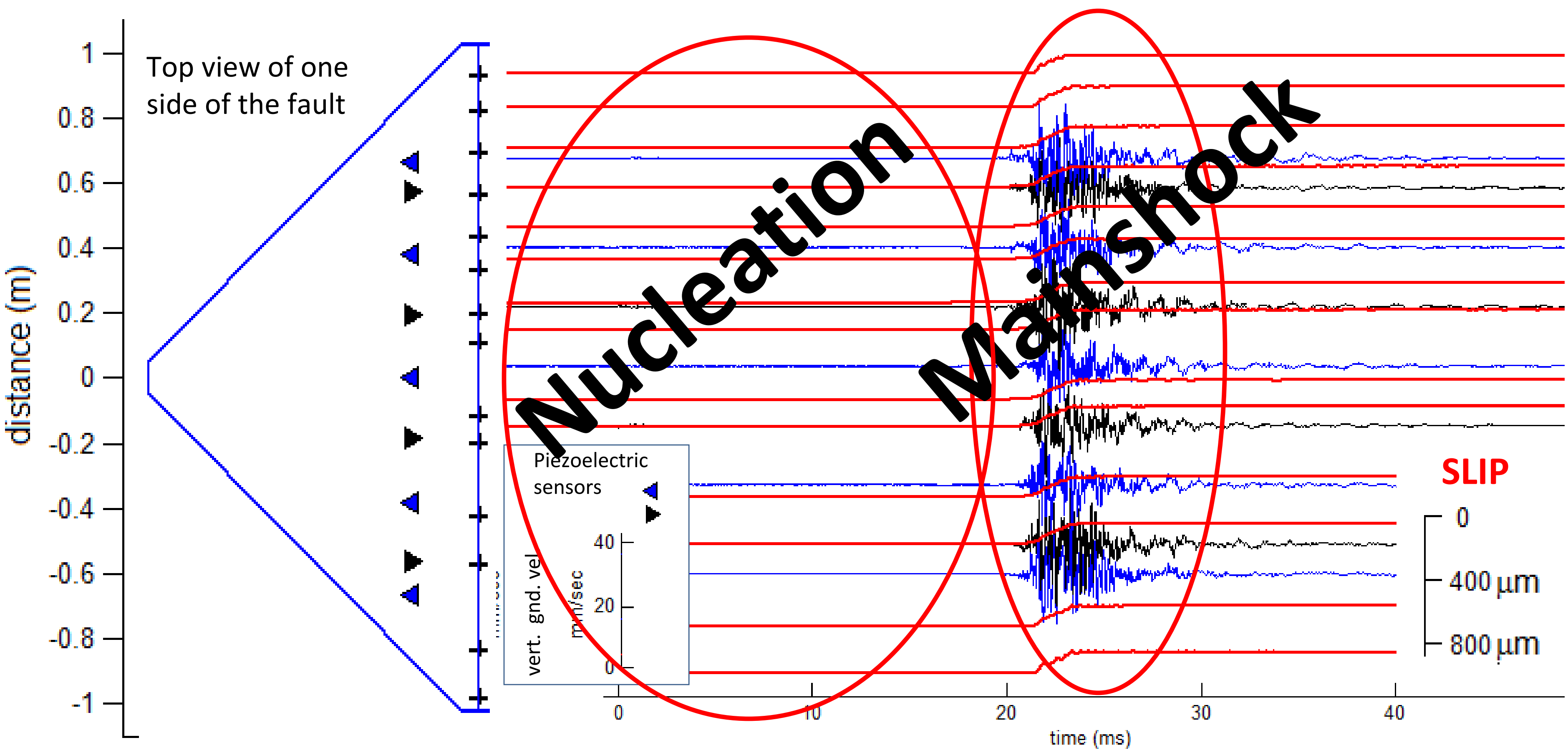
2 meter biaxial press



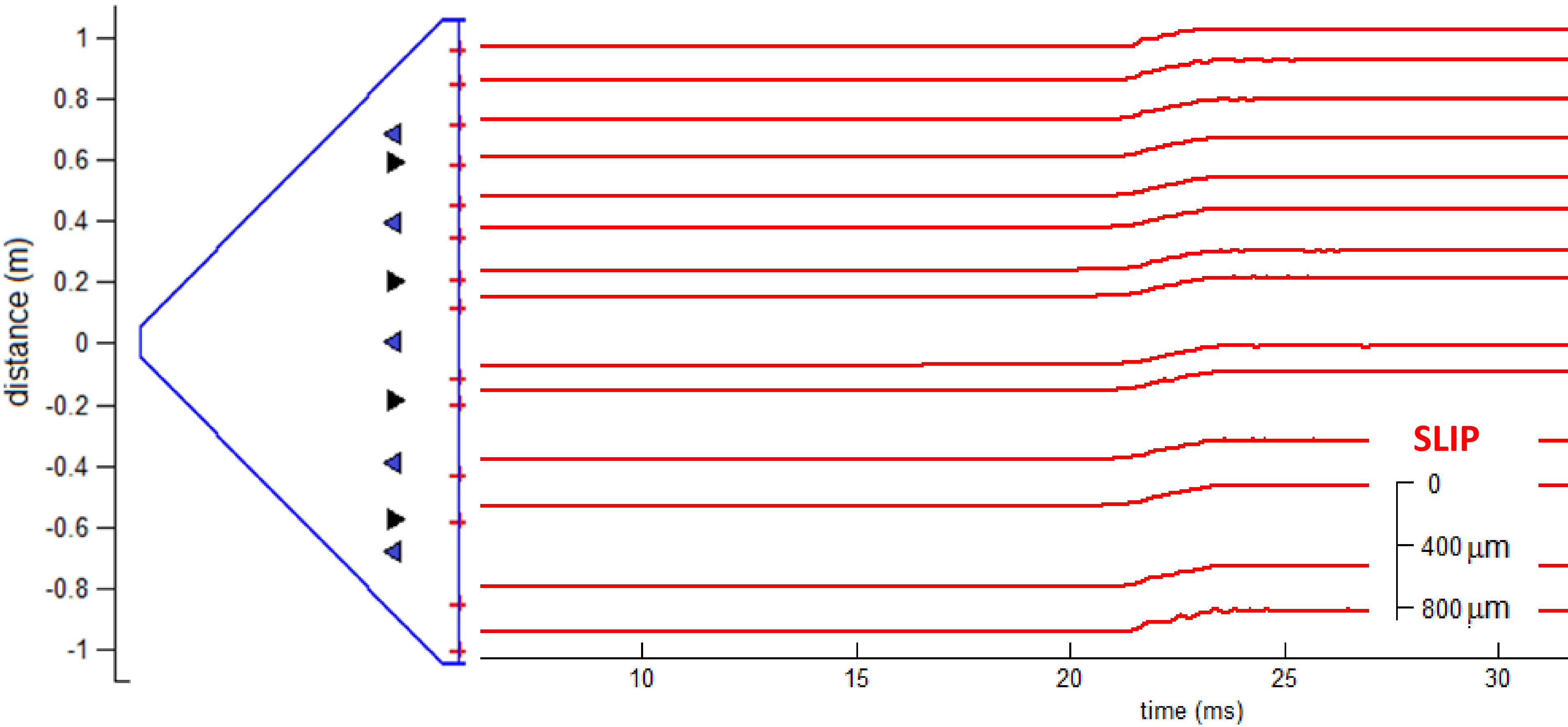
2 meter biaxial press: stick slip and laboratory earthquake



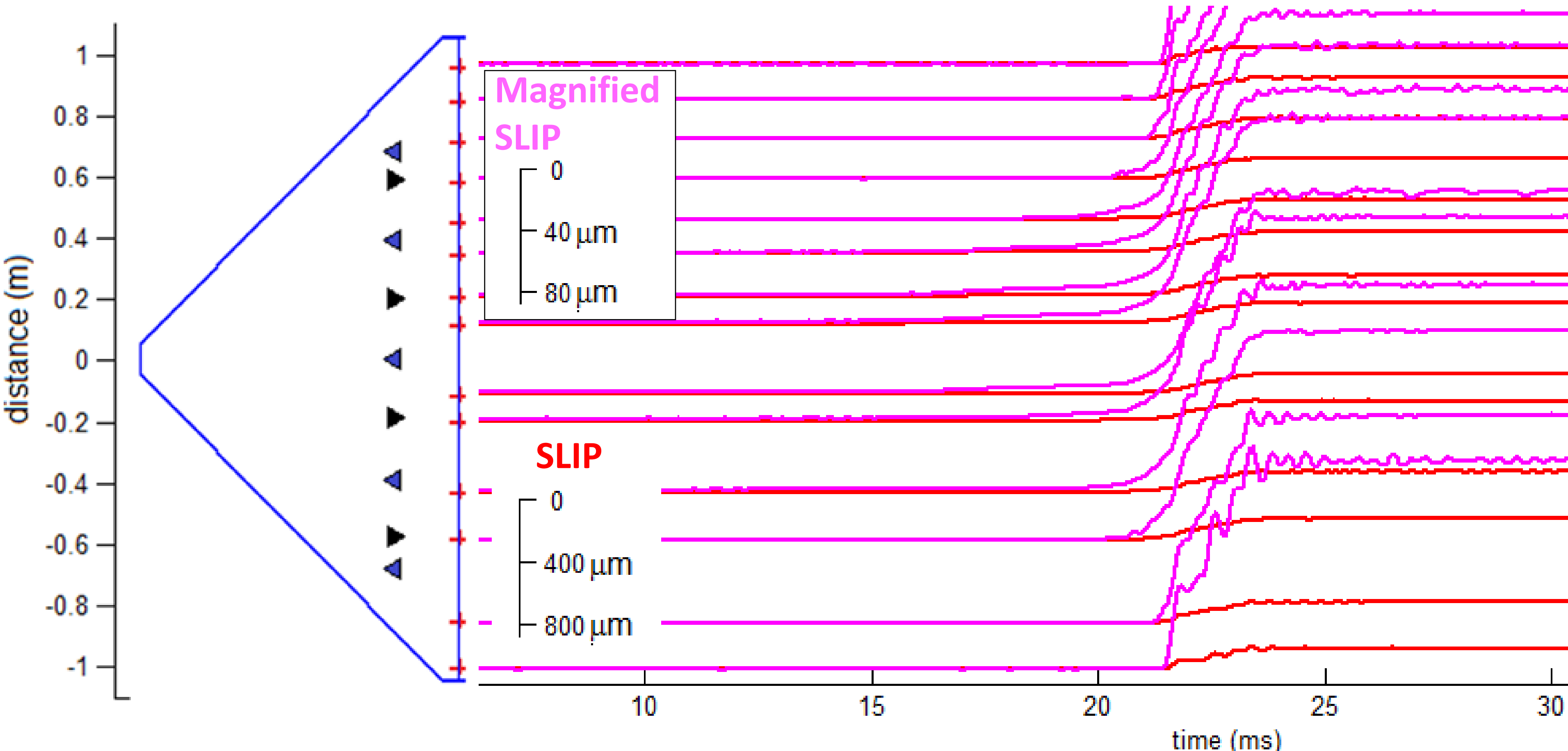
2 meter biaxial press: stick slip and laboratory earthquake



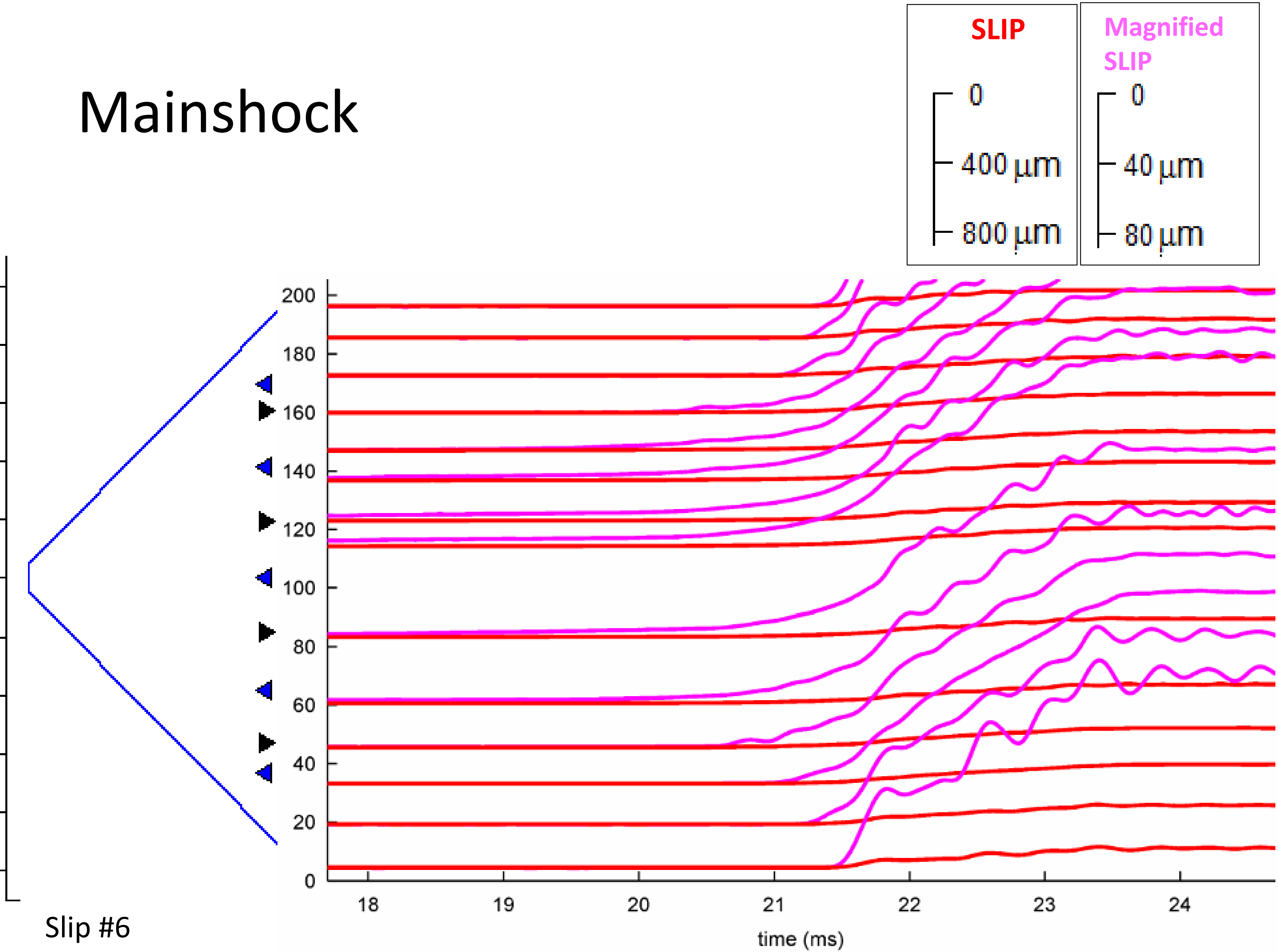
2 meter biaxial press



2 meter biaxial press

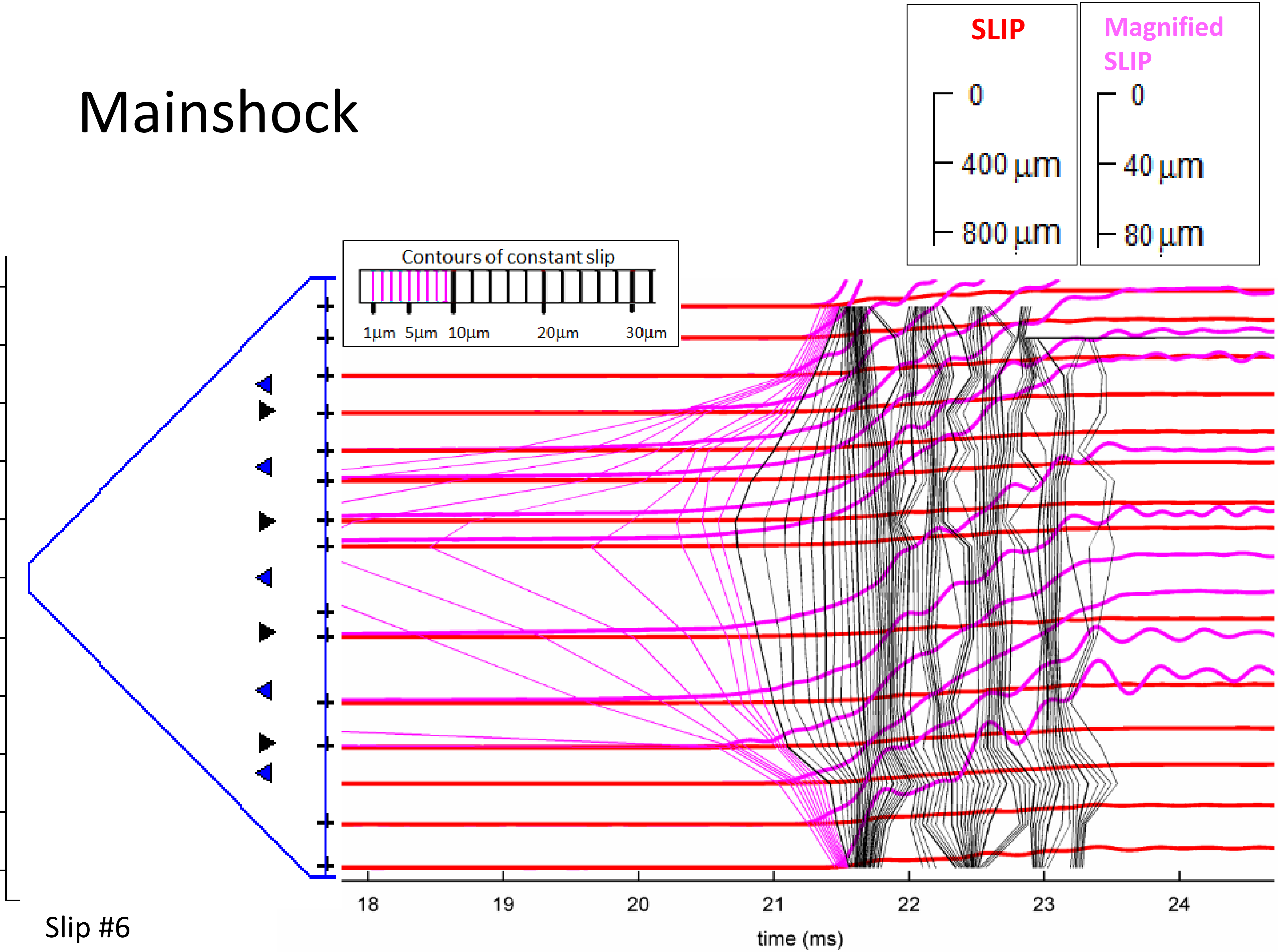


Mainshock



Slip #6

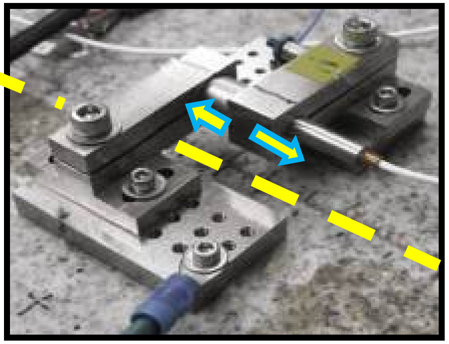
Mainshock

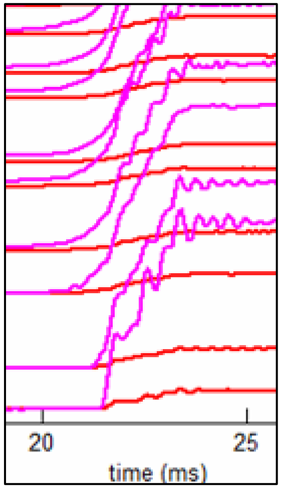


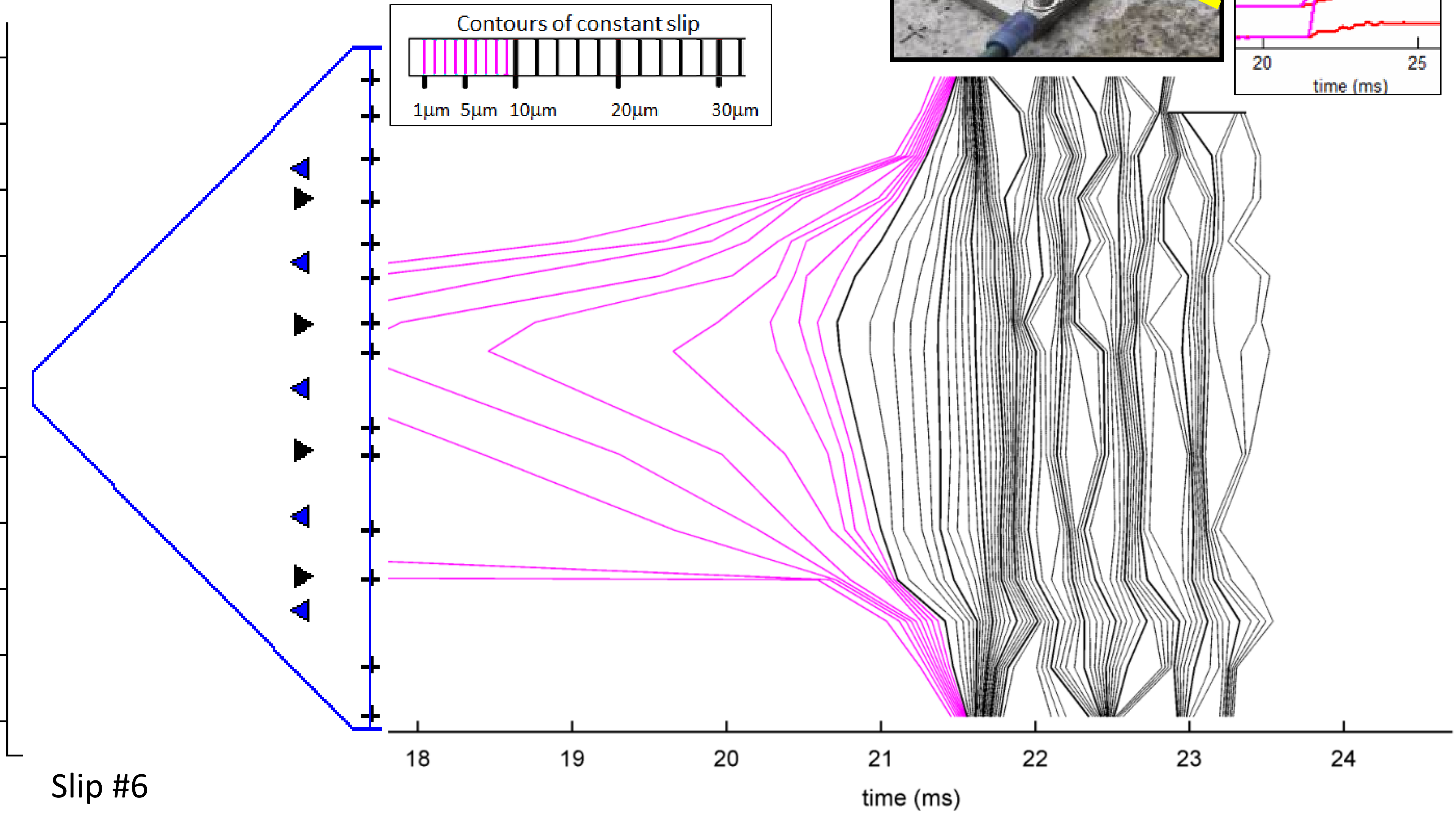
Slip #6

Mainshock

Capacitive slip sensor
(measures fault slip)

