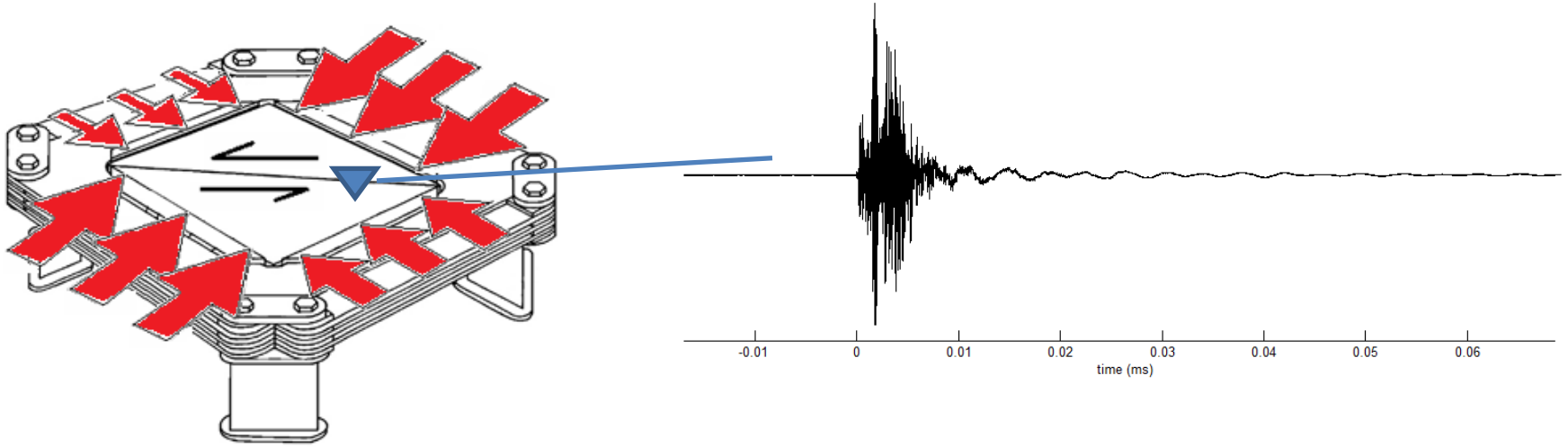
Earthquake nucleation: stressing rate effects, foreshock occurrence, and minimum earthquake size