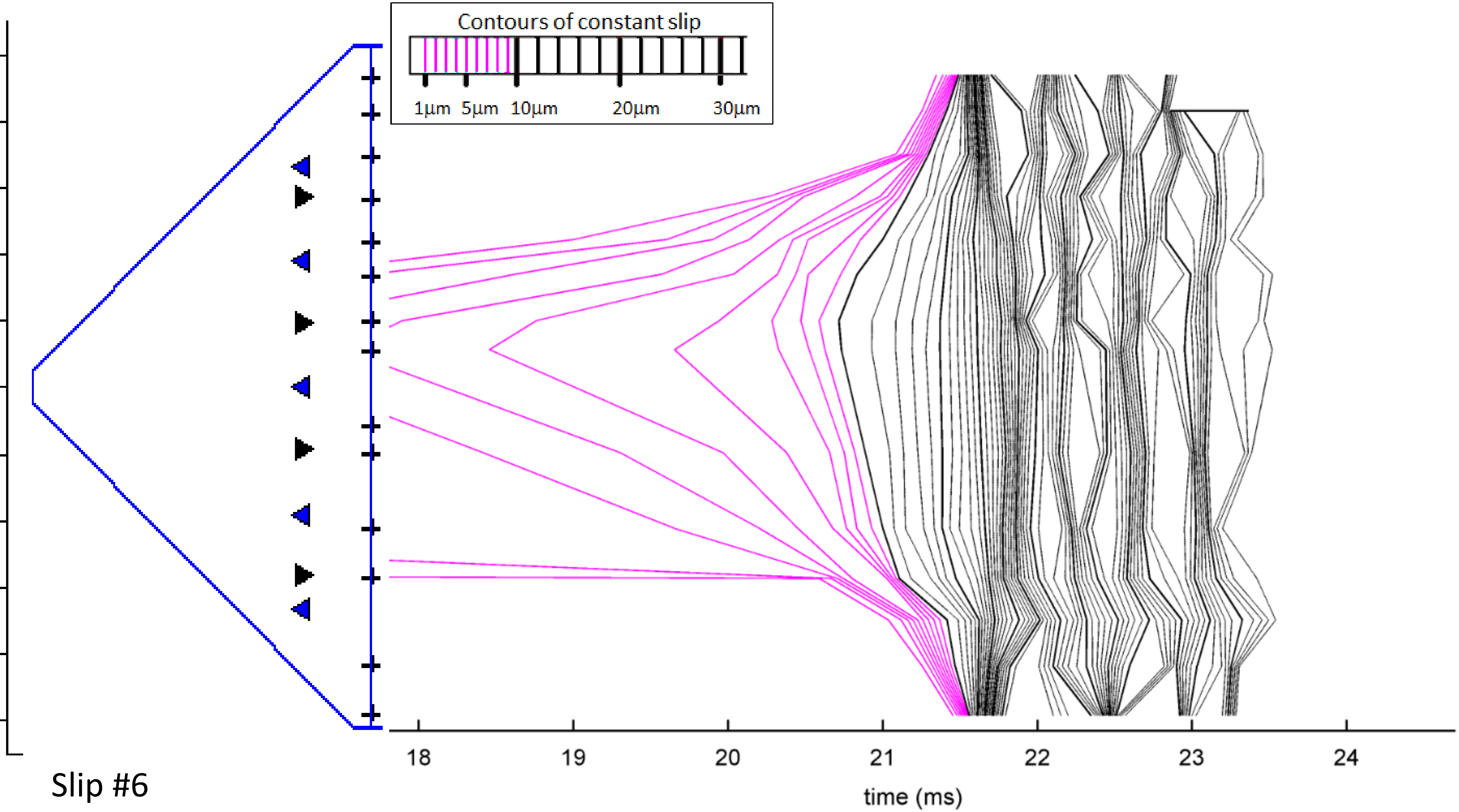






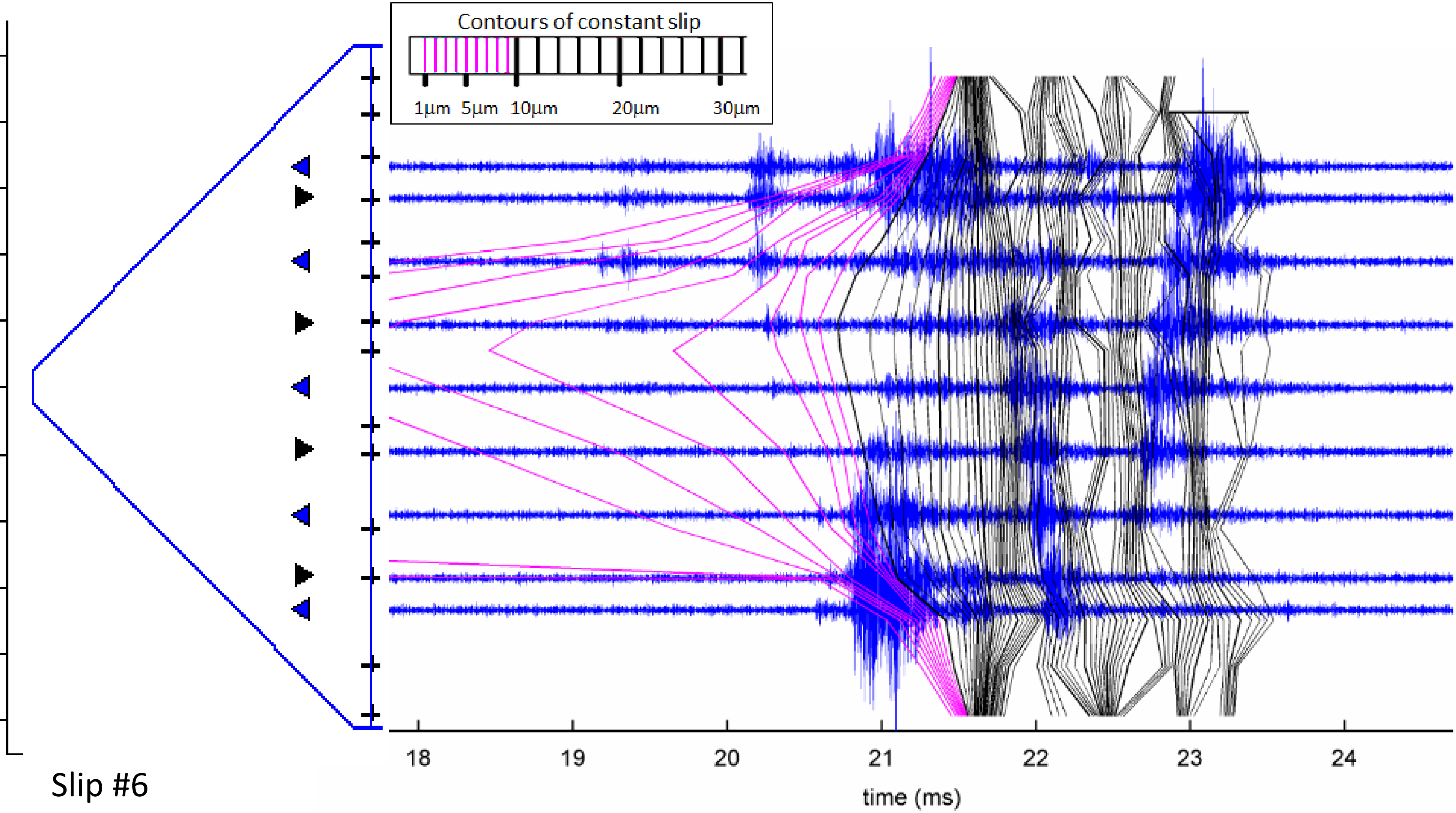
Slip #6

Mainshock



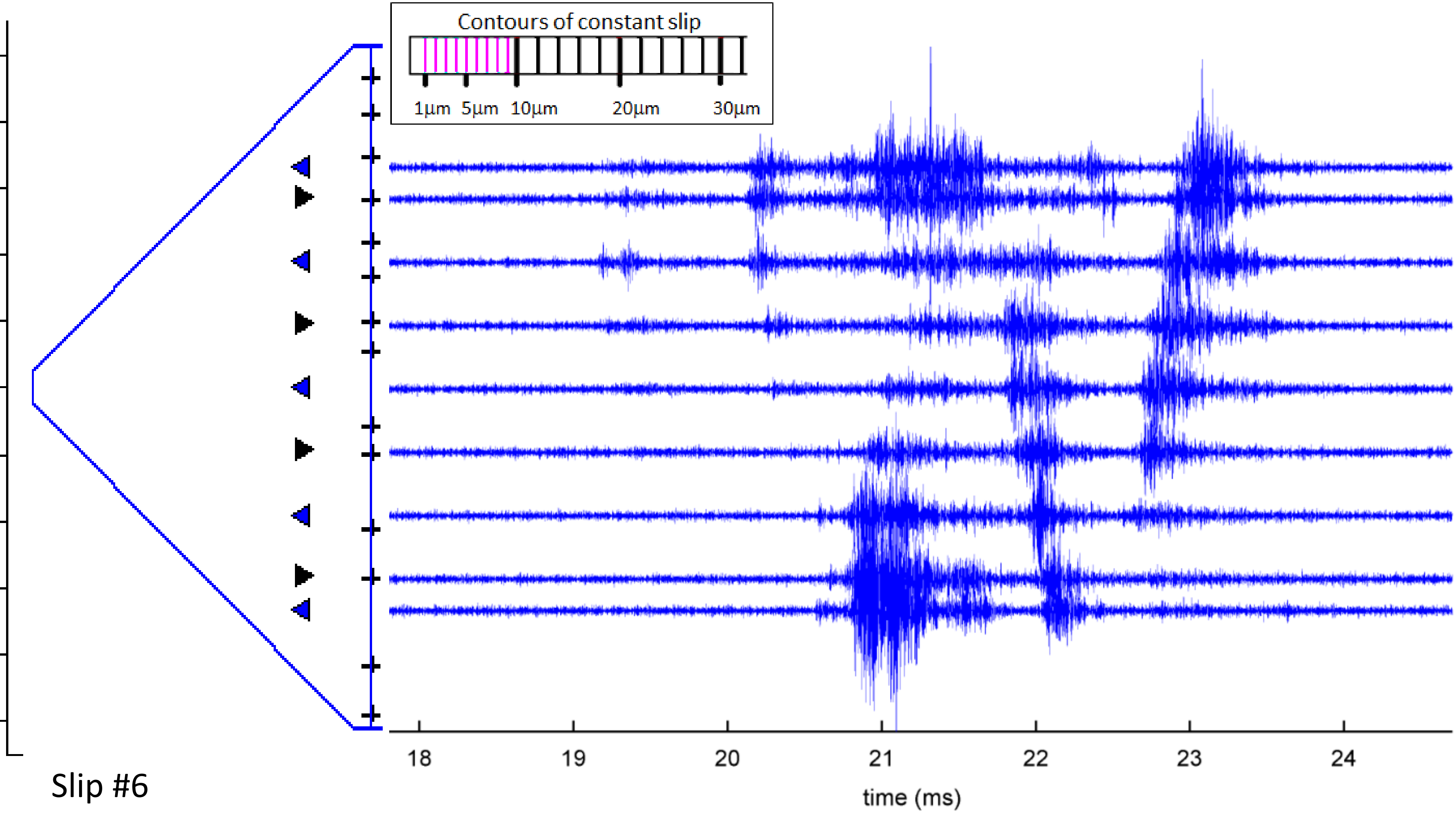
Slip #6

Mainshock

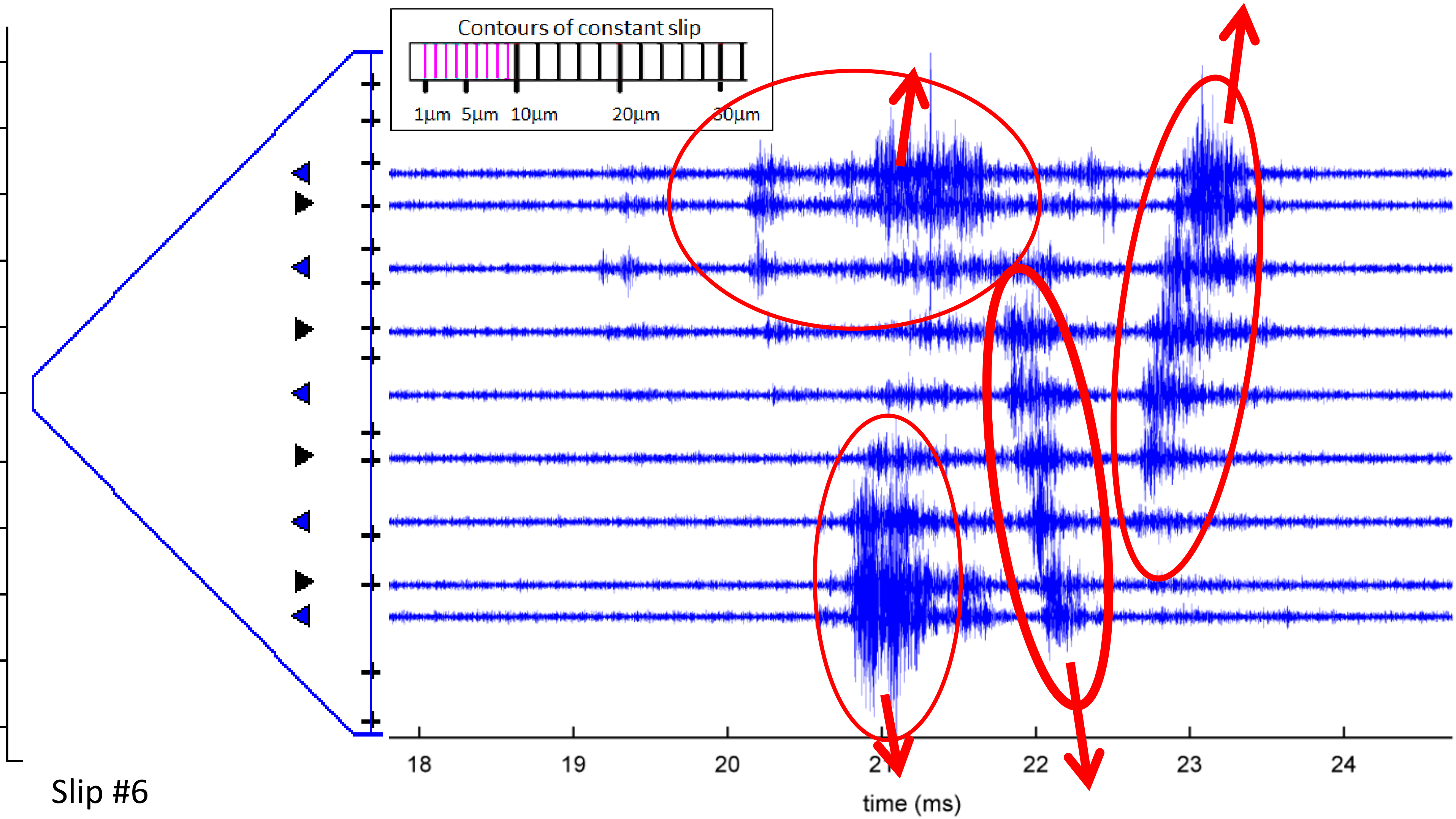


Slip #6

Mainshock

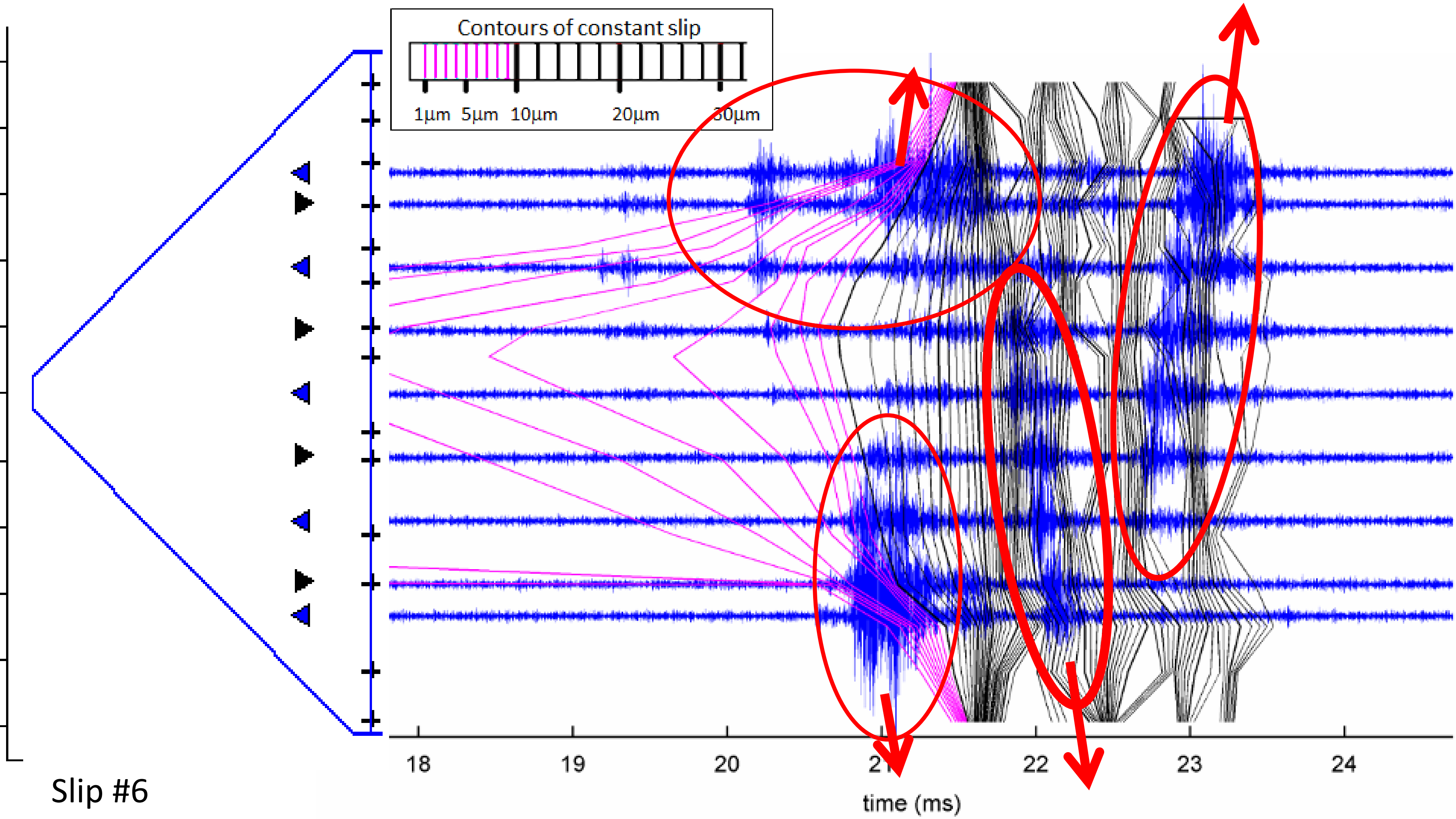

Contours of constant slip
1µm 5µm 10µm 20µm 30µm
18
19
20
21
22
23
24
time (ms)
Slip #6

Mainshock



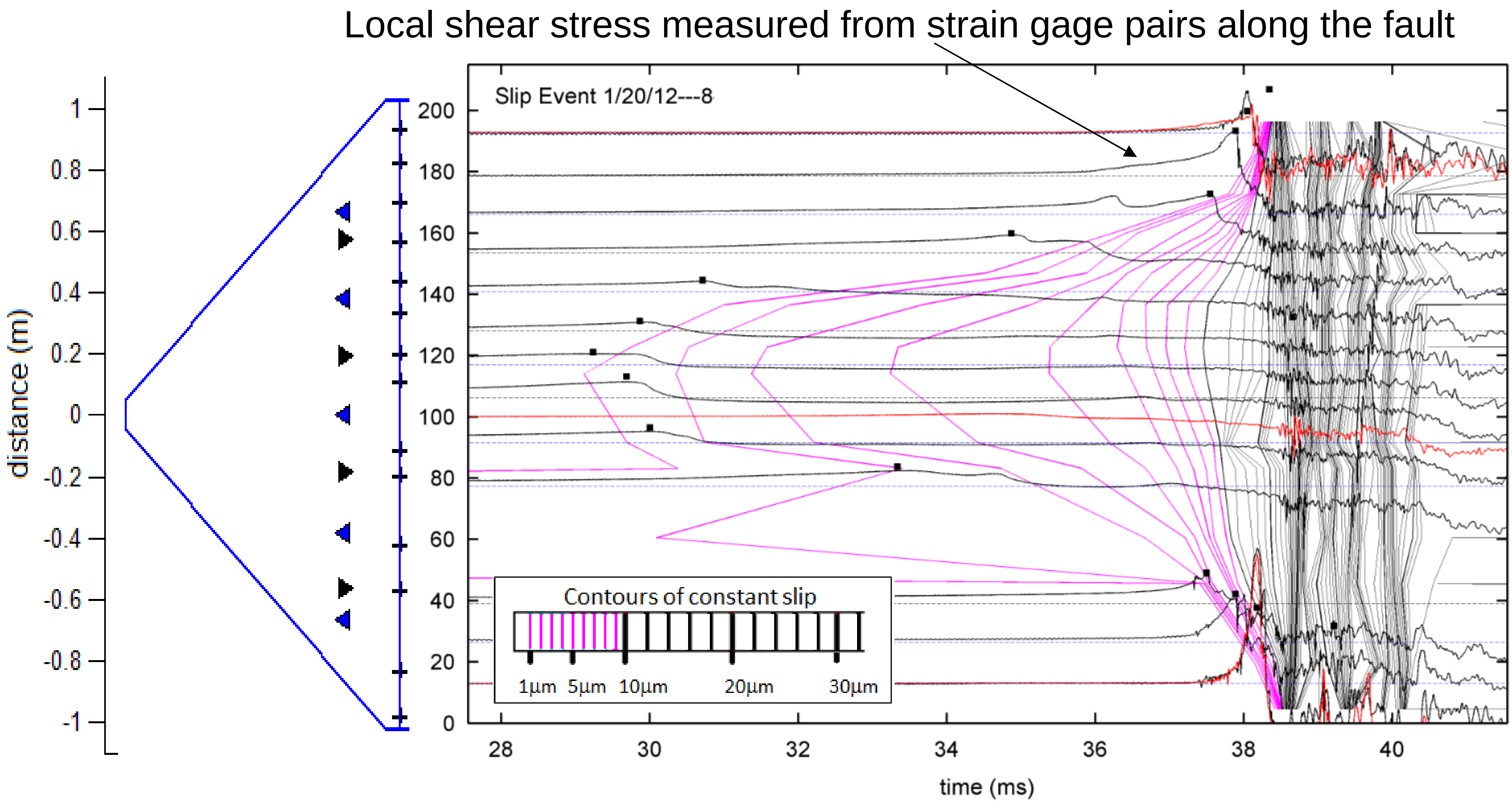
Slip #6

Mainshock



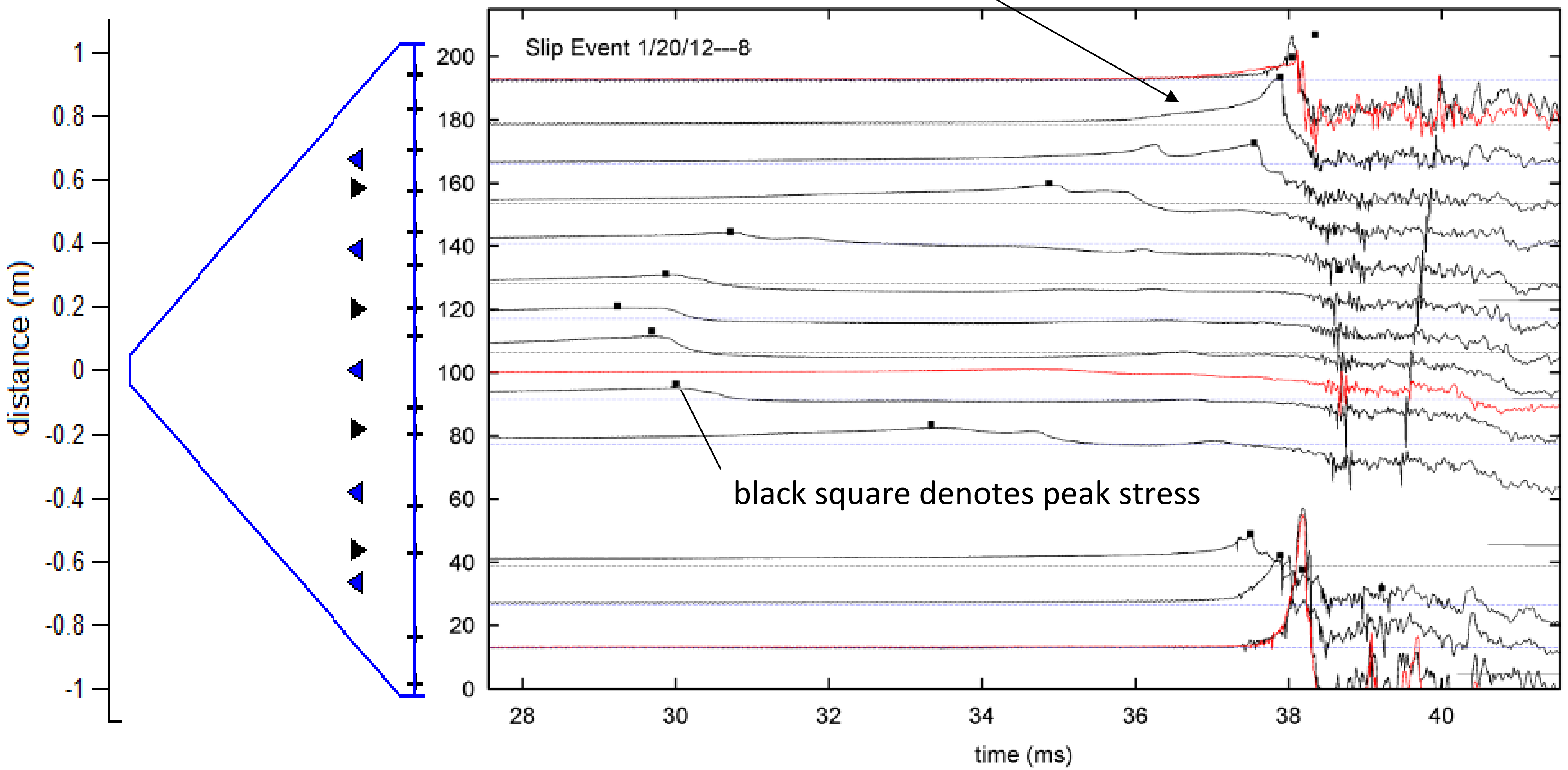
Contours of constant slip
1μm
5μm
10μm
20μm
30μm
18
19
20
21
22
23
24
time (ms)
Slip #6