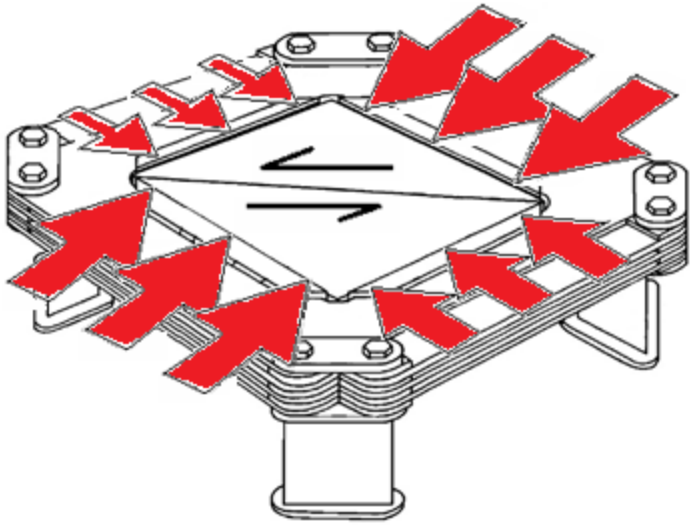
Greg McLaskey

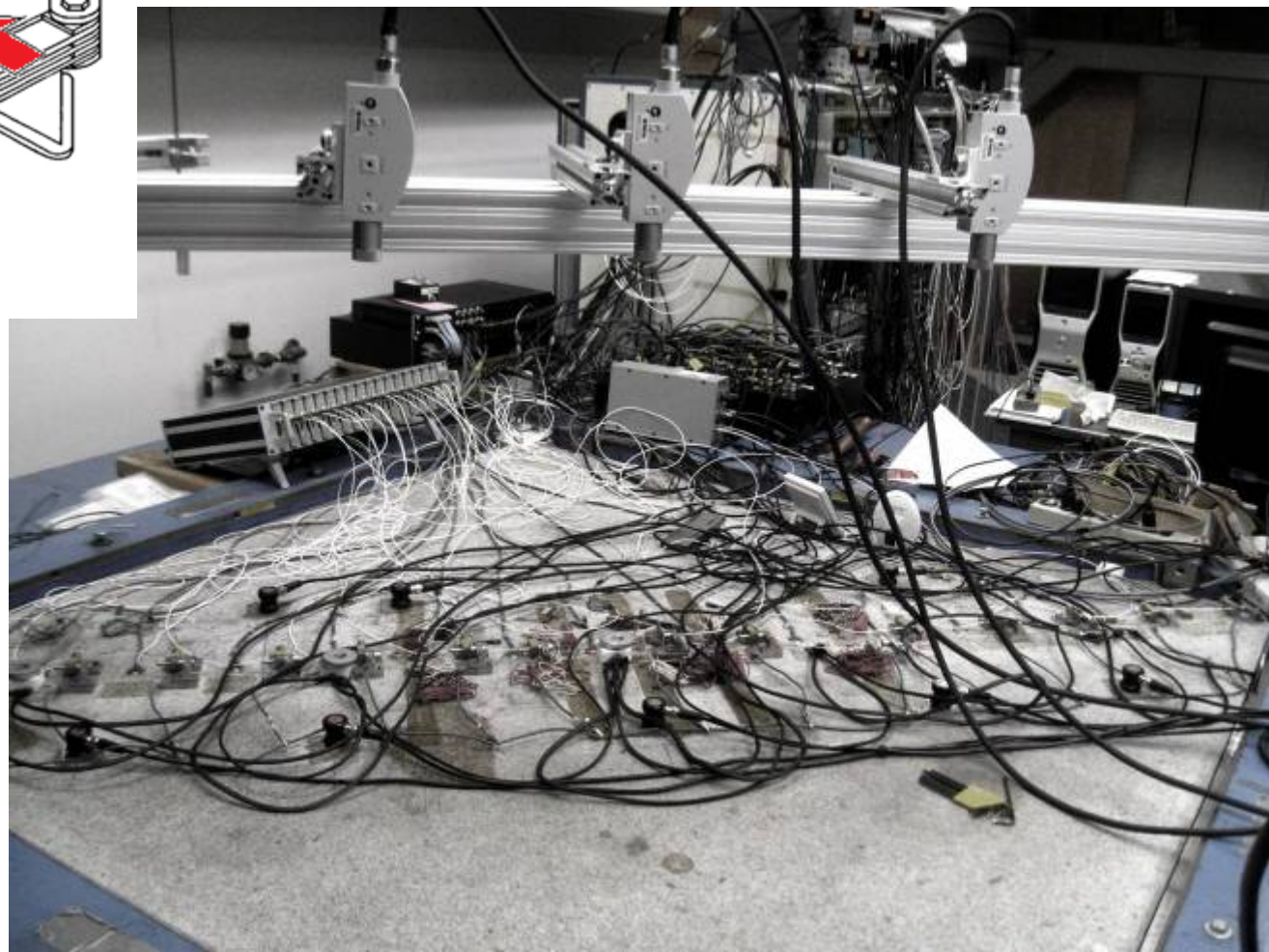
USGS Menlo Park

Oct 5th, 2012

Collaborators: Brian Kilgore, Dave Lockner, Nick Beeler

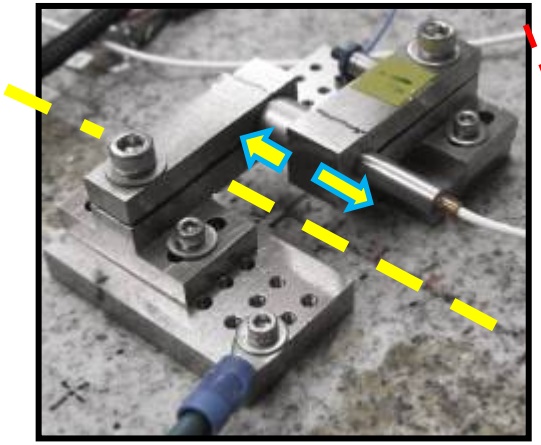
2 meter biaxial press





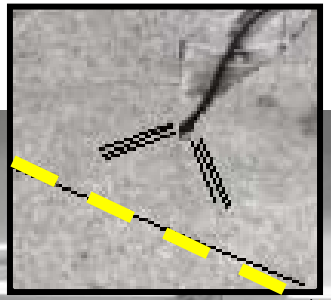
2 meter biaxial press: instrumentation

Capacitive slip sensor
(measures fault slip)