Slow slip during nucleation

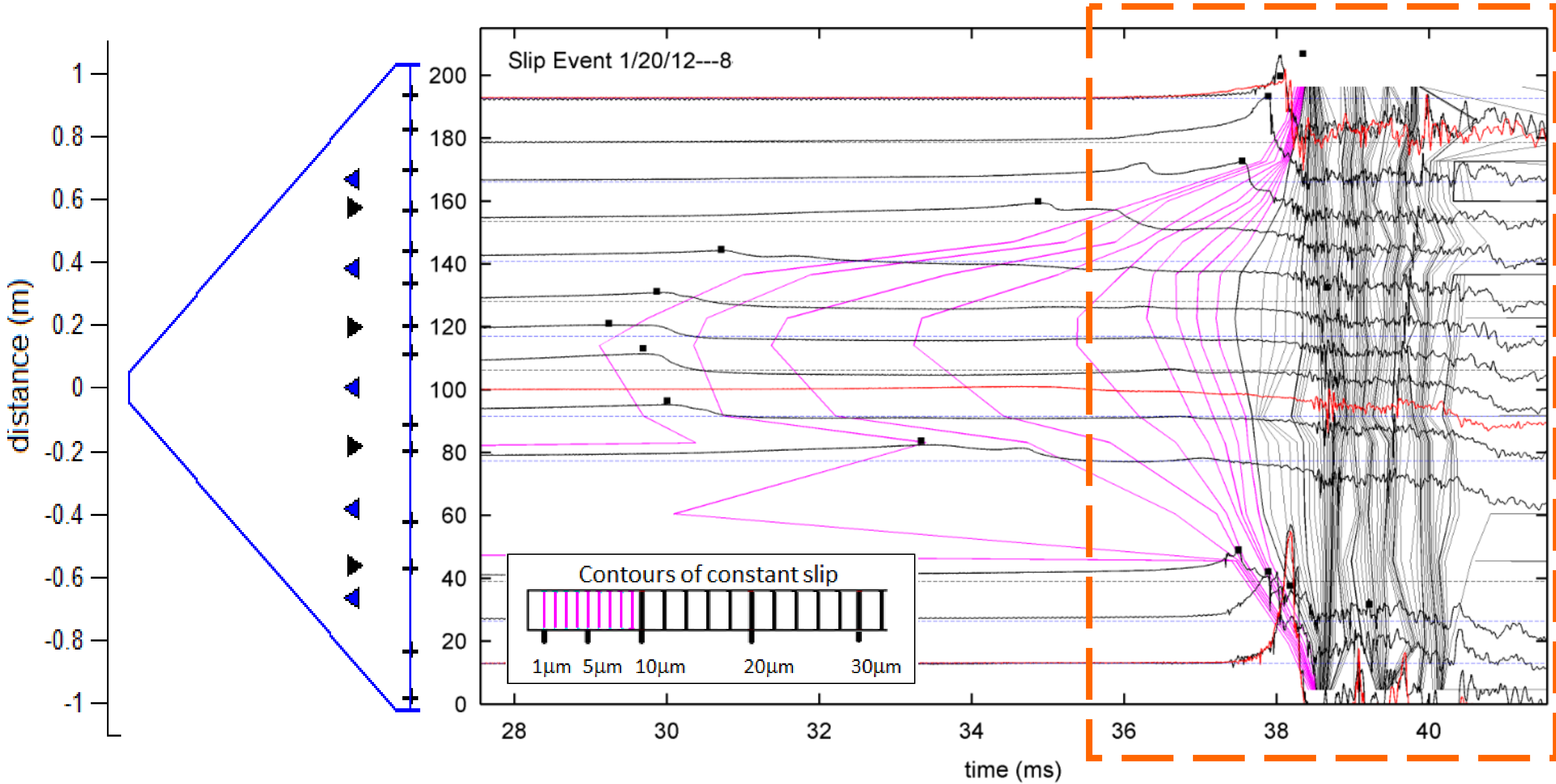


Slow slip during nucleation

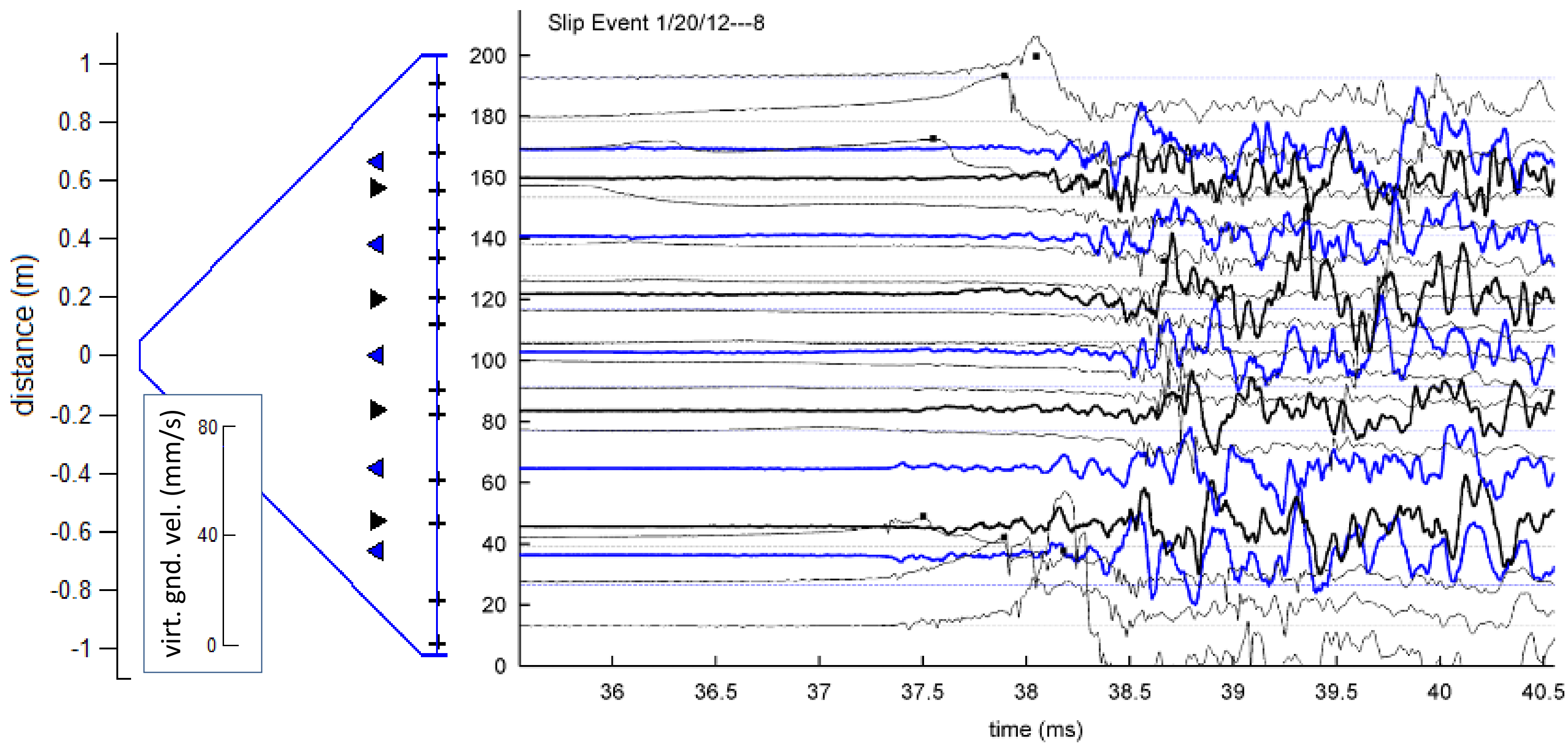
Local shear stress measured from strain gage pairs along the fault



Zoom in on ground motions during "mainshock"

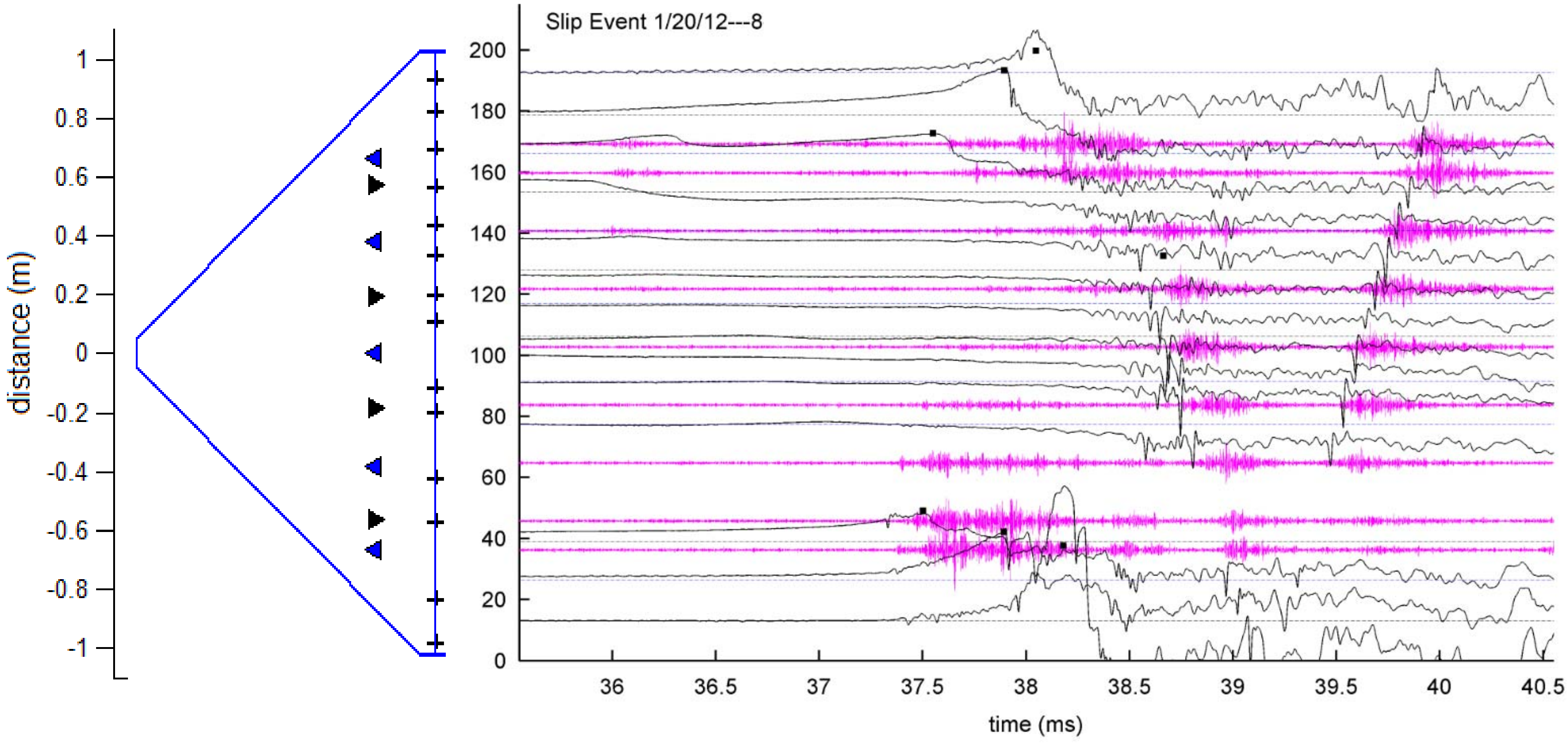


Complexity of HF seismicity during dynamic fault rupture



Complexity of HF seismicity during dynamic fault rupture

200 kHz high pass filtered

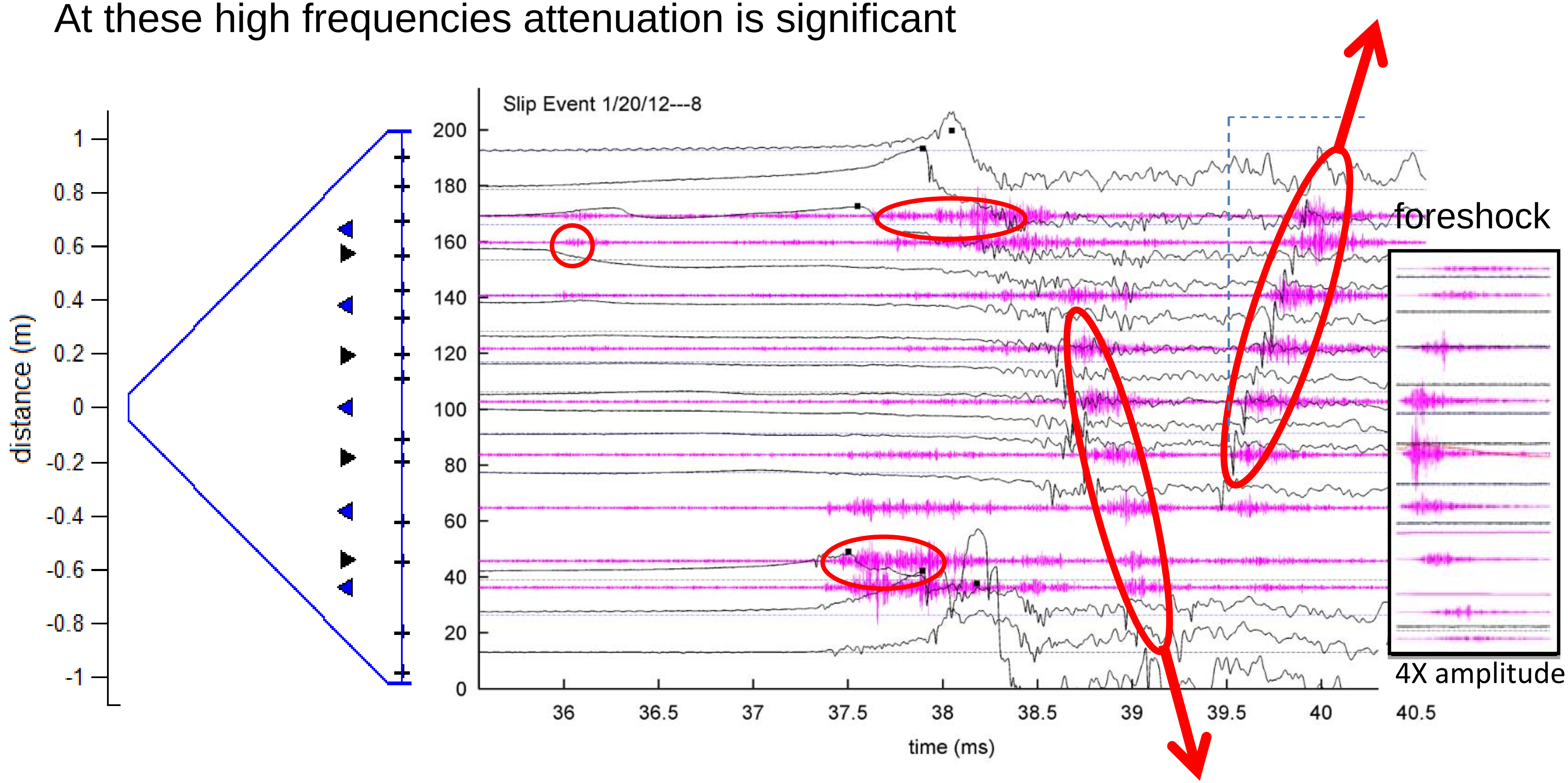


Moving sources of high frequency during dynamic fault rupture

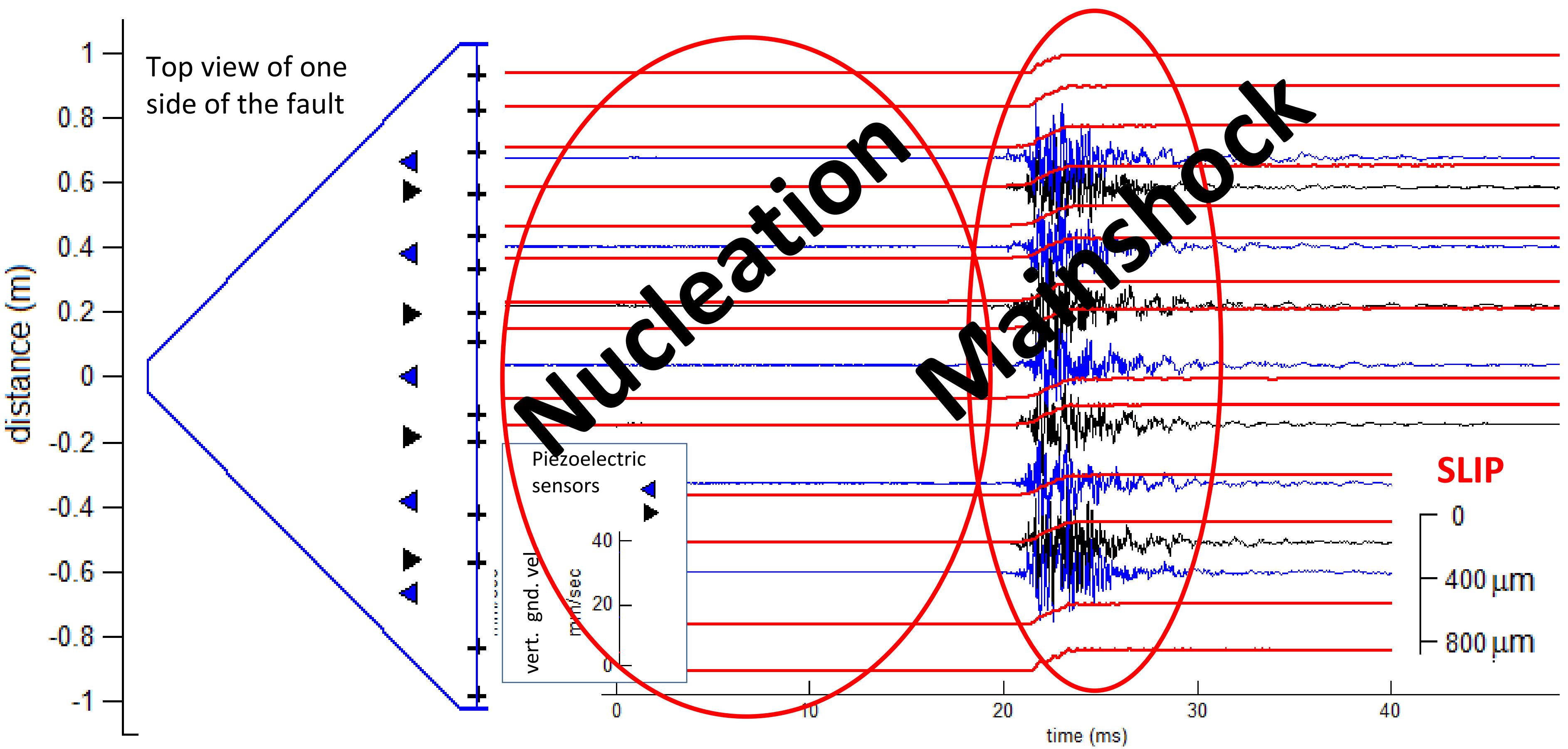
Magenta = 200 kHz high pass filtered ground motions recorded from piezoelectric sensor array.

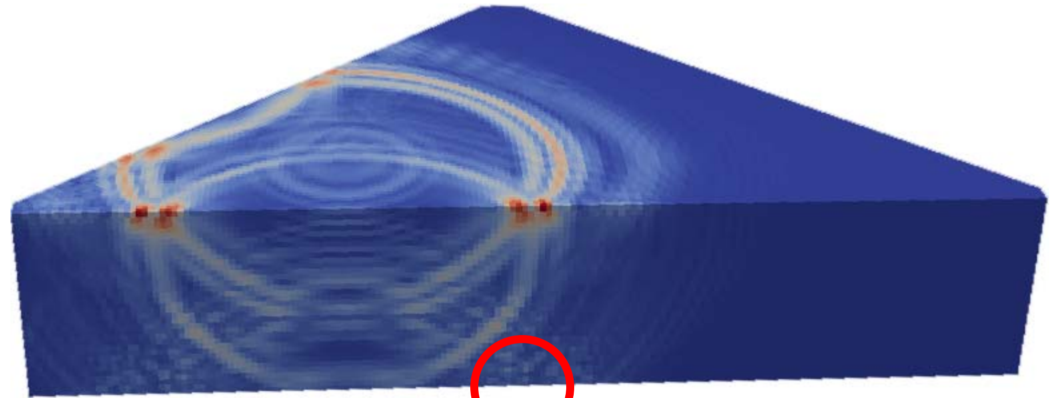
At these high frequencies attenuation is significant

Propagation velocity ~2000 m/s



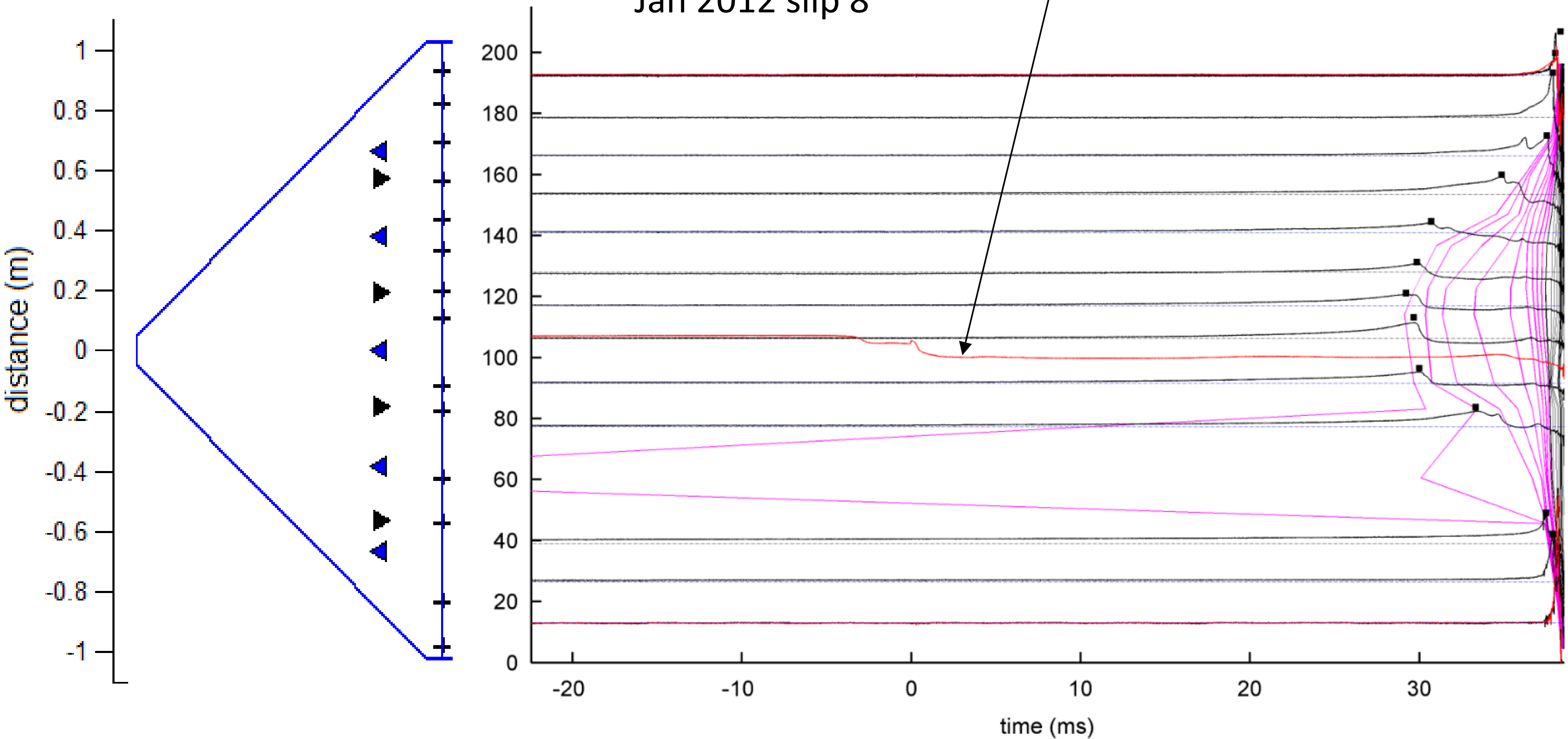
But this talk is about nucleation!



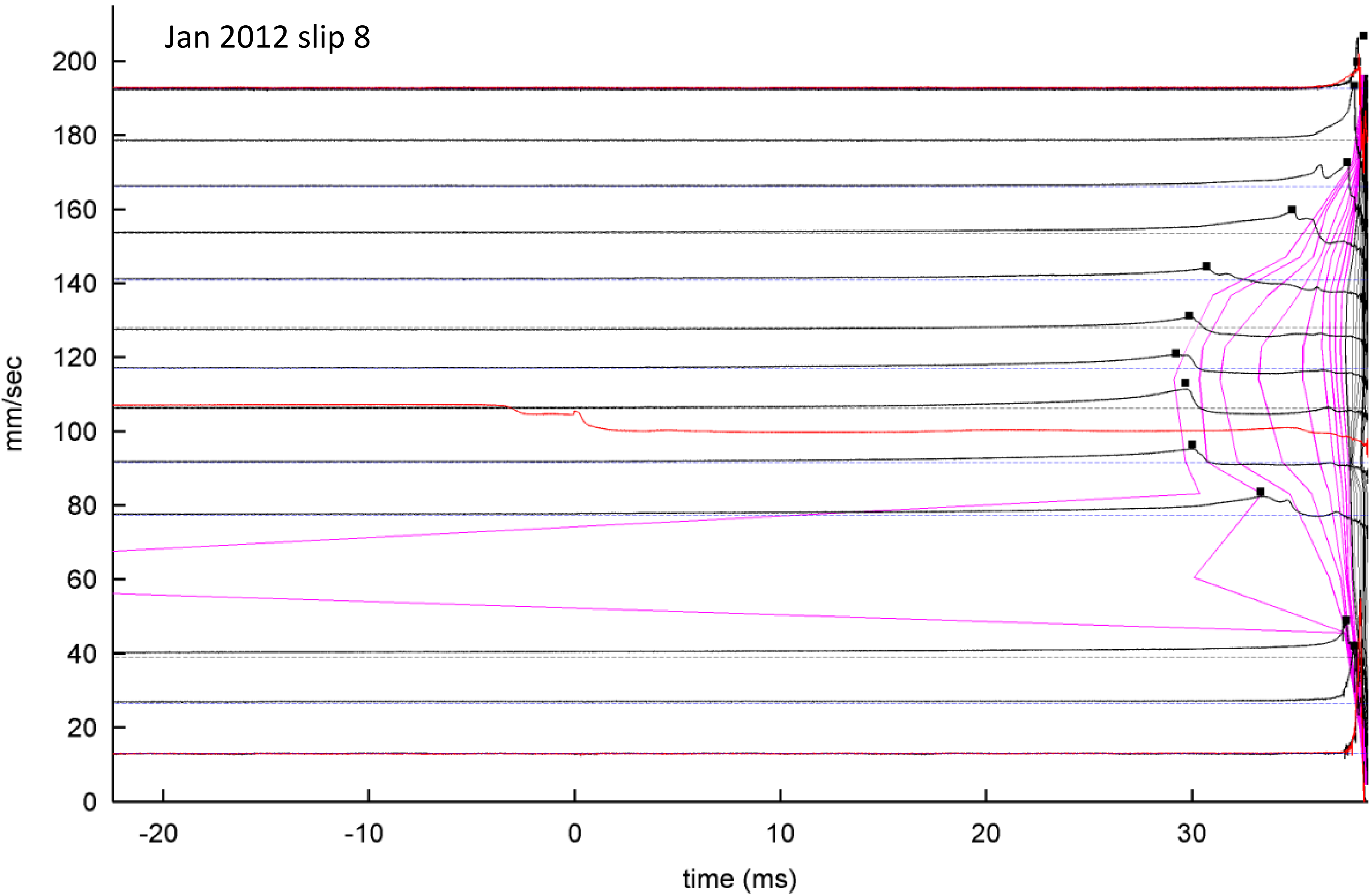


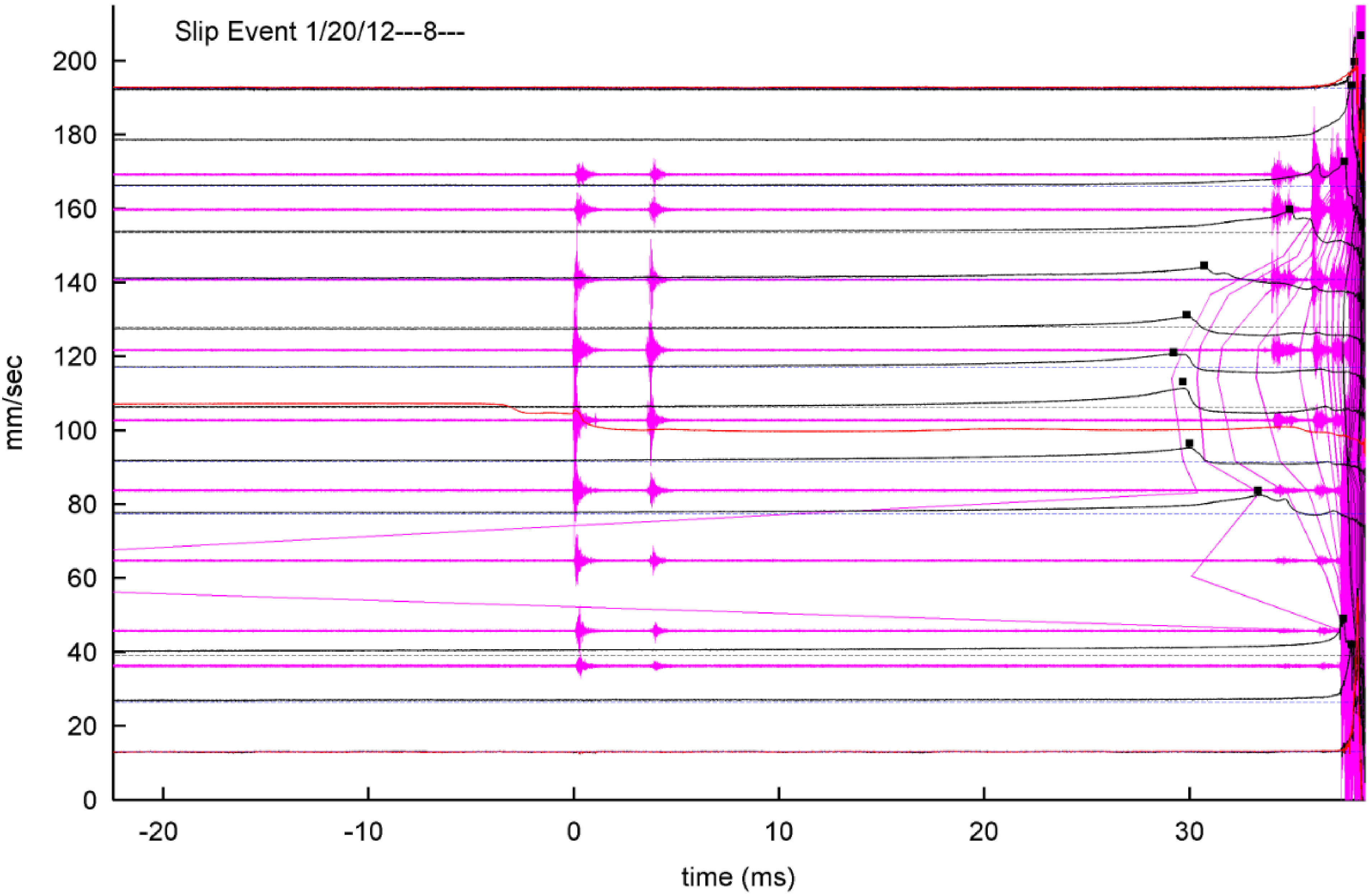
Local shear stress measured from strain gage pairs along the fault

Jan 2012 slip 8



Local shear stress measured from strain gage pairs along the fault

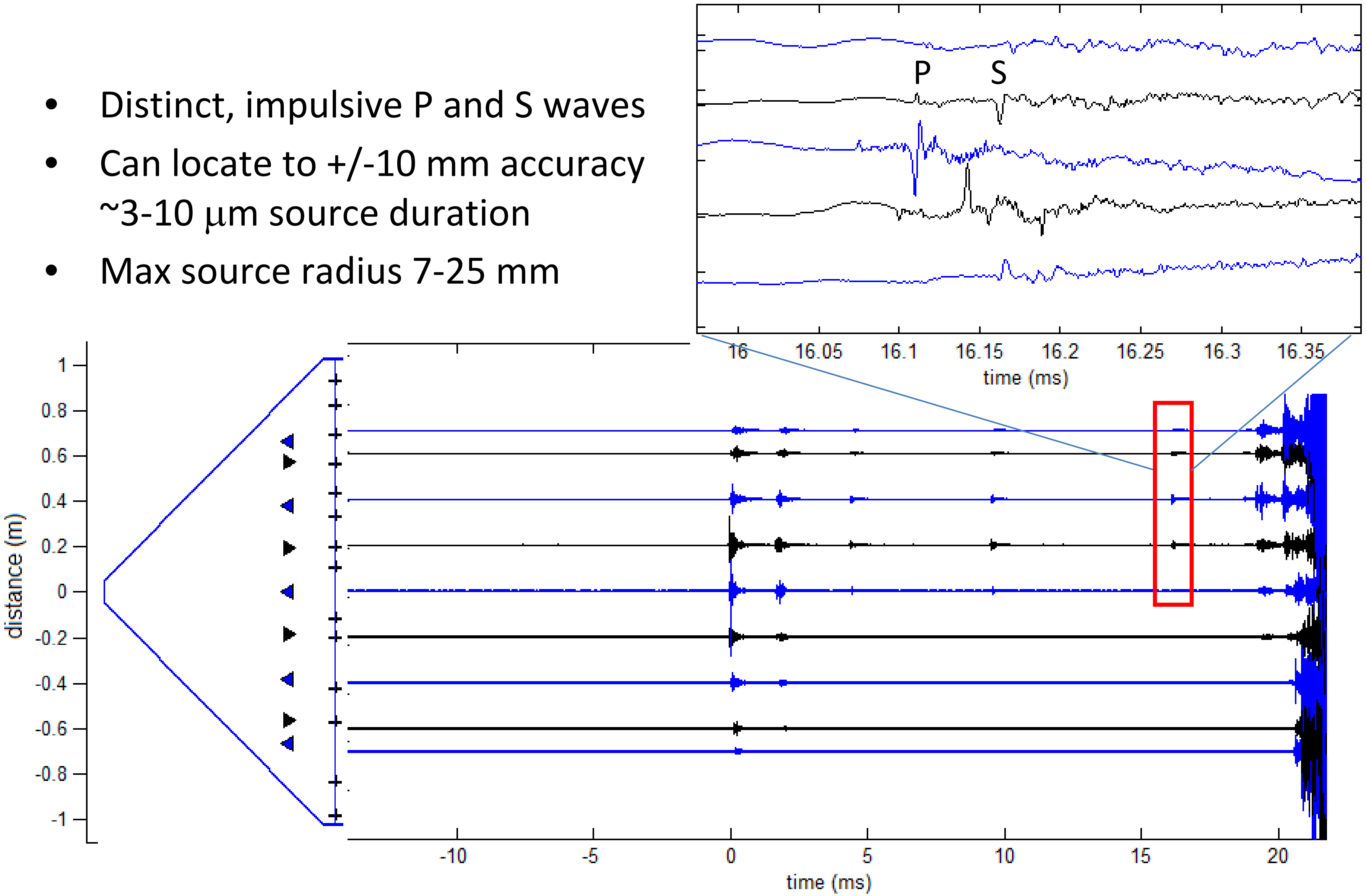




Slip Event 1/20/12---8---
mm/sec
0
20
40
60
80
100
120
140
160
180
200
-20
-10
0
10
20
30
time (ms)

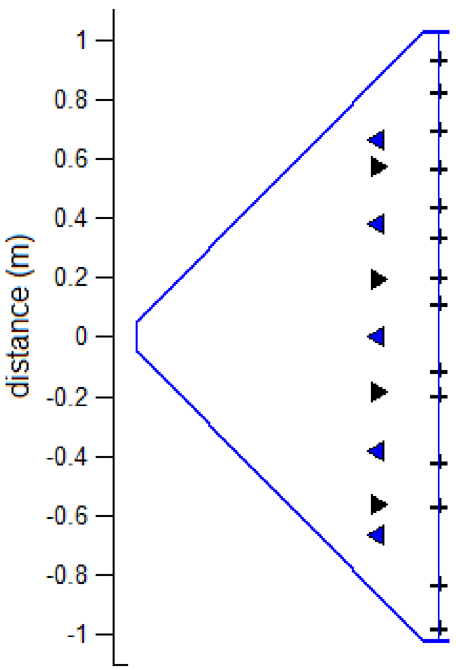
Nucleation: foreshocks

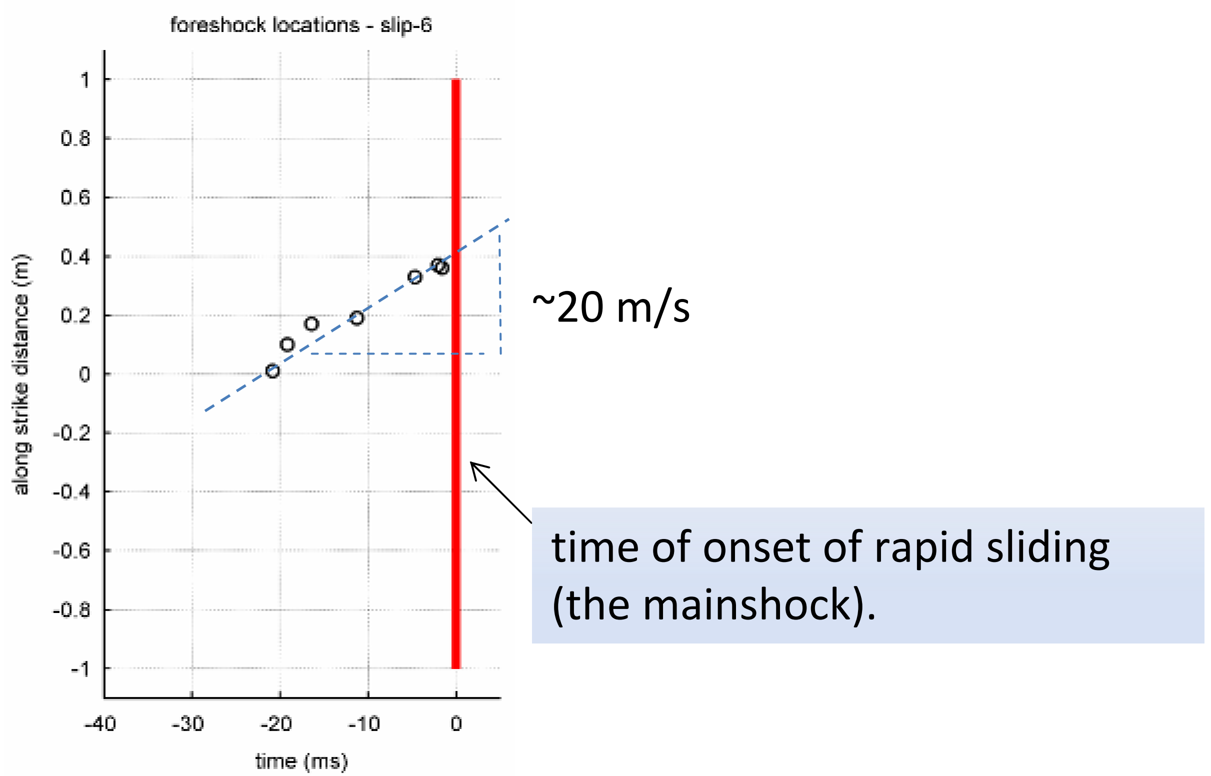
- Distinct, impulsive P and S waves
- Can locate to +/-10 mm accuracy
  ~3-10 μm source duration
- Max source radius 7-25 mm



Foreshock migration

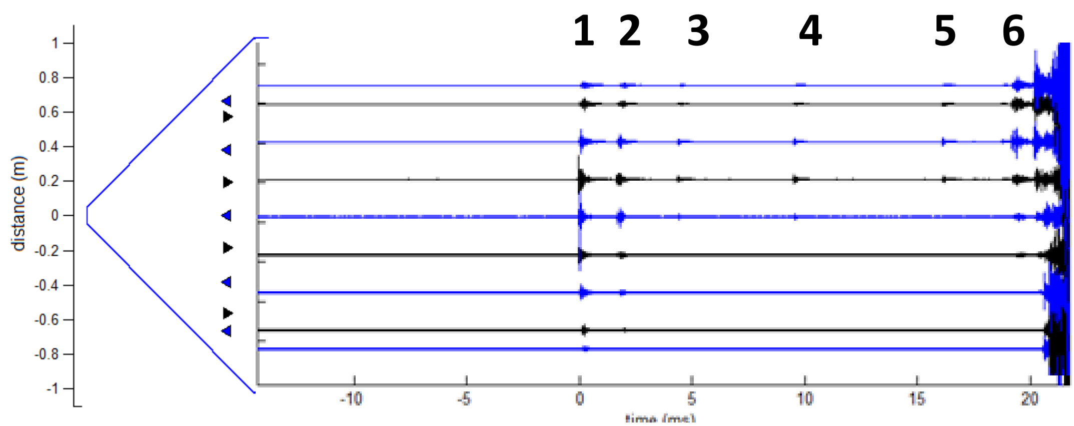
- Impulsive foreshocks can be located to ~+/- 10 mm accuracy
- Foreshock migration velocity along strike ~20 m/s
  - 2 orders of magnitude slower than migration of high frequency sources during dynamic rupture.

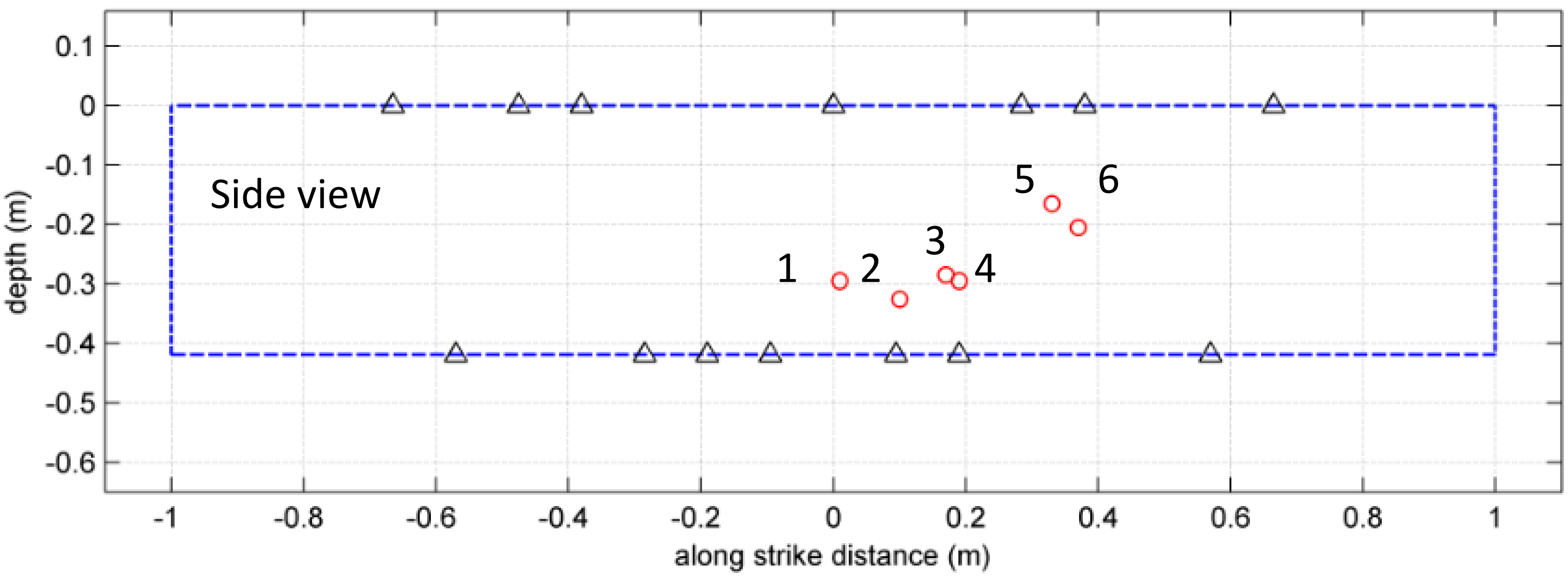


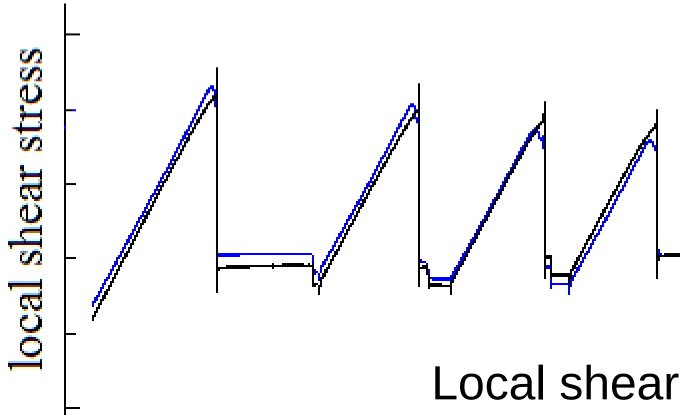


Foreshock locations:
along strike and depth

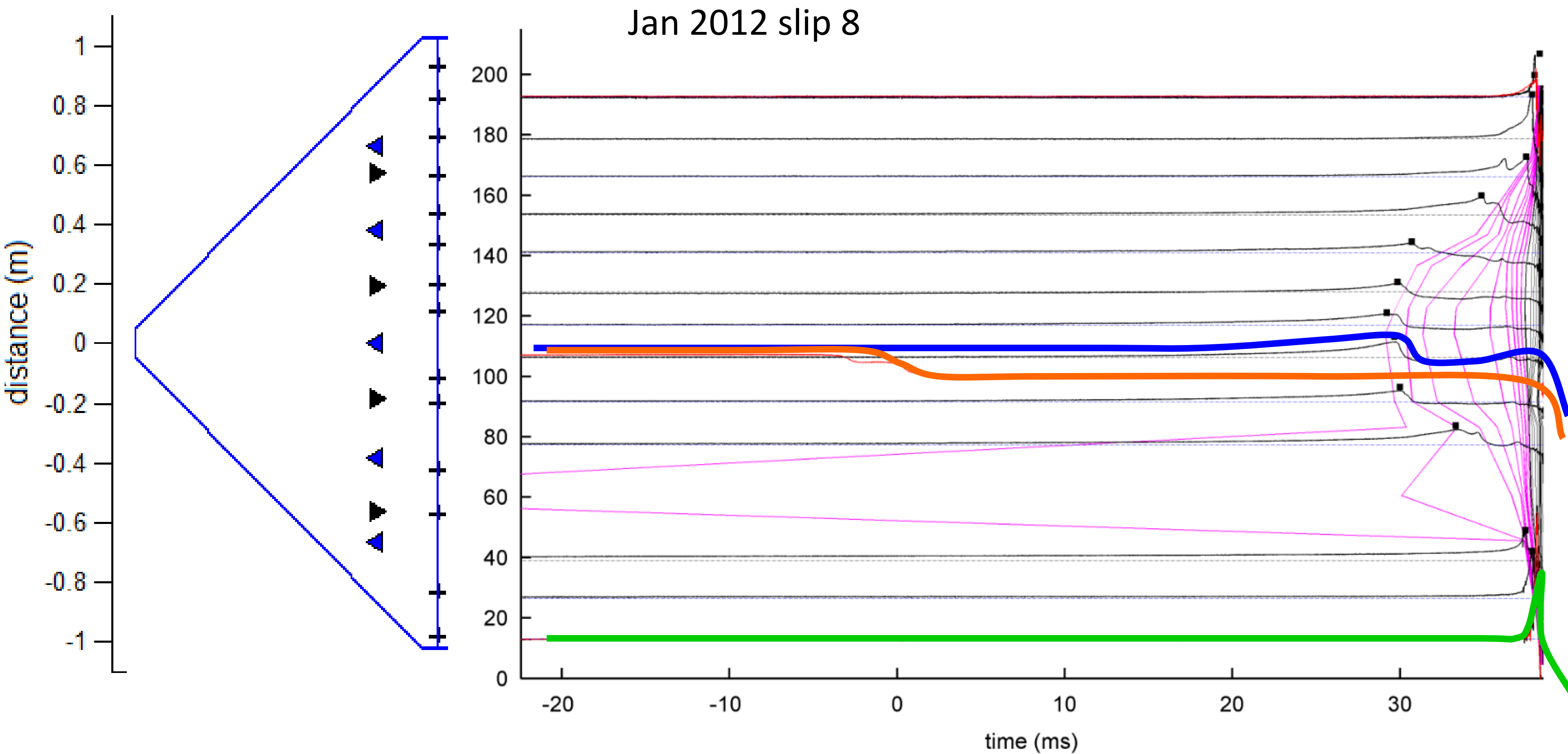
- Foreshock locations from one stick slip event (Slip #6)