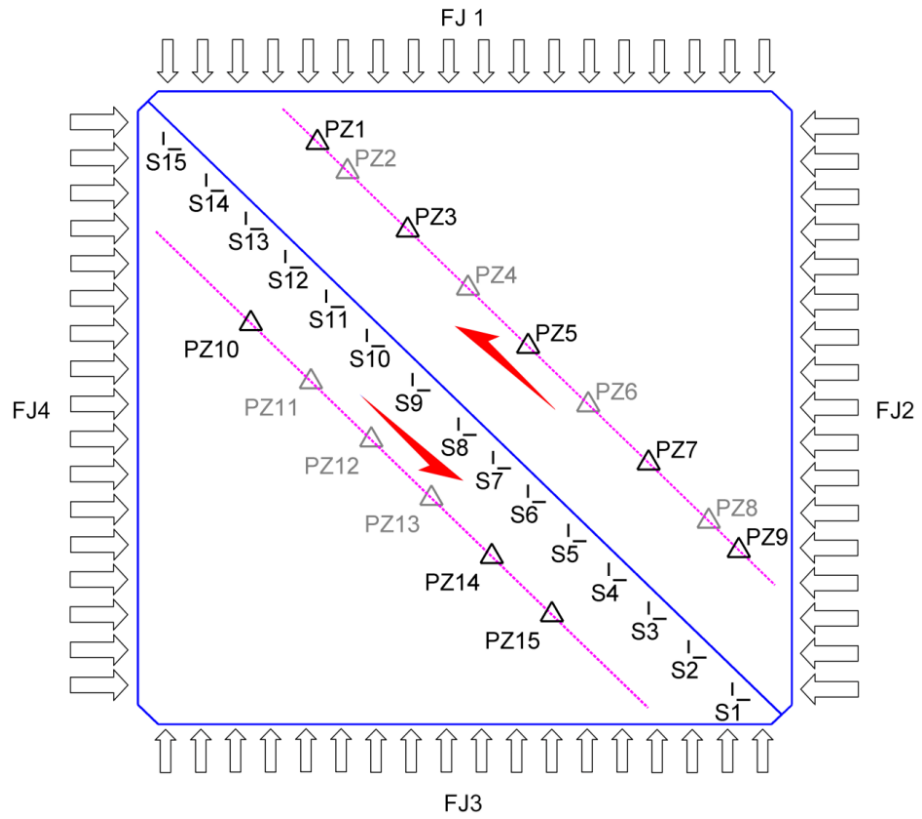


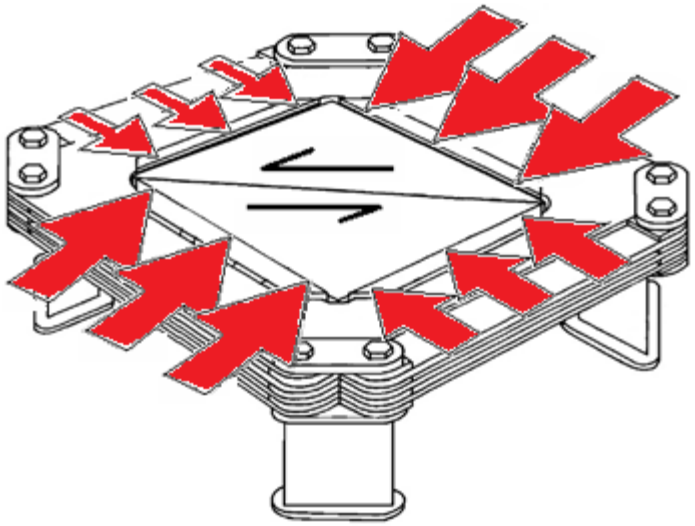
Piezoelectric sensor
(detects surface normal motion)