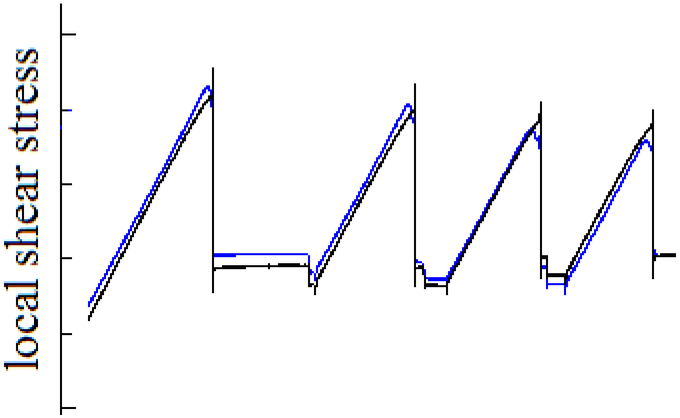


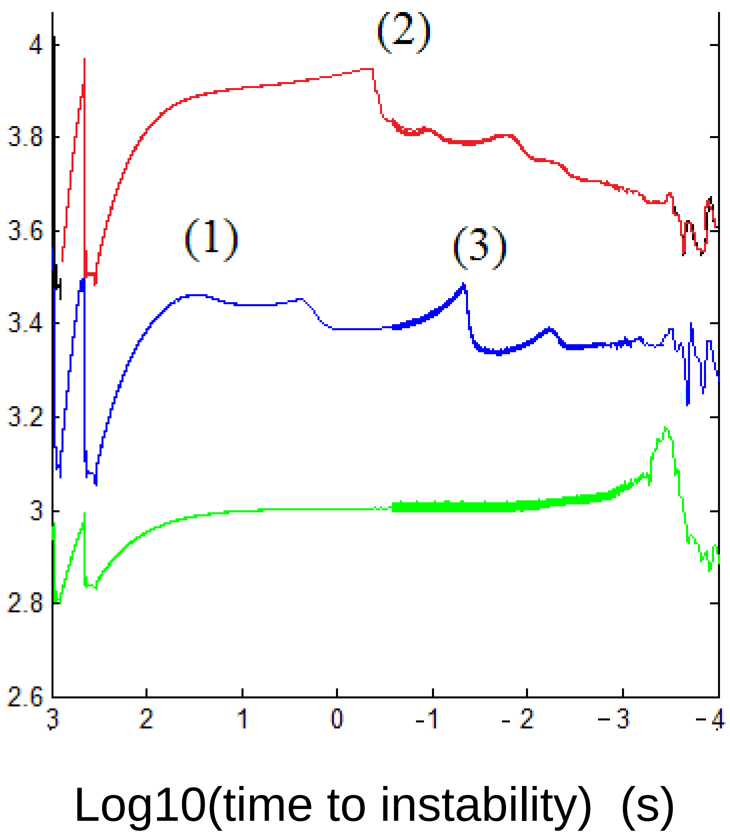


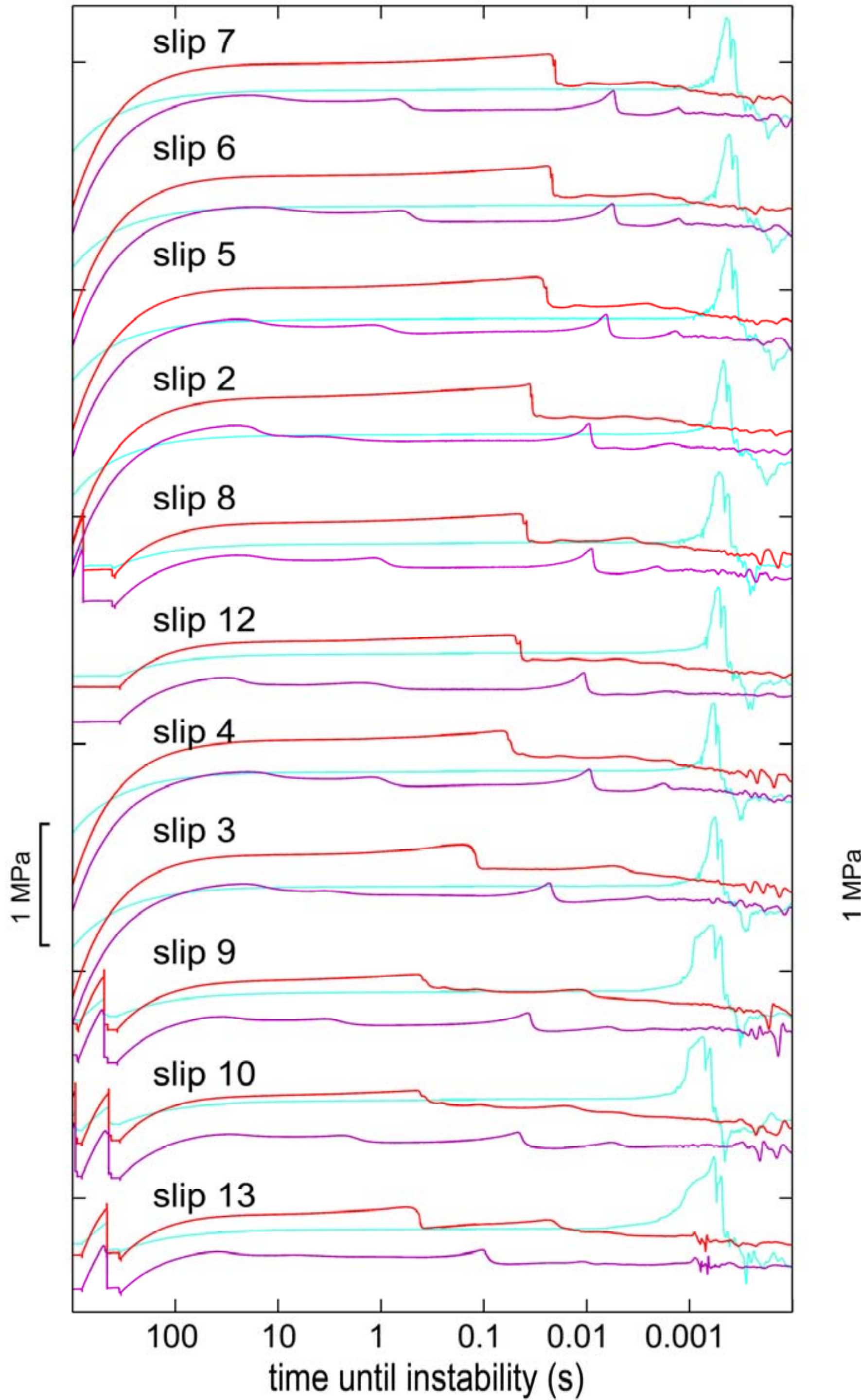


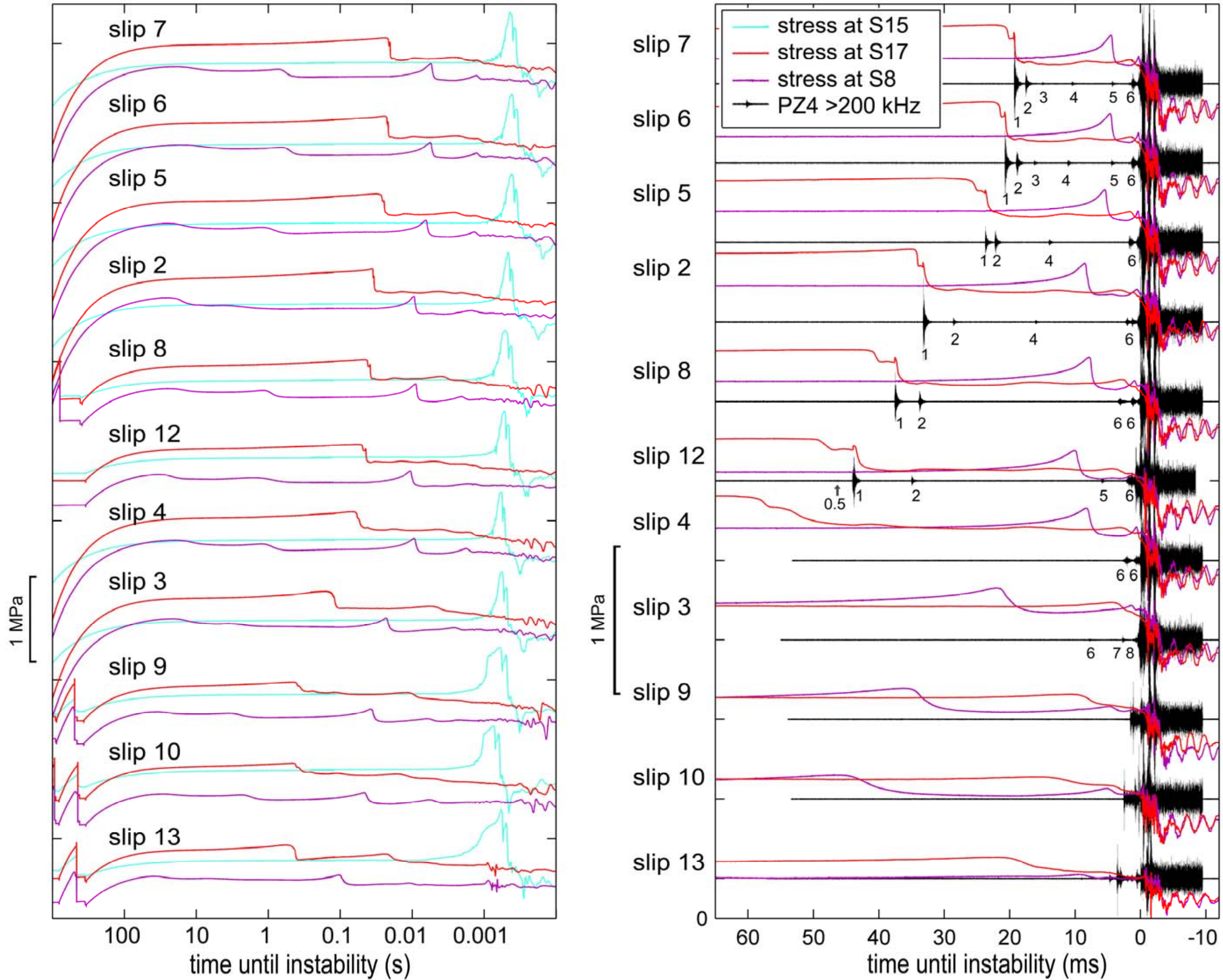
Local shear stress measured from strain gage pairs along the fault



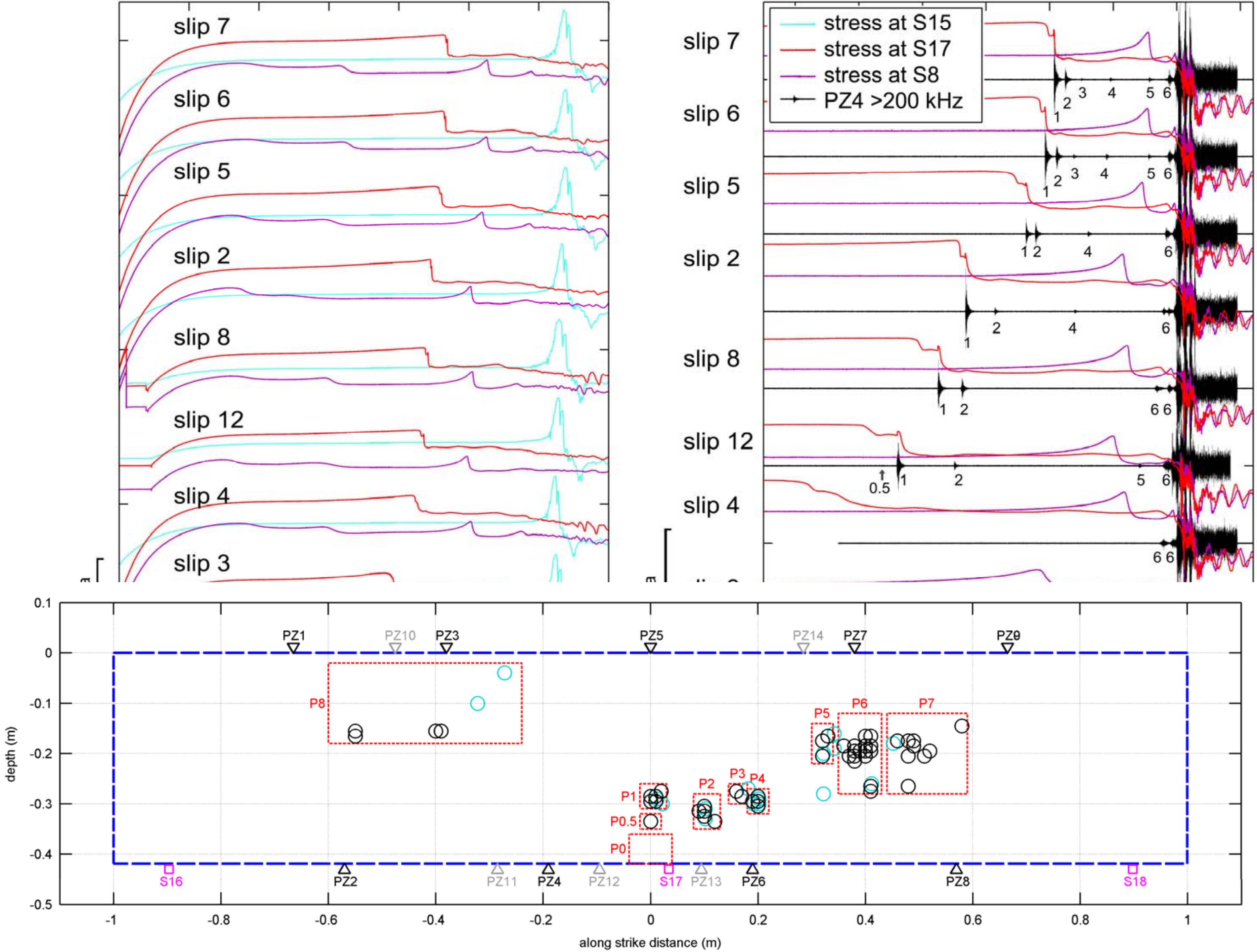

local shear stress


(1)
(2)
(3)
4
3.8
3.6
3.4
3.2
3
2.8
2.6
3
2
1
0
-1
- 2
- 3
- 4
Log10(time to instability) (s)

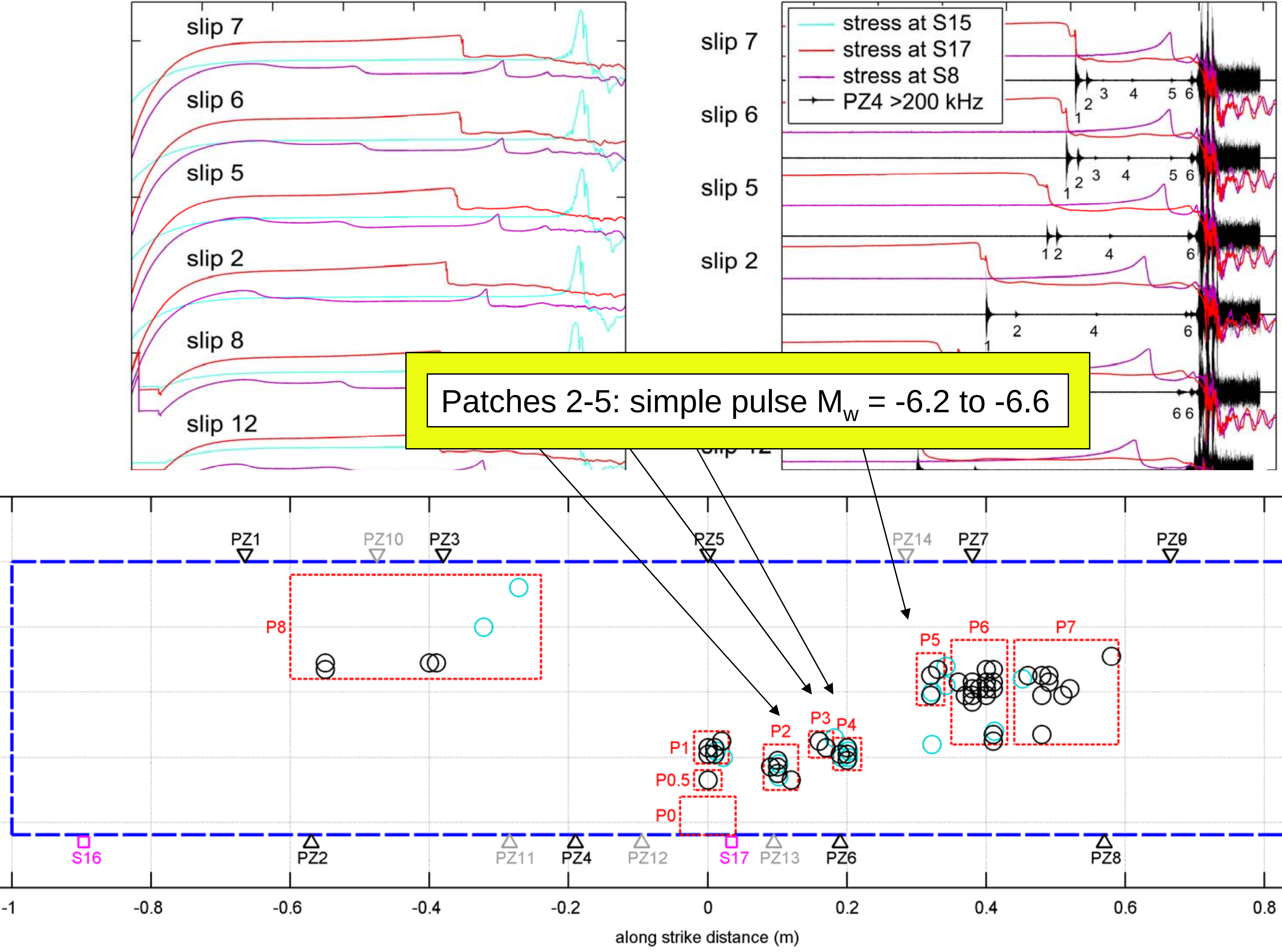

slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
slip 4
slip 3
slip 9
slip 10
slip 13
1 MPa
100
10
1
0.1
0.01
0.001
time until instability (s)
1 MPa



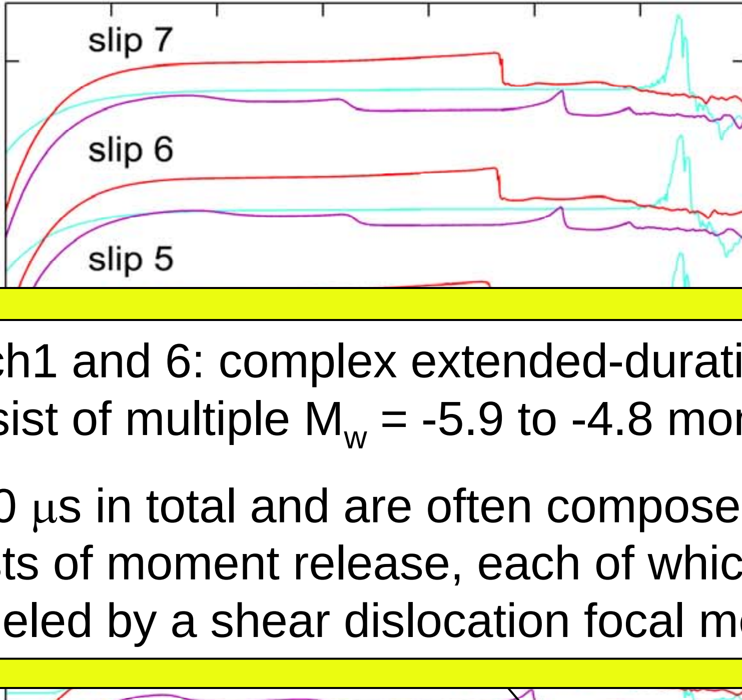
slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
slip 4
slip 3
slip 9
slip 10
slip 13
1 MPa
100
10
1
0.1
0.01
0.001
time until instability (s)
stress at S15
stress at S17
stress at S8
PZ4 >200 kHz
0.5
60
50
40
30
20
10
0
-10
time until instability (ms)

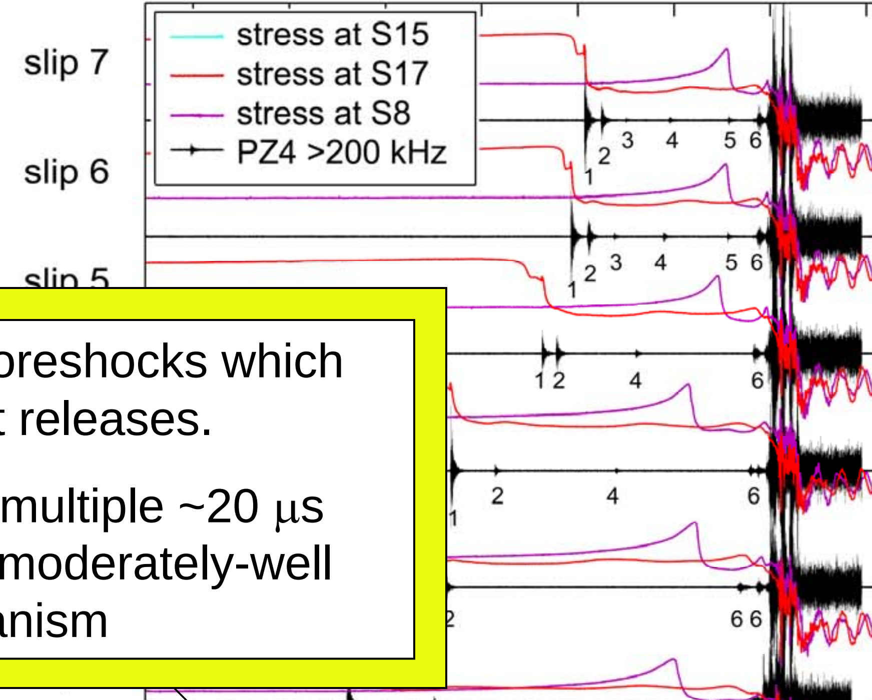


slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
slip 4
slip 3
stress at S15
stress at S17
stress at S8
PZ4 >200 kHz
1 2 3 4 5 6
0.5
P0
P0.5
P1
P2
P3
P4
P5
P6
P7
P8
PZ1
PZ2
PZ3
PZ4
PZ5
PZ6
PZ7
PZ8
PZ9
PZ10
PZ11
PZ12
PZ13
PZ14
S16
S17
S18
depth (m)
along strike distance (m)



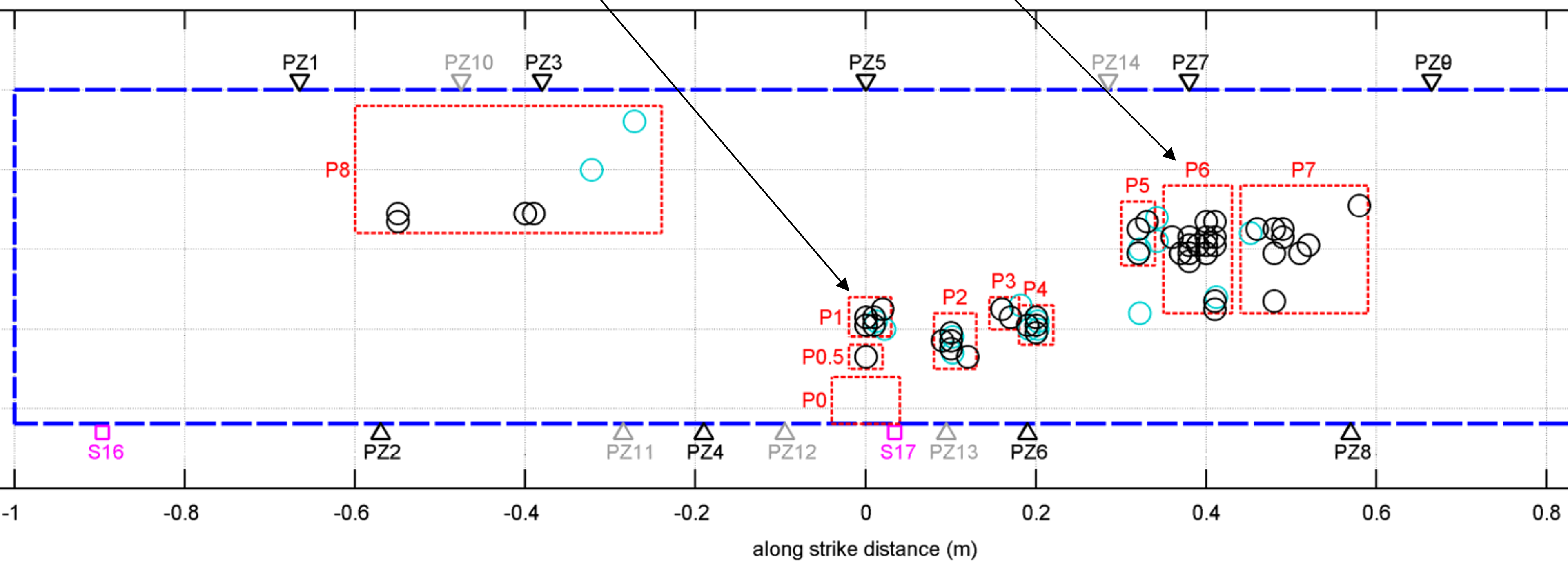
slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
stress at S15
stress at S17
stress at S8
PZ4 >200 kHz
Patches 2-5: simple pulse Mw = -6.2 to -6.6
PZ1
PZ10
PZ3
PZ5
PZ14
PZ7
PZ9
P8
P5
P6
P7
P1
P2
P3
P4
P0.5
P0
S16
PZ2
PZ11
PZ4
PZ12
S17
PZ13
PZ6
PZ8
along strike distance (m)

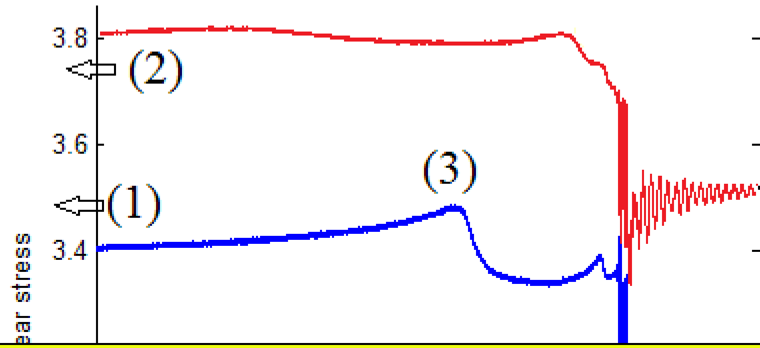


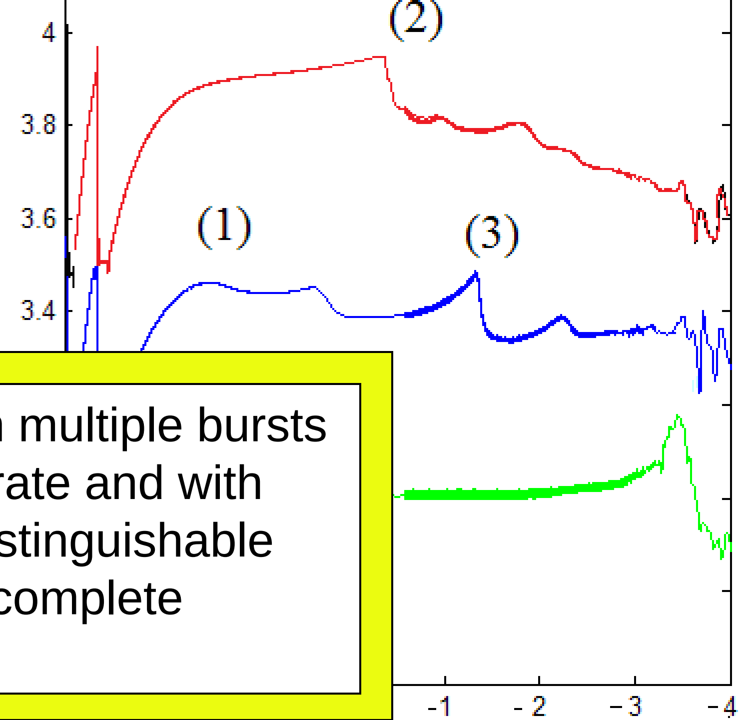


Patch1 and 6: complex extended-duration foreshocks which consist of multiple M_w = -5.9 to -4.8 moment releases.