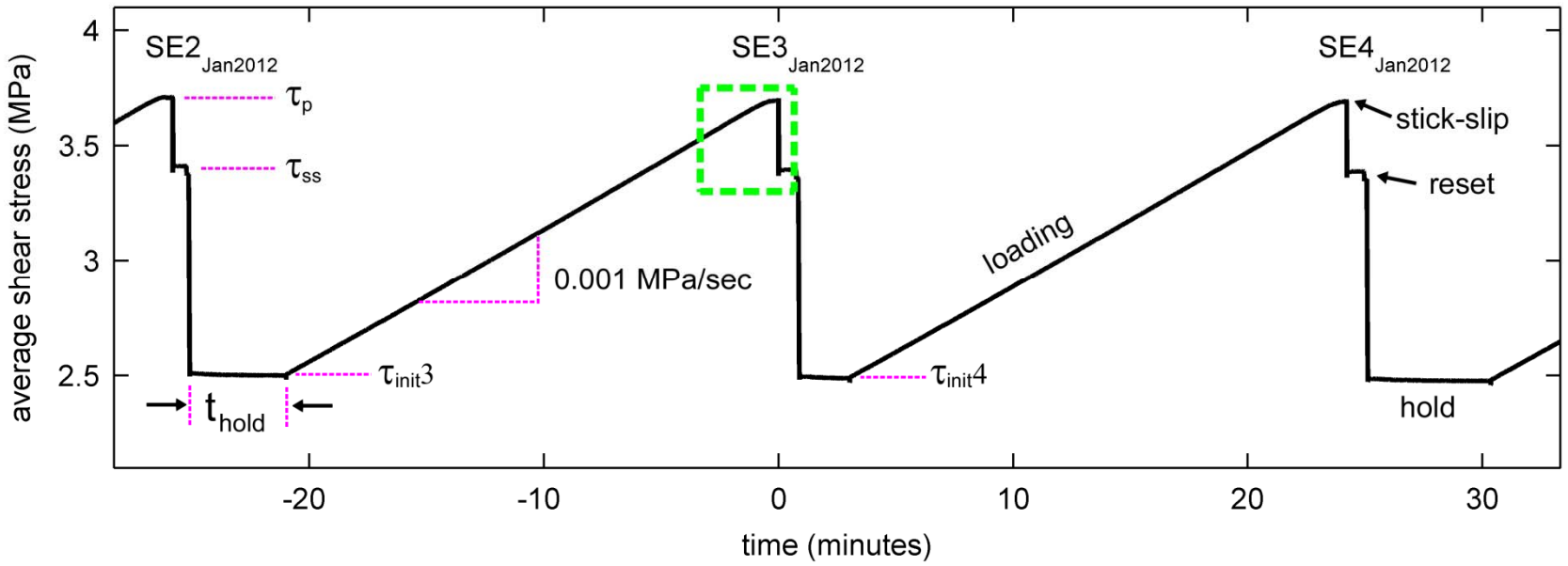
Strain gage pair
(local shear stress)



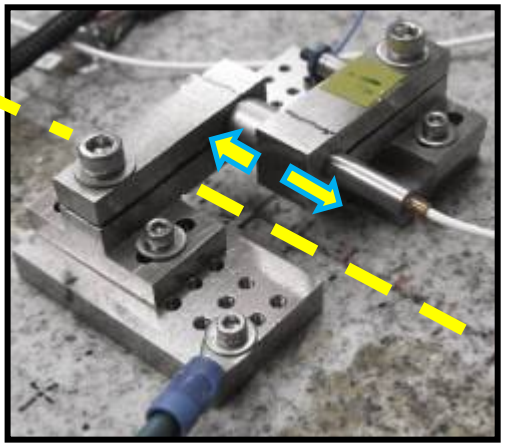
Laser vibrometer
(measures surface normal velocity)
used for calibration and verification