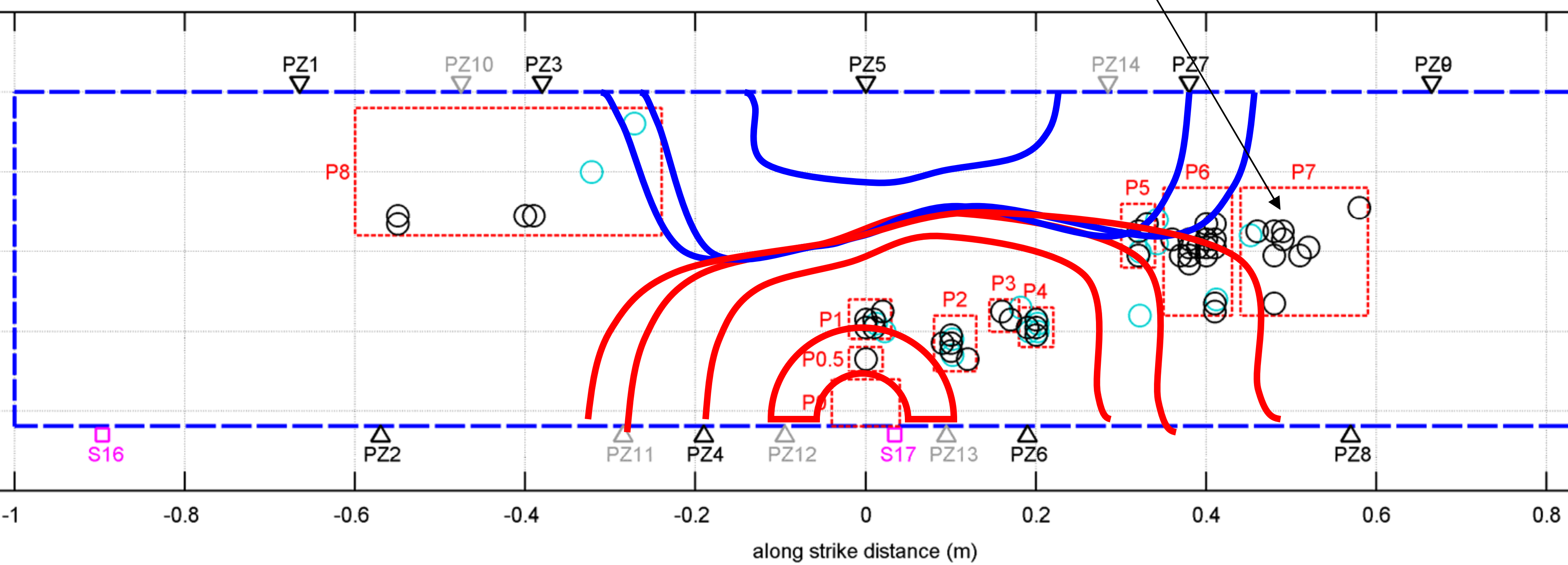
~100 μs in total and are often composed of multiple ~20 μs bursts of moment release, each of which is moderately-well modeled by a shear dislocation focal mechanism





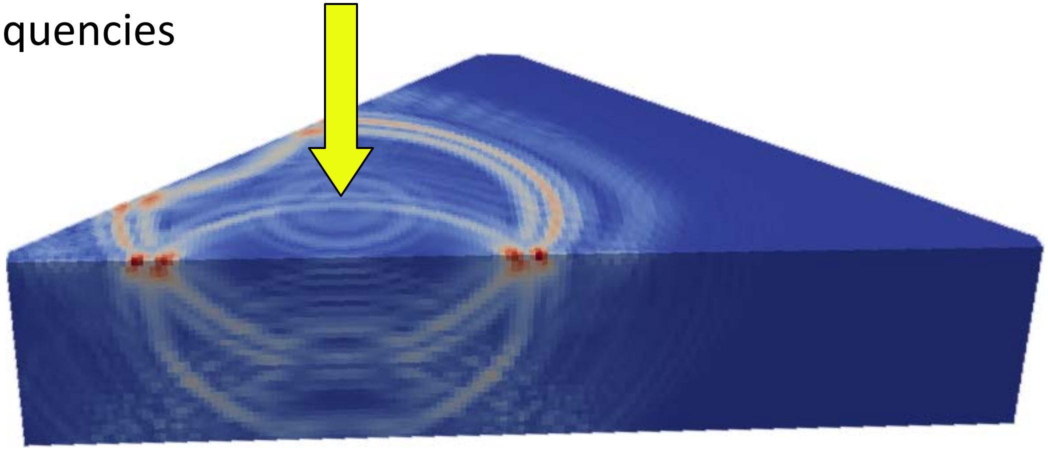


Patch 7 : very complex extended-duration with multiple bursts which continue to occur at a faster and faster rate and with larger and larger amplitudes until they are indistinguishable from the seismic waves generated during the complete dynamic rupture of the entire fault.



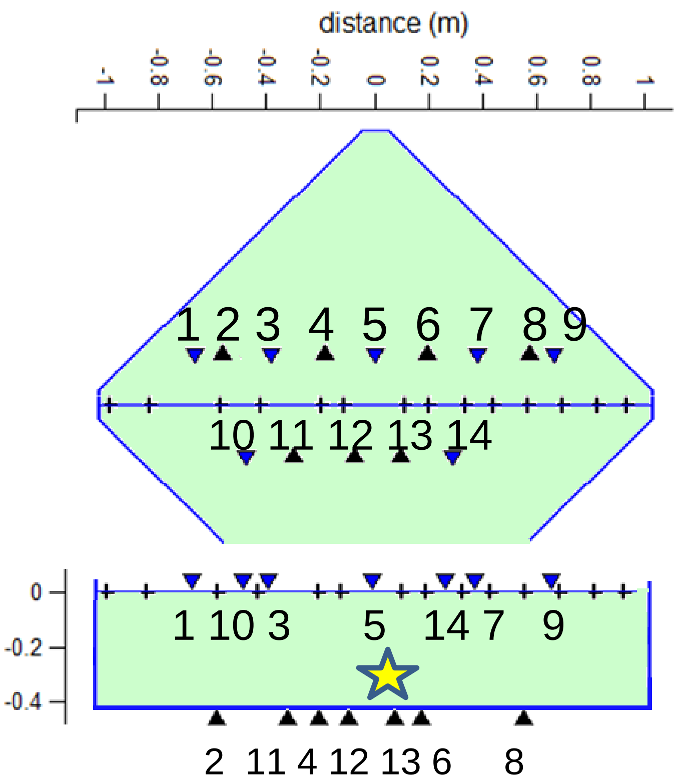
Modeling Laboratory Earthquakes

- Wave propagation modeling- Sierra White Granite
  - Goal is to develop a Green's function
  - Generalized ray theory, infinite plate
    - Good for simple geometry and few rays
  - Finite element models
    - Good for complicated geometry
    - Difficult to get high frequencies

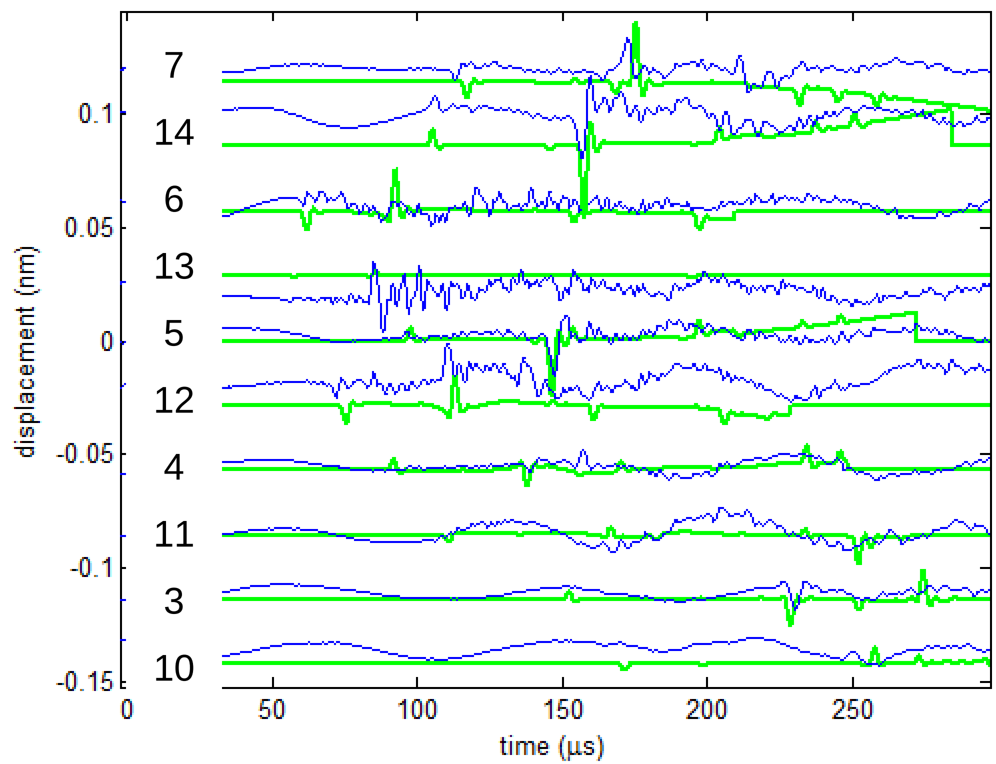


Waveform modeling of impulsive, high-frequency foreshocks

- Foreshock modeled as a ~3 μs pulse in moment rate
- Patch size (~7 mm upper bound)

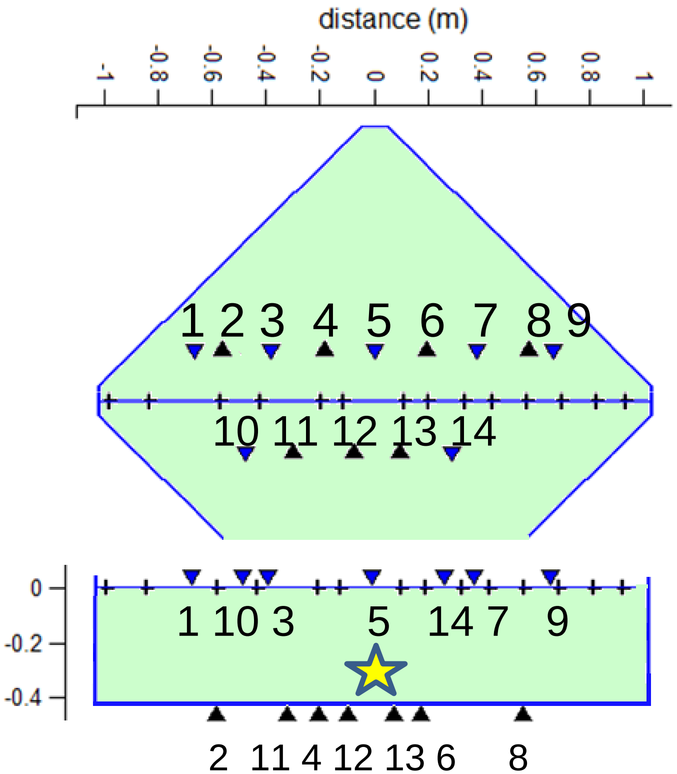


Patch 2 foreshock

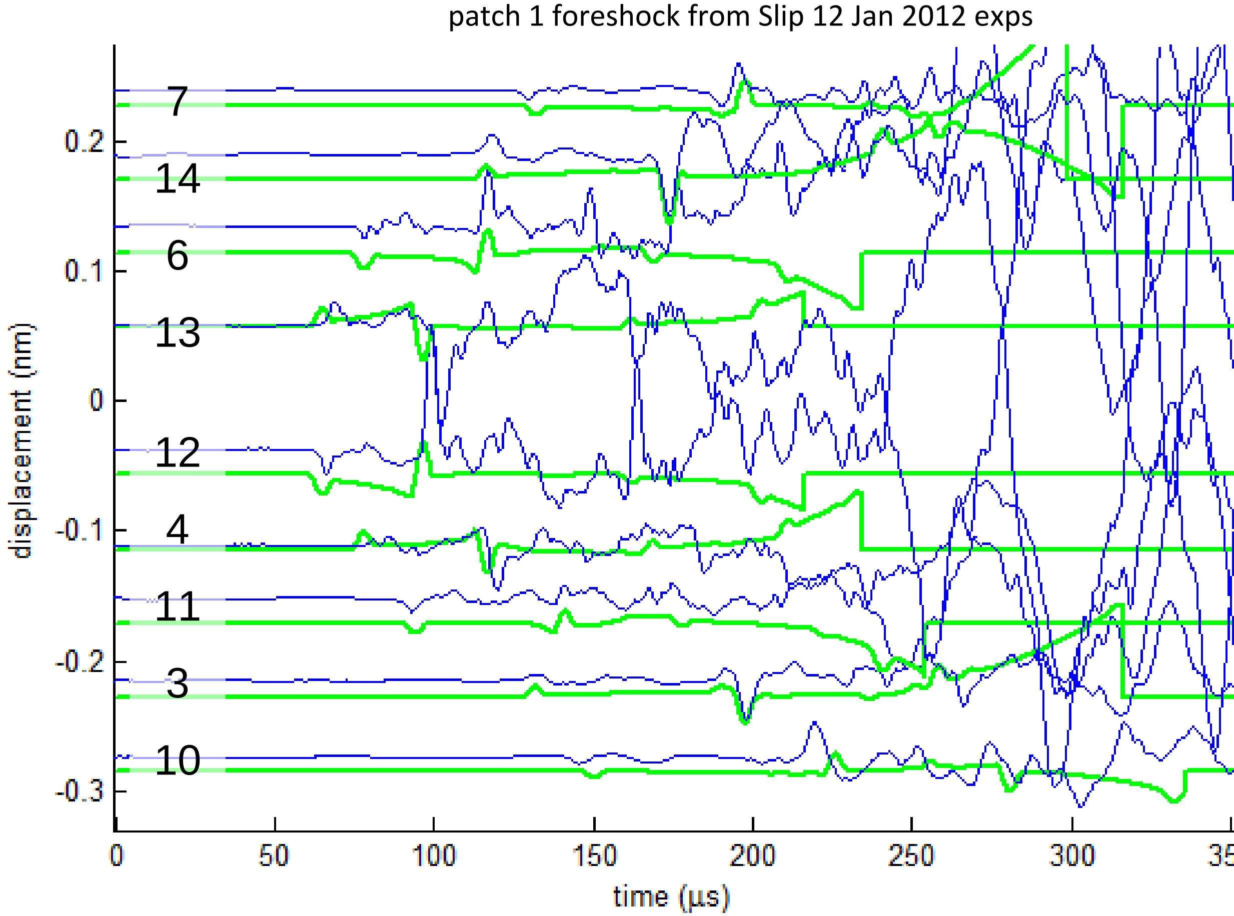


Waveform modeling of impulsive, high-frequency foreshocks

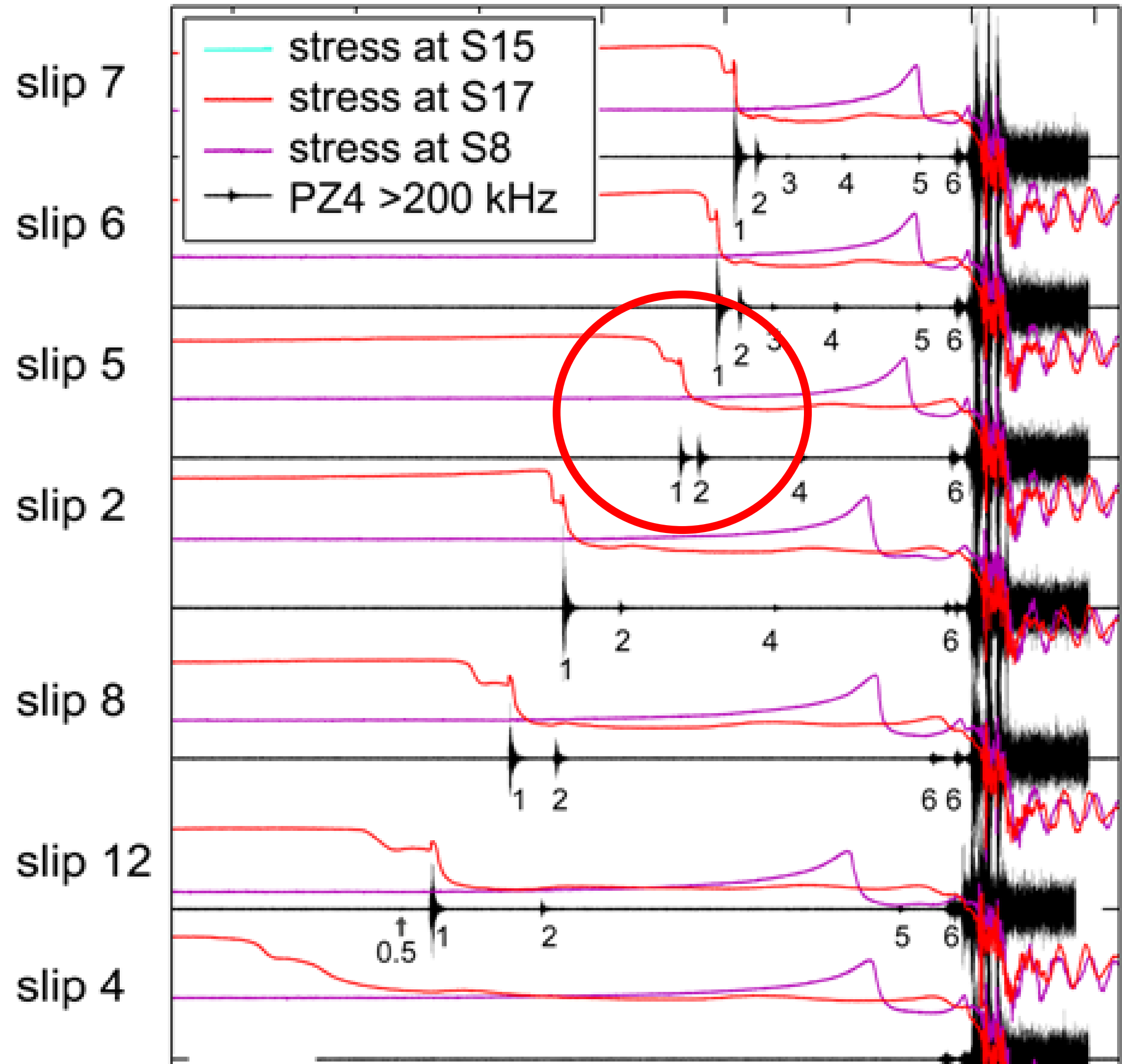
- Foreshock modeled as a ~8 μs pulse in moment rate, more complexity later.



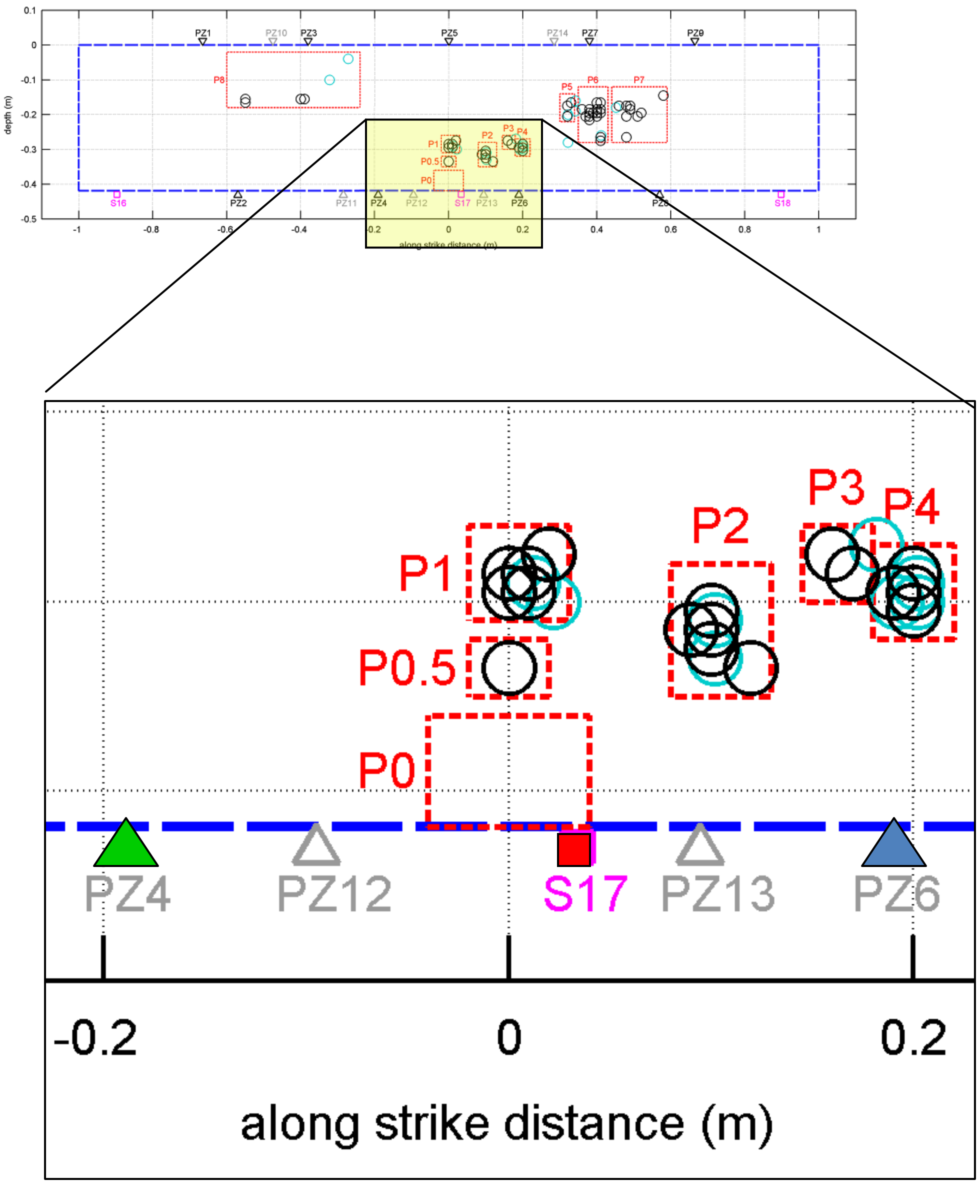
Patch 1 foreshock

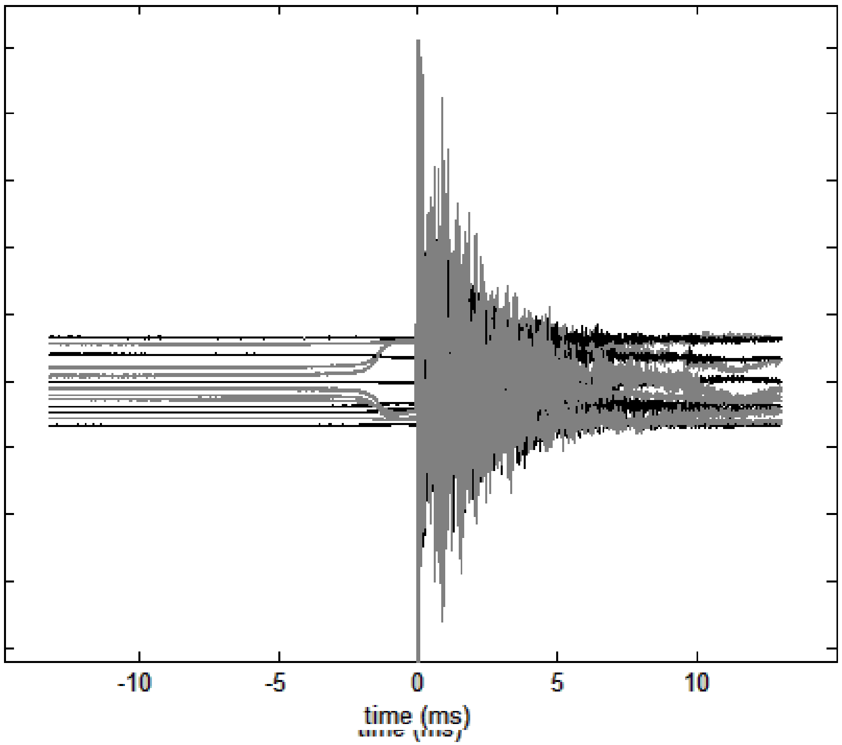


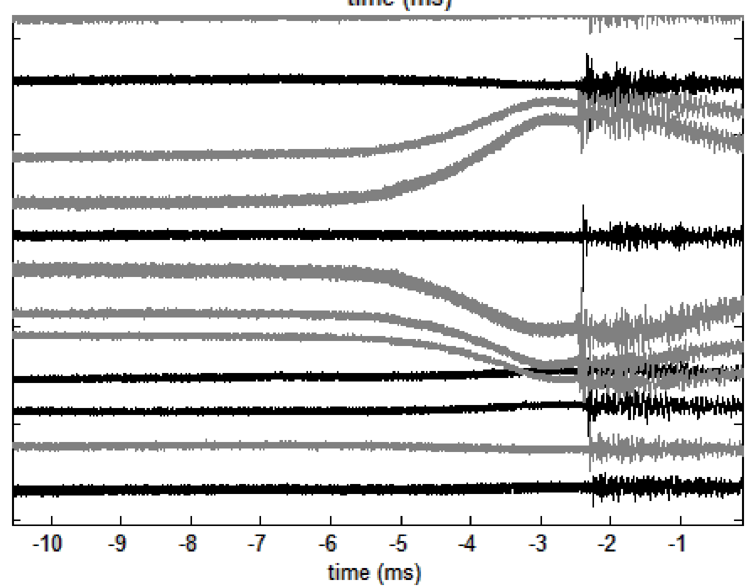
Patch 1 foreshock/stress interactions



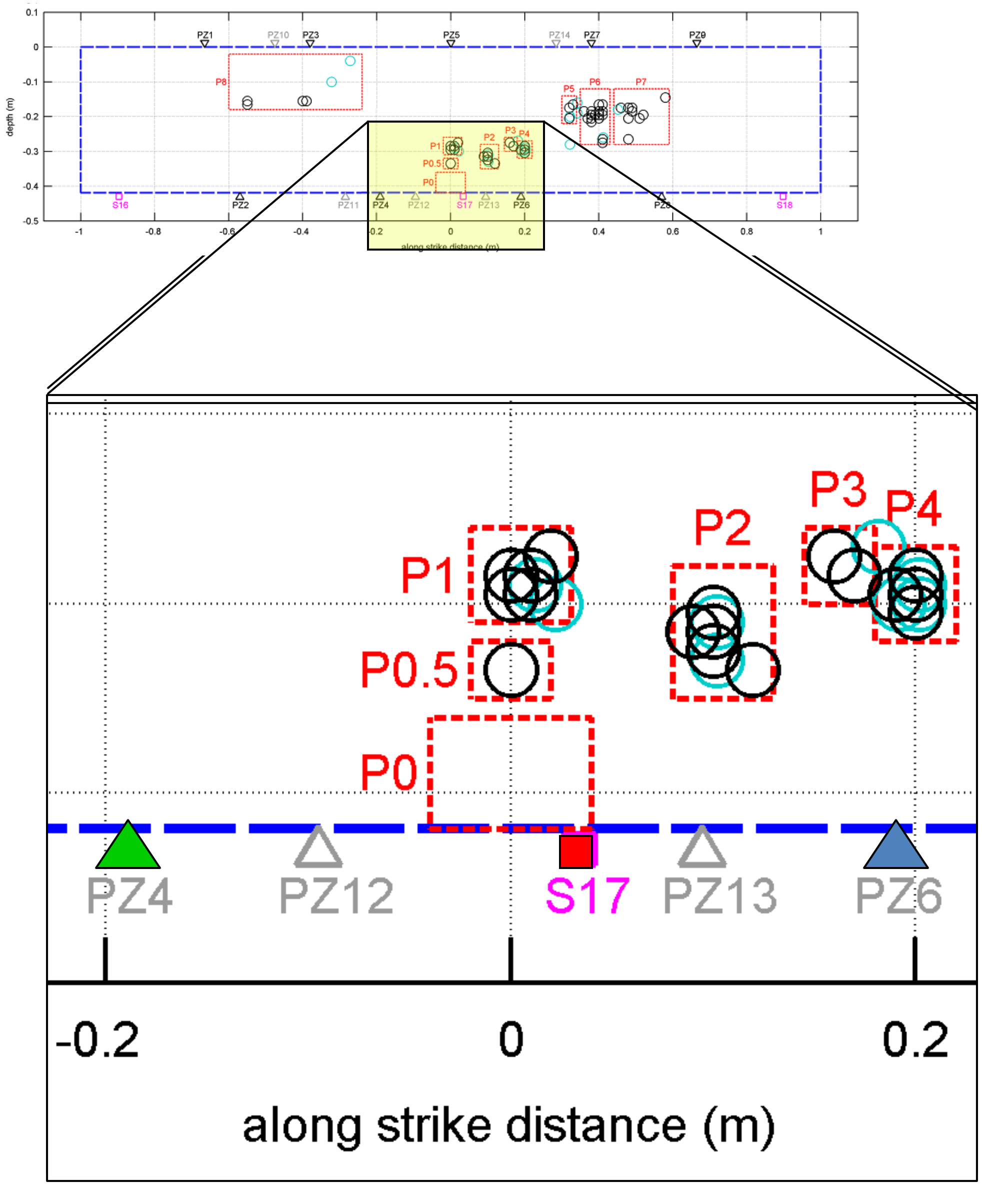
Patch 1 interactions

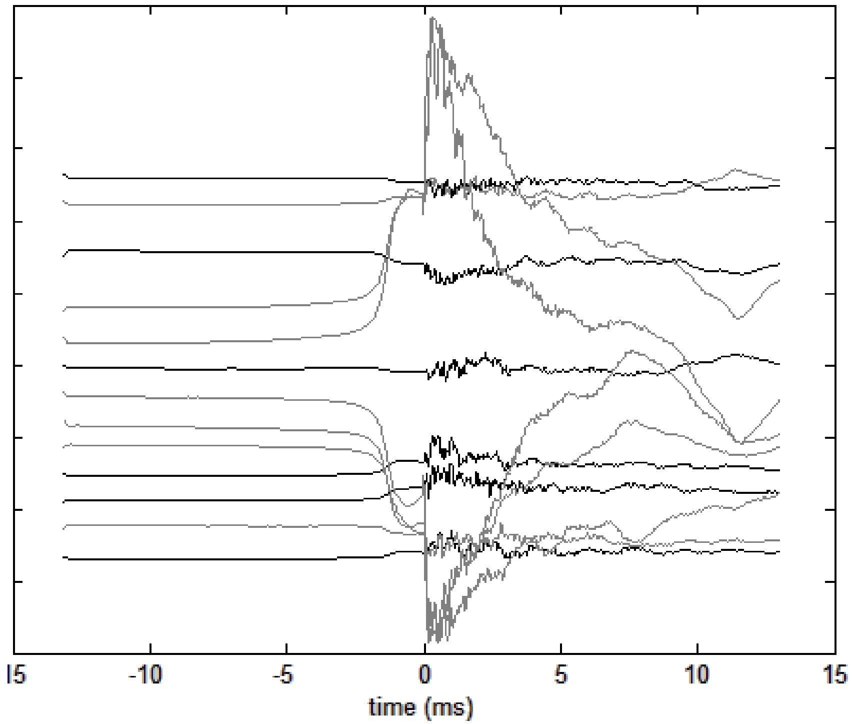


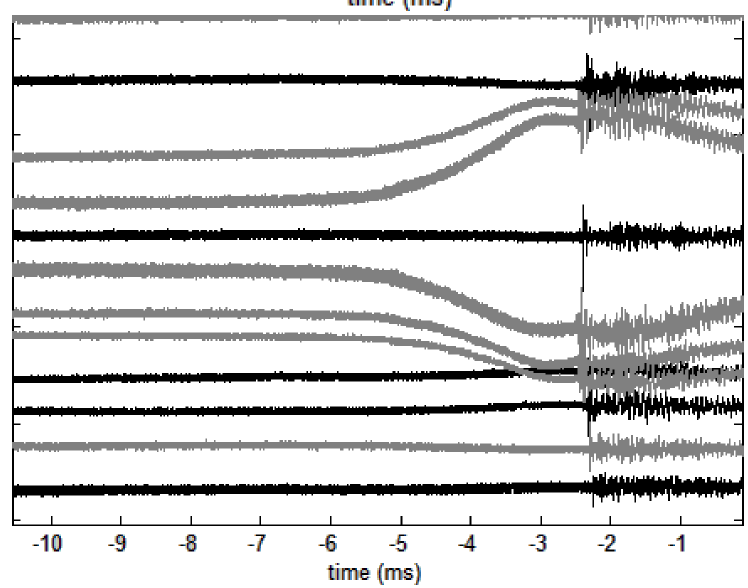


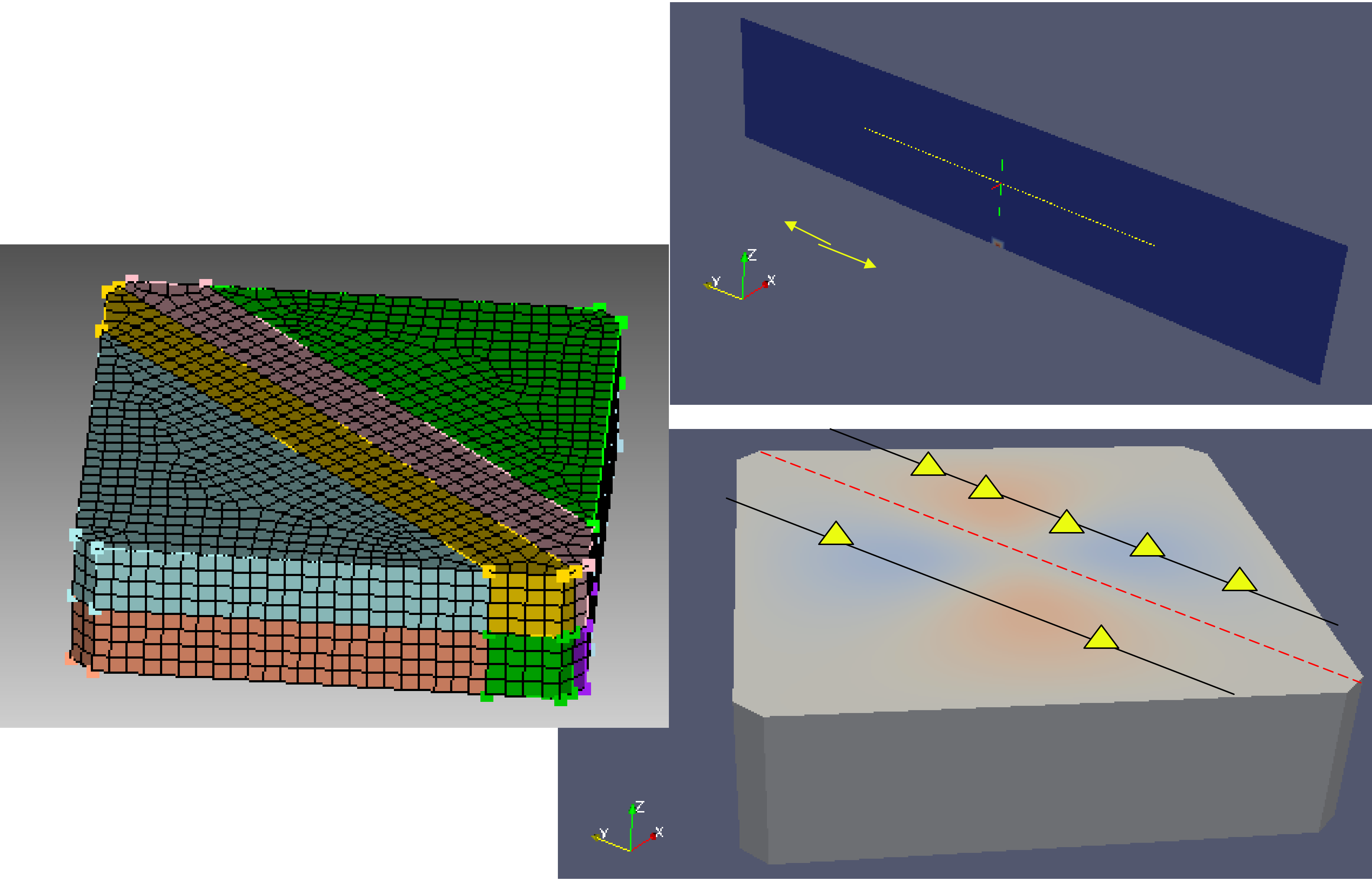


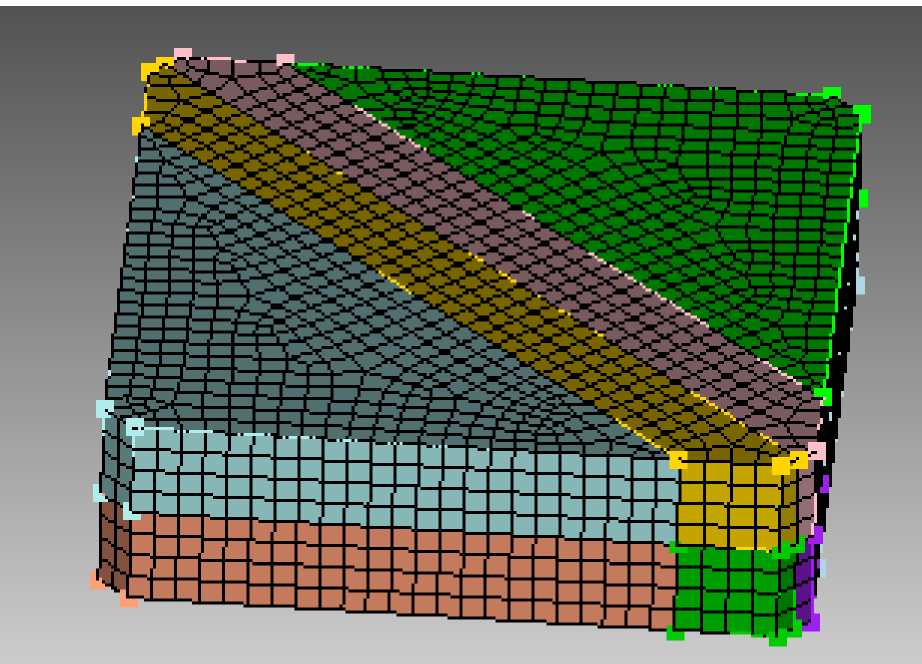
Patch 1 interactions

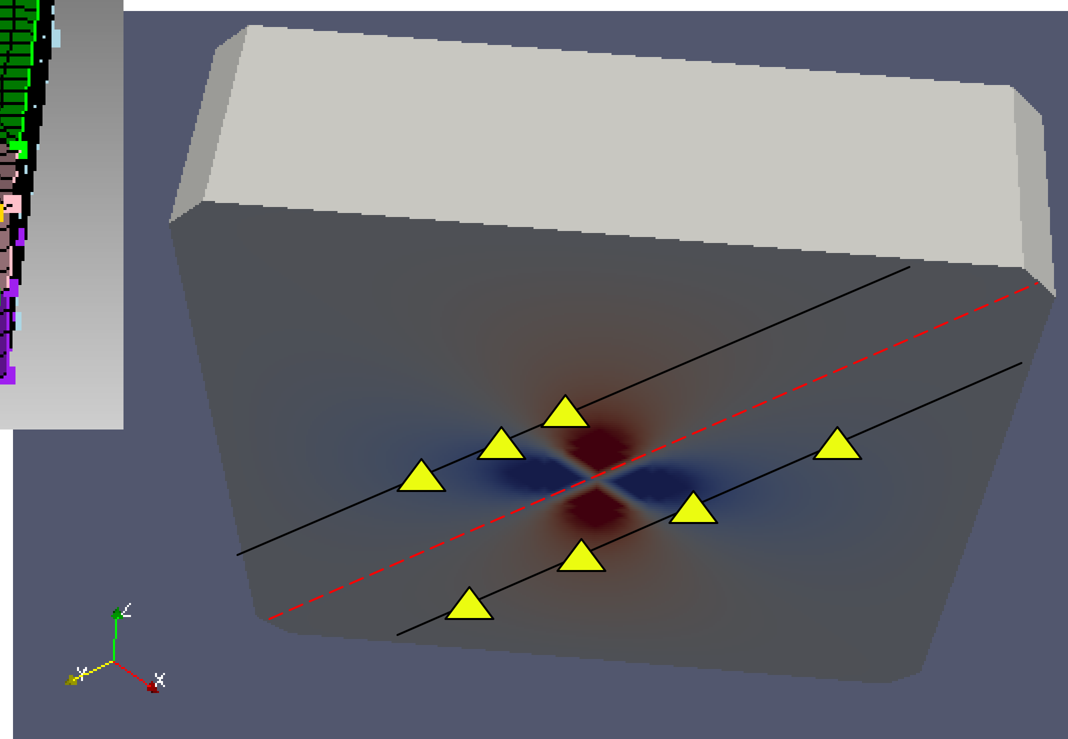


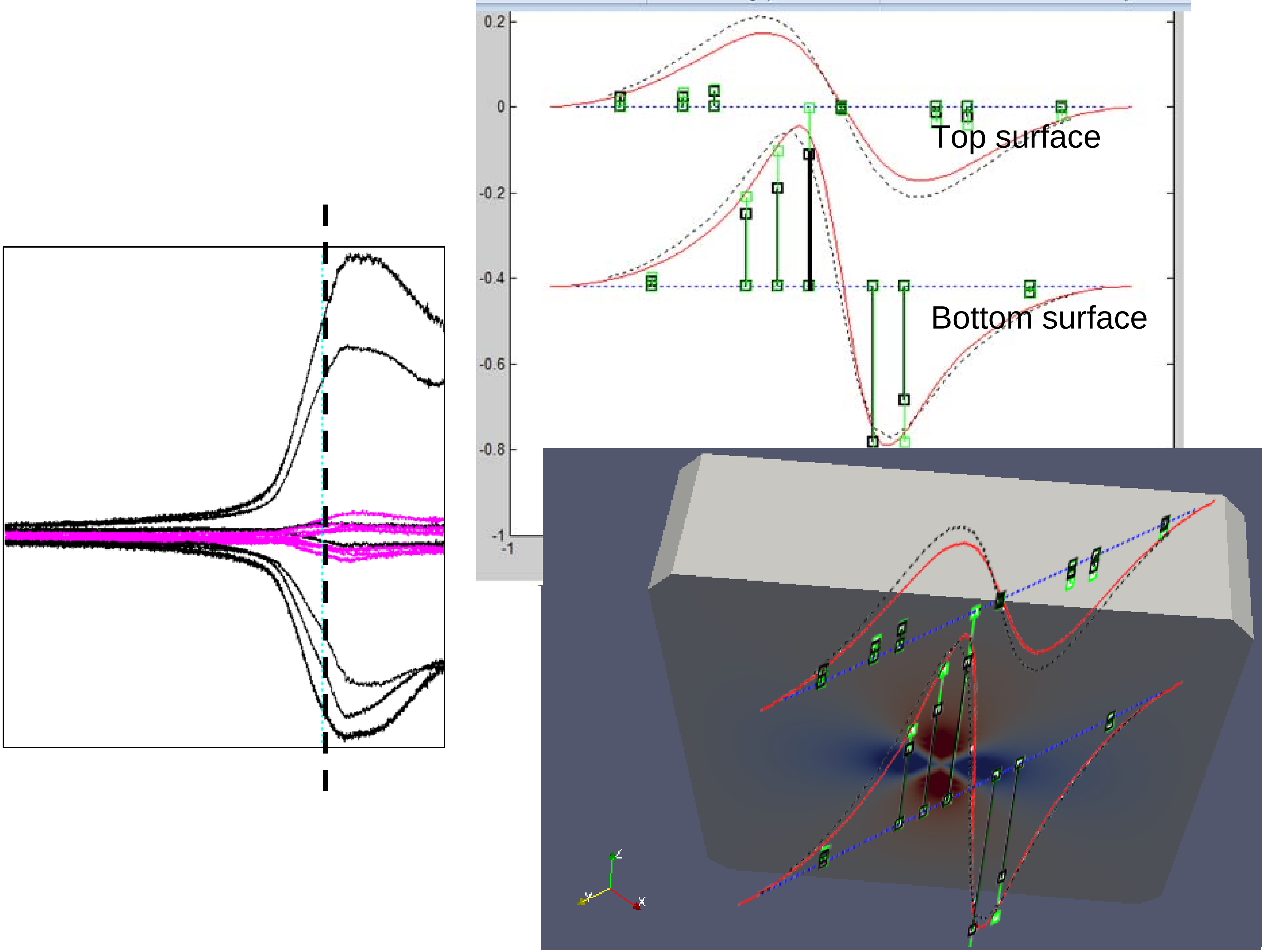




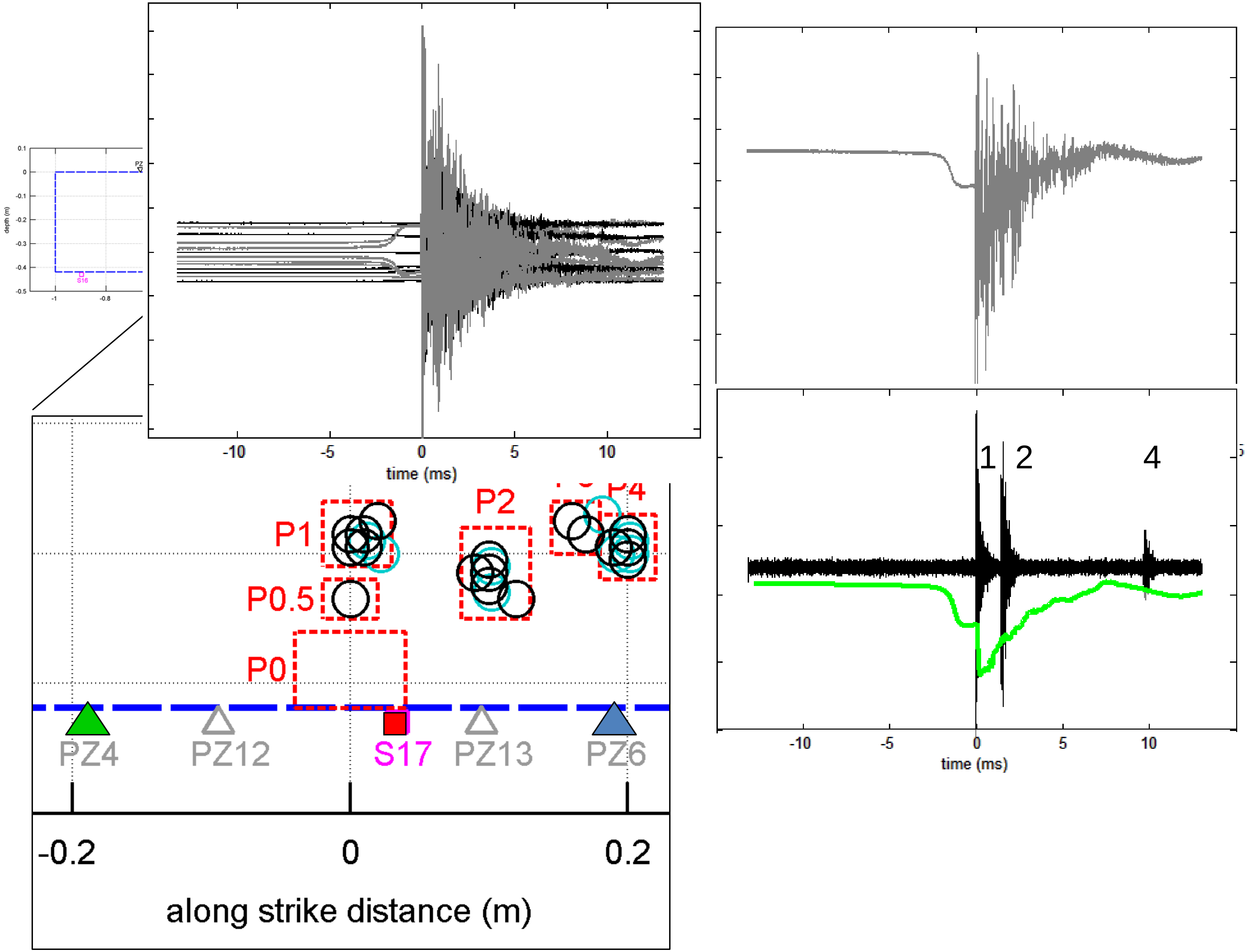

Z
Y
X
Z
Y
X



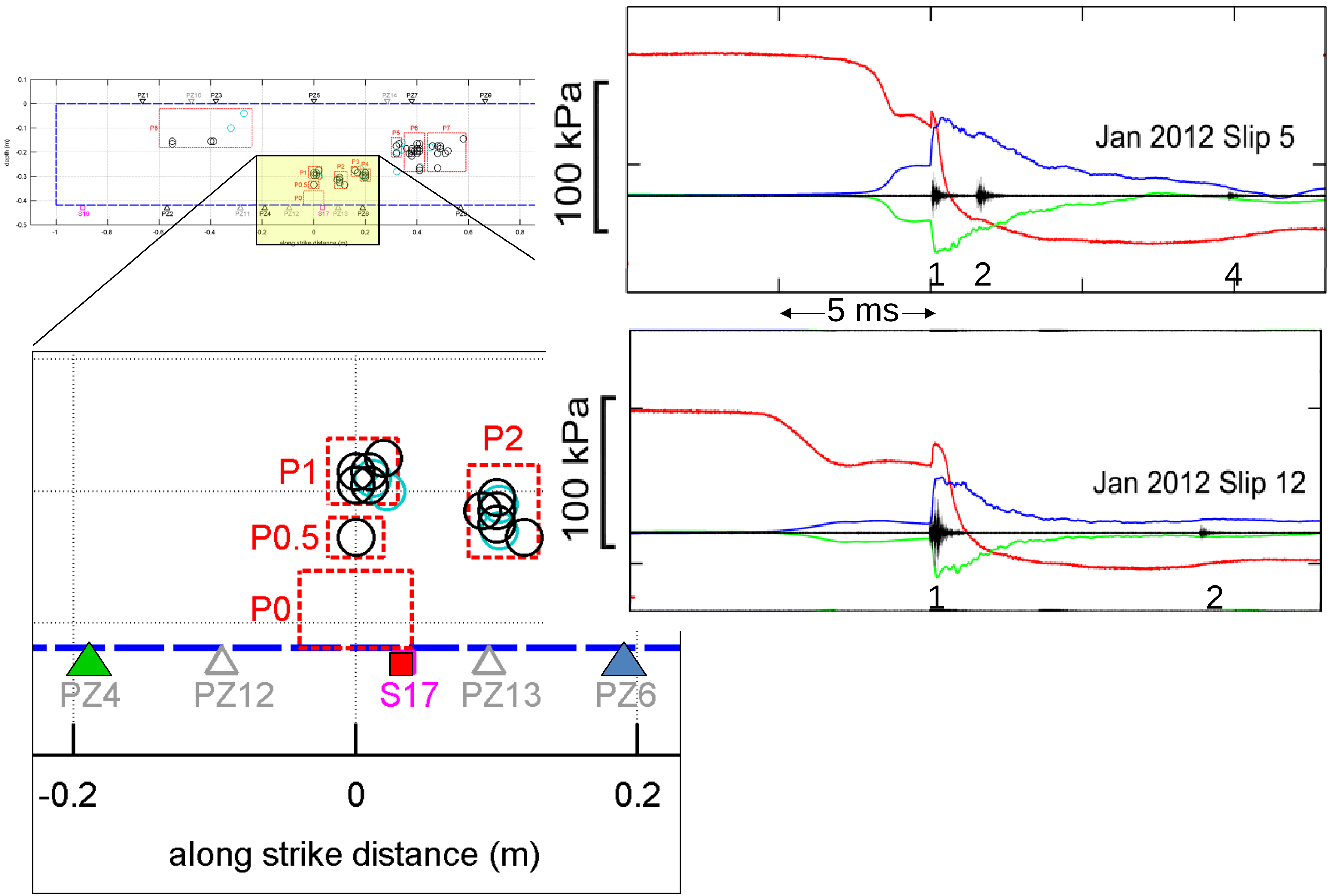




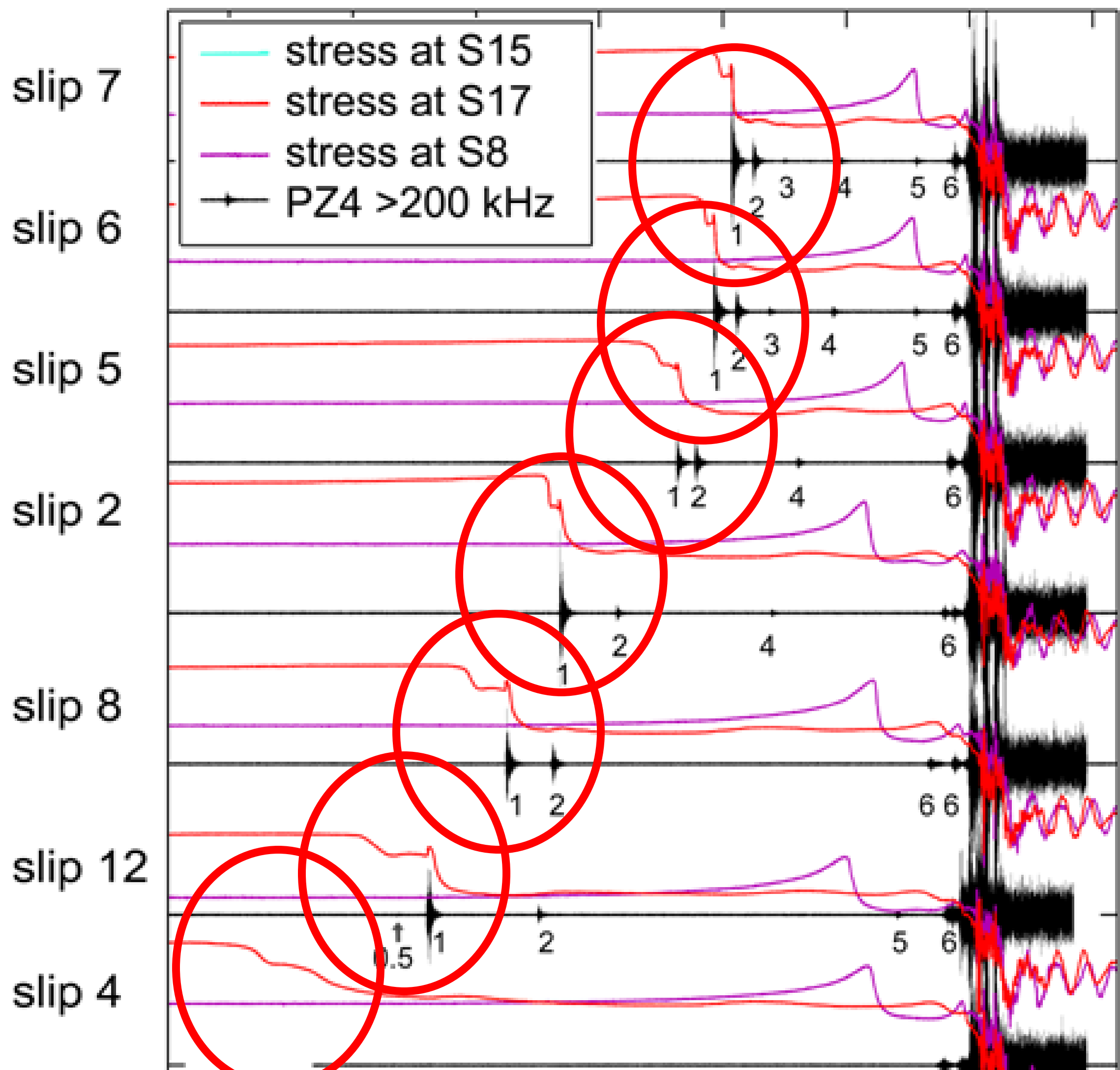
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1
Top surface
Bottom surface



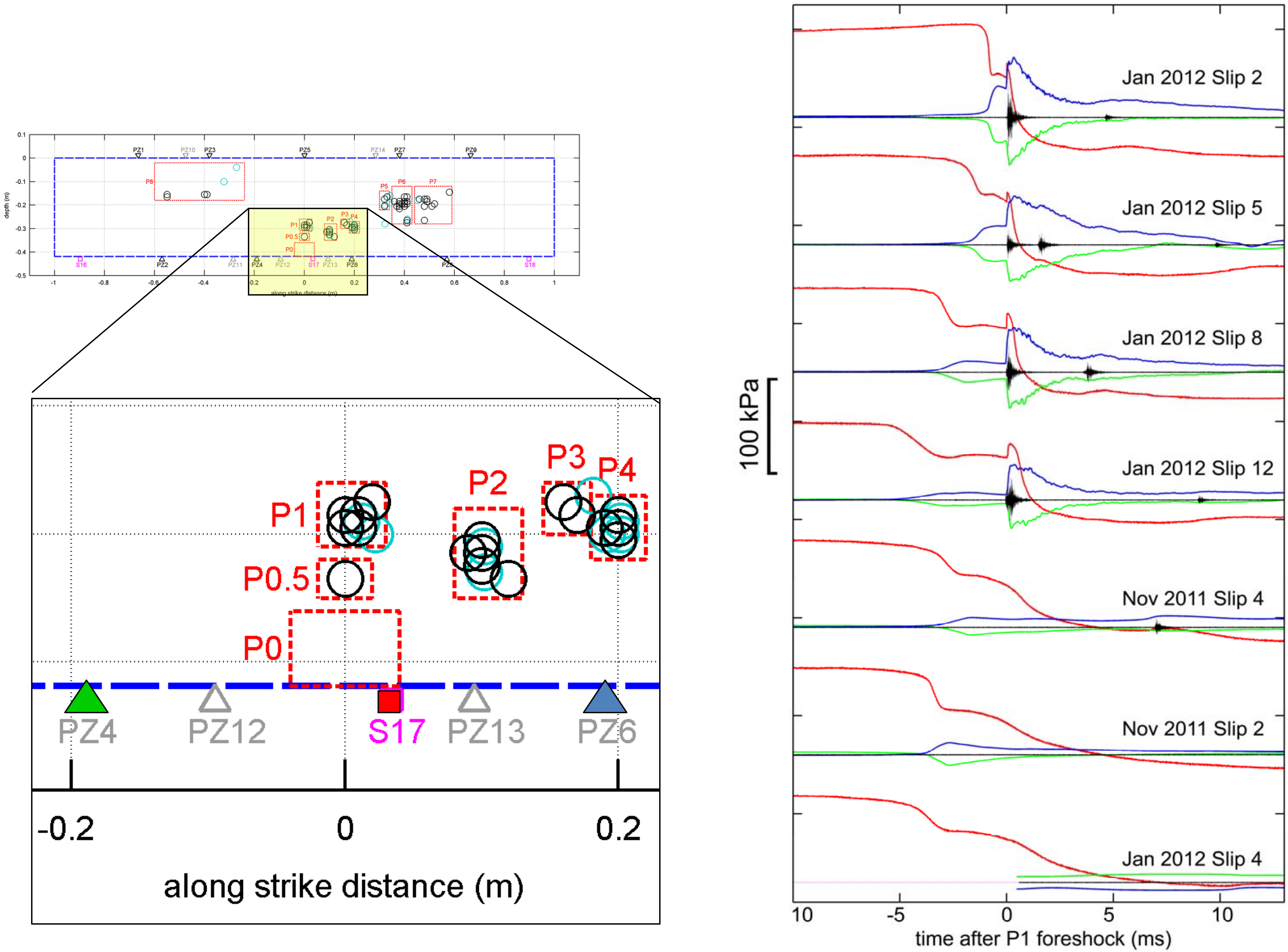
-10
-5
0
5
10
time (ms)
P1
P2
P4
P0.5
P0
PZ4
PZ12
S17
PZ13
PZ6
-0.2
0
0.2
along strike distance (m)
1
2
4
time (ms)



100 kPa
Jan 2012 Slip 5
1
2
4
5 ms
100 kPa
Jan 2012 Slip 12
1
2
P1
P2
P0.5
P0
PZ4
PZ12
S17
PZ13
PZ6
-0.2
0
0.2
along strike distance (m)



slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
slip 4
stress at S15
stress at S17
stress at S8
PZ4 >200 kHz

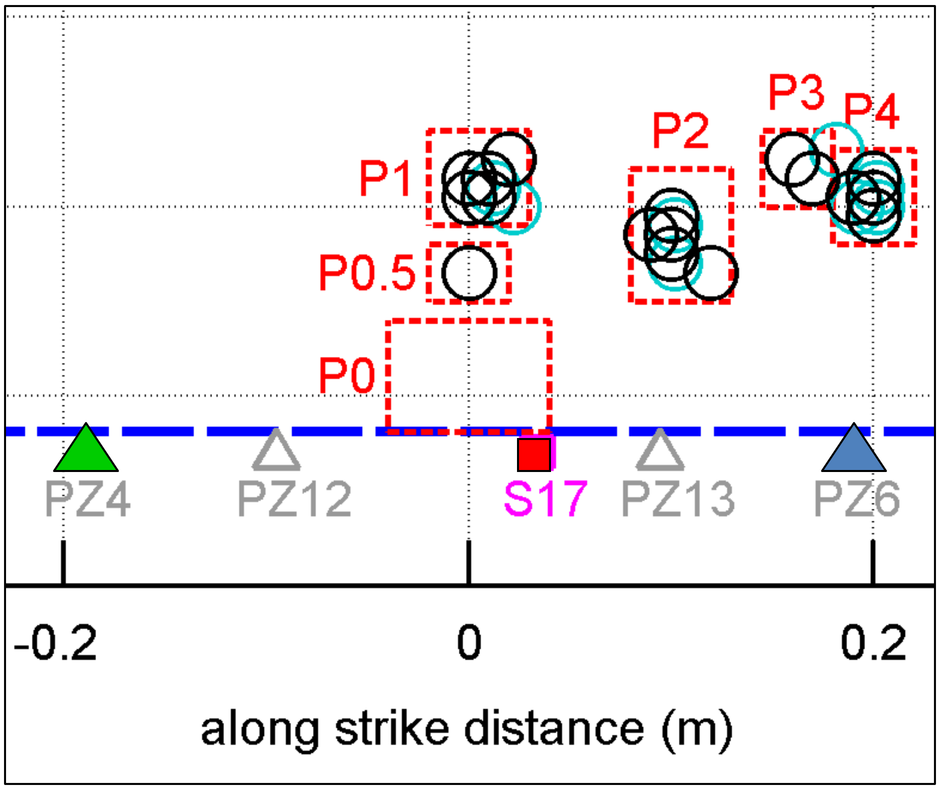

P3
P4
P2
P1
P0.5
P0
PZ4
PZ12
S17
PZ13
PZ6
-0.2
0
0.2
along strike distance (m)
Jan 2012 Slip 2
Jan 2012 Slip 5
Jan 2012 Slip 8
Jan 2012 Slip 12
Nov 2011 Slip 4
Nov 2011 Slip 2
Jan 2012 Slip 4
100 kPa
10
-5
0
5
10
time after P1 foreshock (ms)

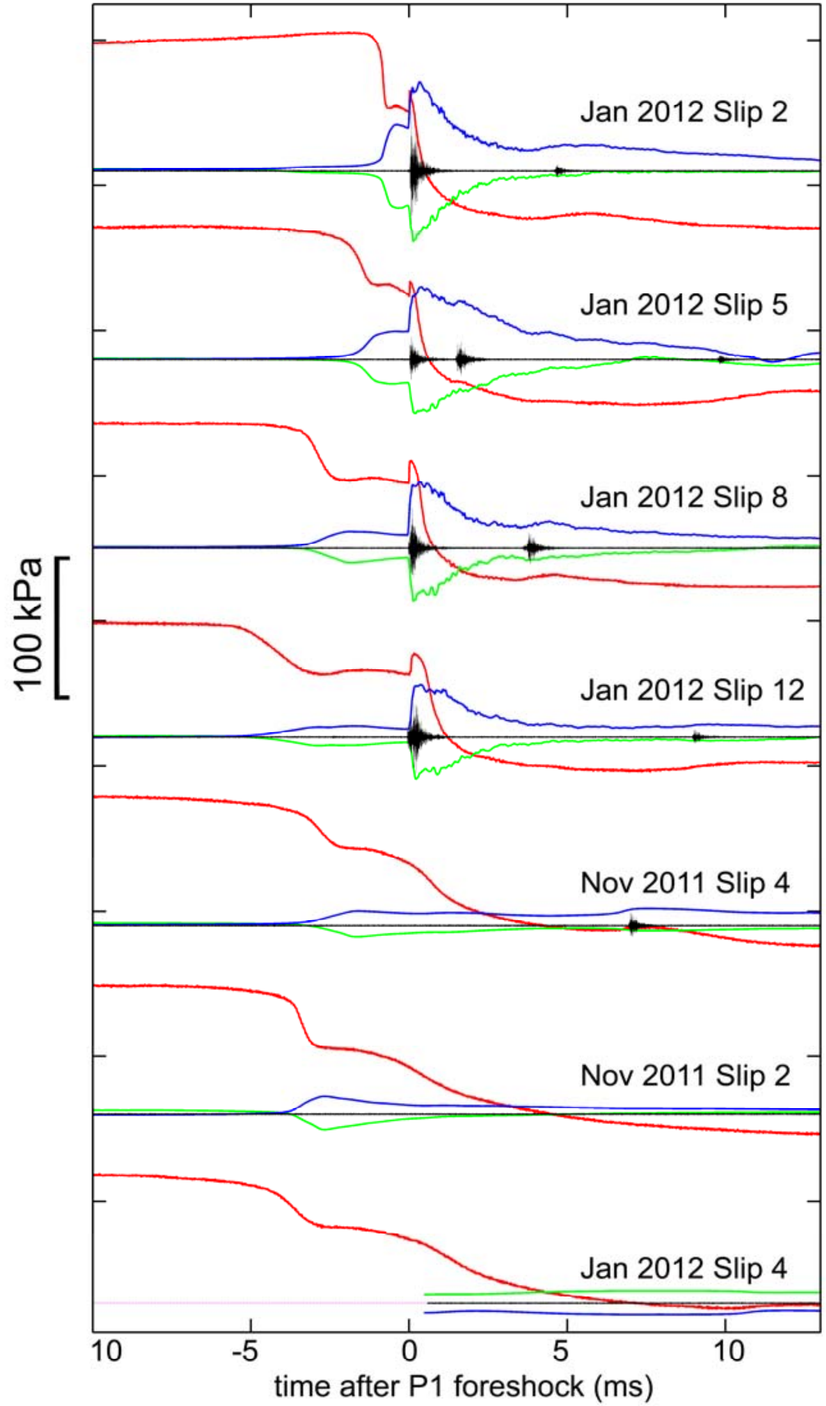
Aseismic slip rapidly loads foreshock patch

Slip transient is slowed or “hung up” by foreshock patch

The foreshock accelerates the aseismic slip transient

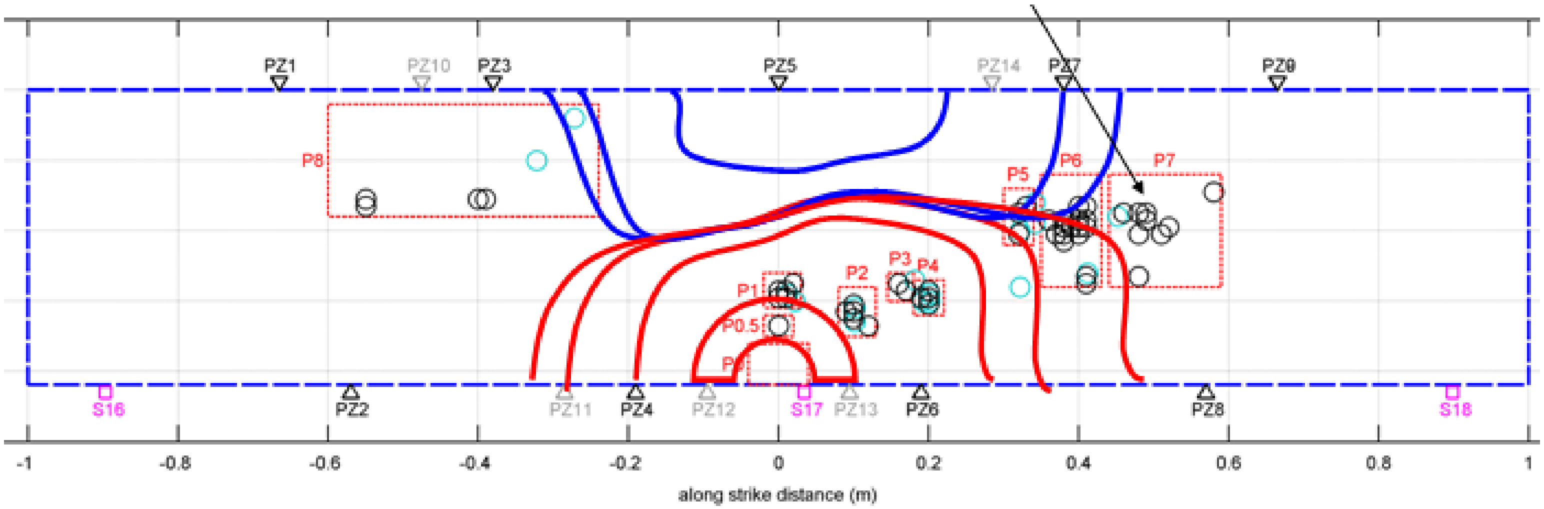
If the foreshock patch is loaded more slowly, it will slip aseismically.





Summary of Observations

- Foreshocks represent local instabilities within a larger, quasi-stable slipping region consistent with nucleation models.
- Much of the fault is aseismic
- Repeating foreshocks means strength heterogeneity is required for foreshocks
- Transition from aseismic to seismic is very abrupt



Scaling of lab results?

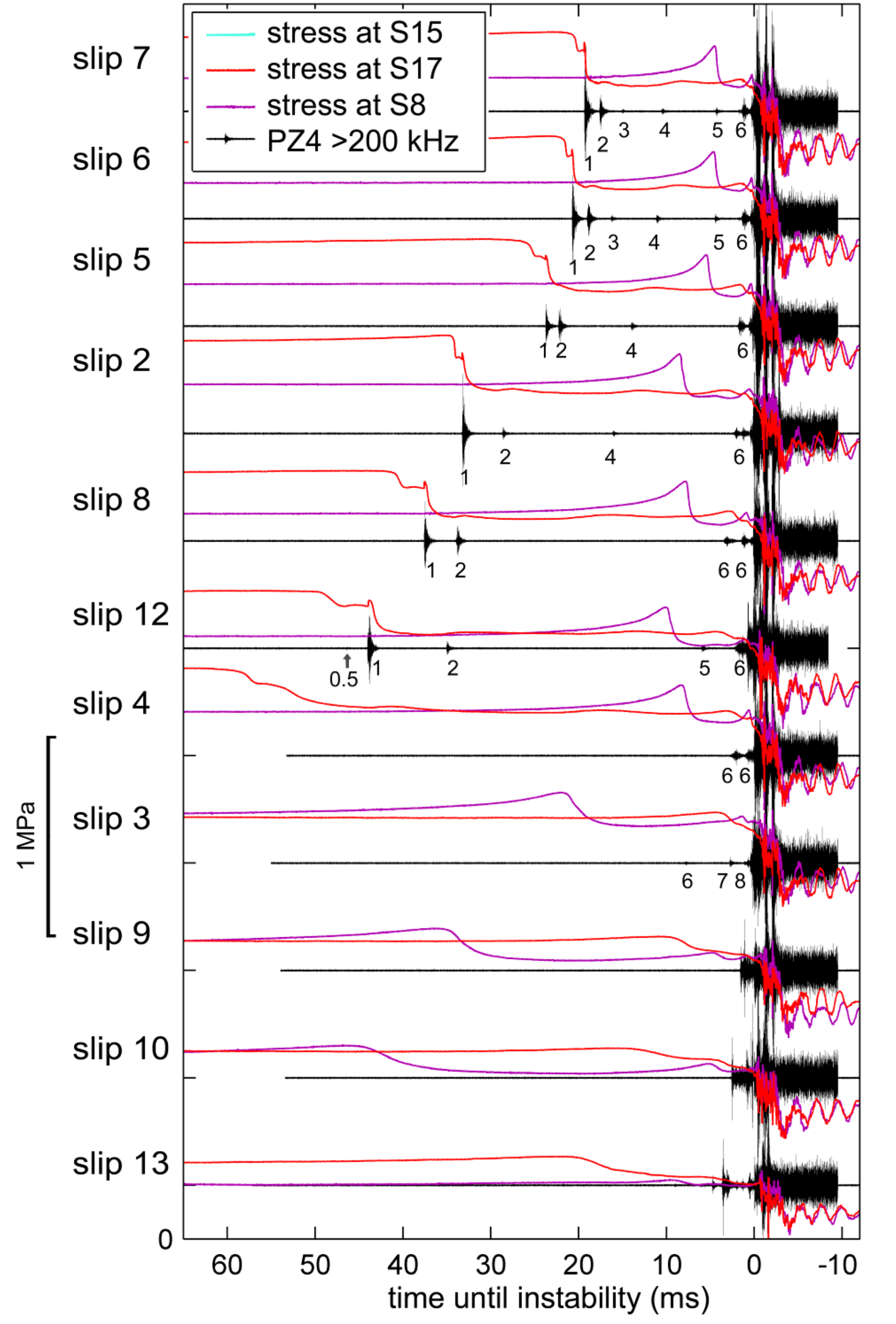
- If we assume no scaling at all…
  - A sequence of M_w -4 to -6 foreshocks 20 ms prior to a M_w ~0 event.
- Lab versus Field:
  - Same --- elastic moduli, density, wave velocity
  - Different ---mineralogy, temp, pressure, fluids?, roughness
- Scaling of D_c?

Scaling of D_c?

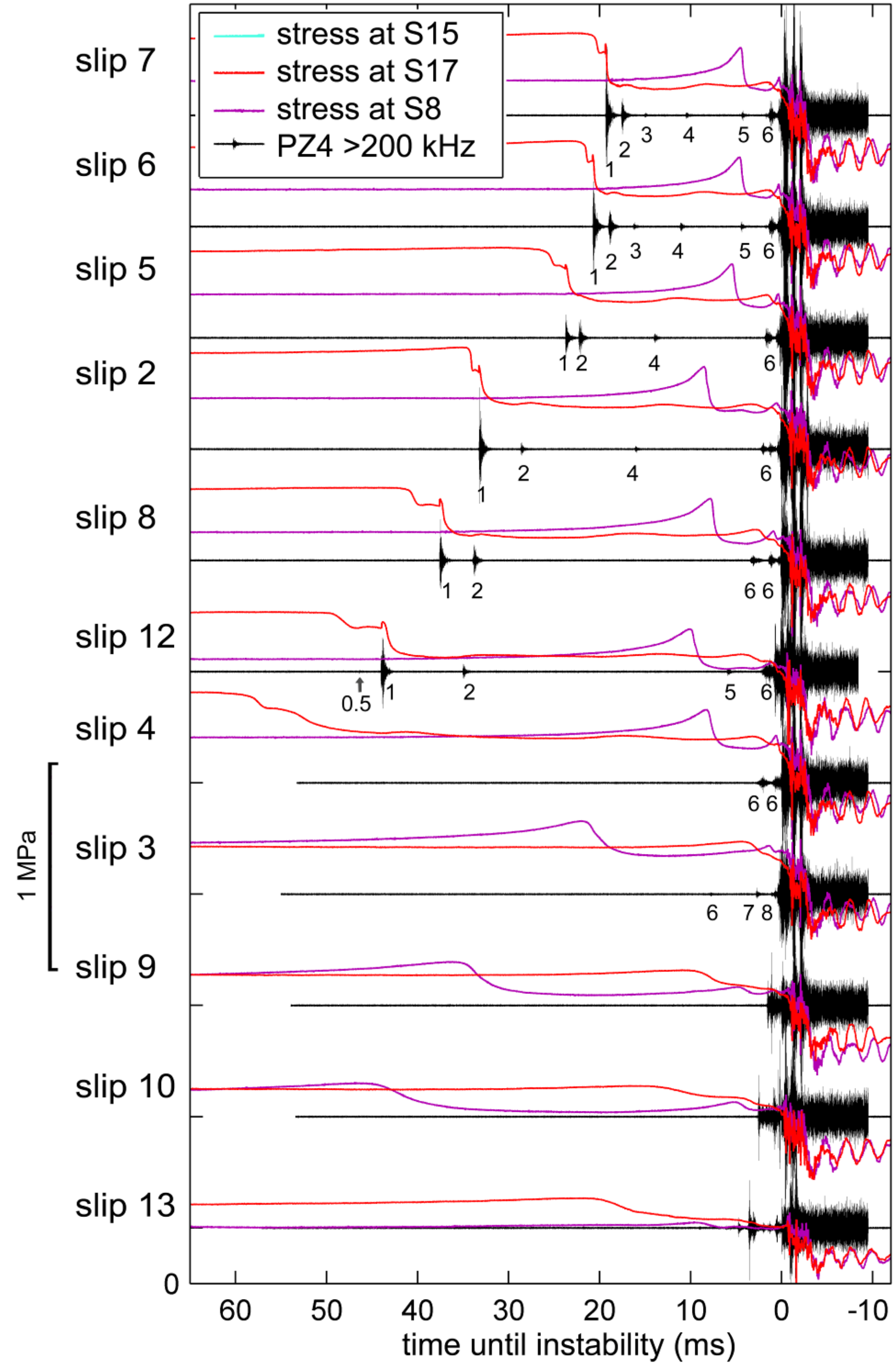
- Natural faults may be rougher and have a thicker layer of fault gouge
  - Dc (~μm lab, mm field?)
- Nucleation zone size, slip, and duration increases with Dc.

Foreshock Models

- ETAS versus "Preslip" foreshock model?
  - Foreshocks are certainly driven by underlying aseismic slip
  - Foreshocks also acellerate the aseismic slip, and therefore indirectly trigger more foreshocks



Thanks!



stress at S15
stress at S17
stress at S8
PZ4 >200 kHz
slip 7
slip 6
slip 5
slip 2
slip 8
slip 12
slip 4
slip 3
slip 9
slip 10
slip 13
1 MPa
0
60
50
40
30
20
10
0
-10
time until instability (ms)

- What causes the variation in nucleation rates?
  - Initial stress distribution (left by the last event)
  - Healing!