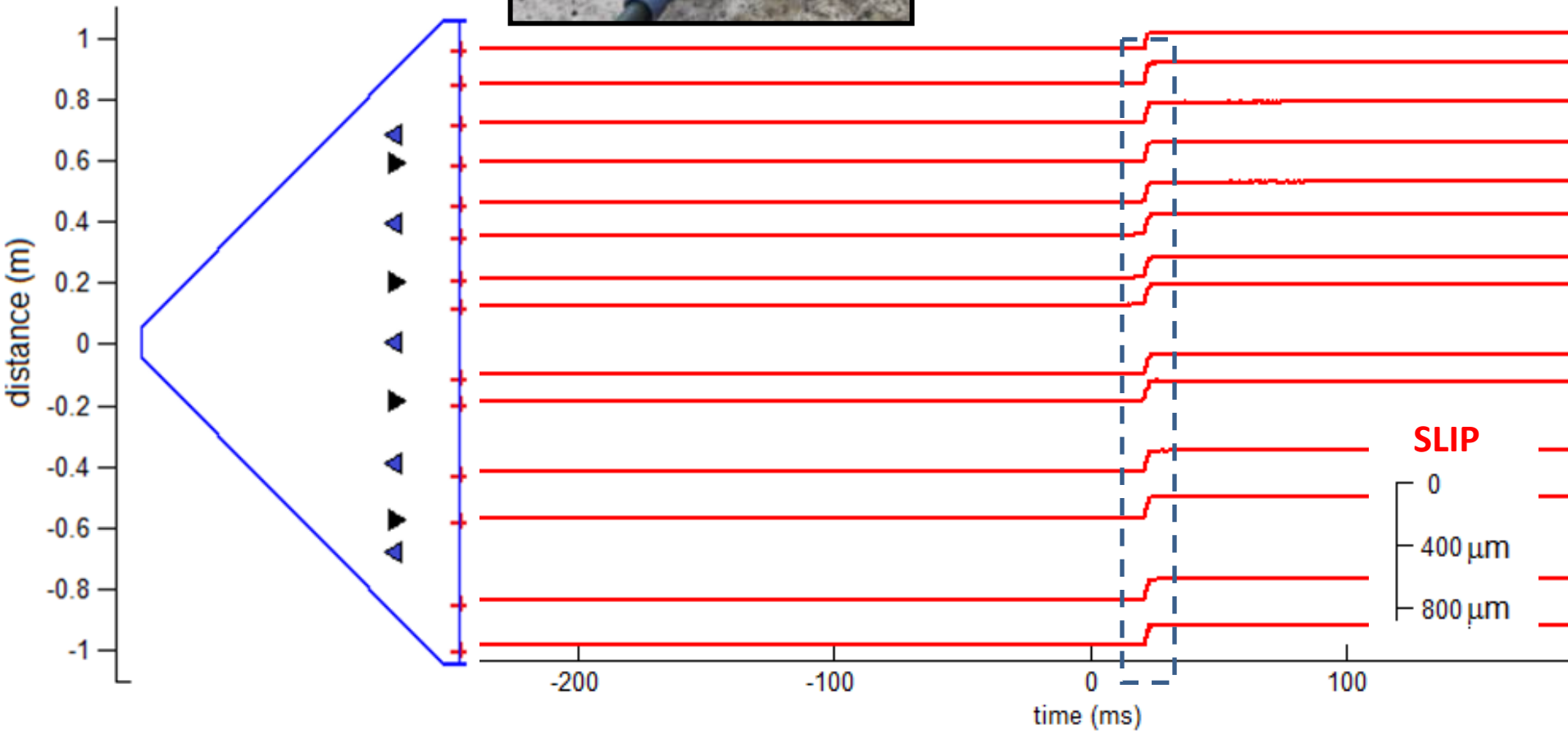

FJ 1
FJ2
FJ3
FJ4
PZ1
PZ2
PZ3
PZ4
PZ5
PZ6
PZ7
PZ8
PZ9
PZ10
PZ11
PZ12
PZ13
PZ14
PZ15
S15
S14
S13
S12
S11
S10
S9
S8
S7
S6
S5
S4
S3
S2
S1




SE2 Jan2012
SE3 Jan2012
SE4 Jan2012
τp
τss
τinit3
τinit4
thold
0.001 MPa/sec
loading
stick-slip
reset
hold
average shear stress (MPa)
time (minutes)
4
3.5
3
2.5
-20
-10
0
10
20
30

Capacitive slip sensor
(measures fault slip)





Capacitive slip sensor
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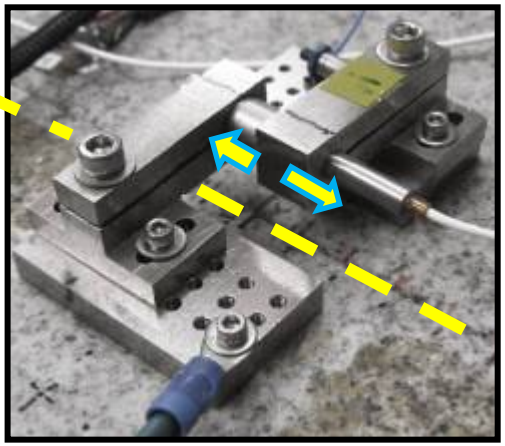
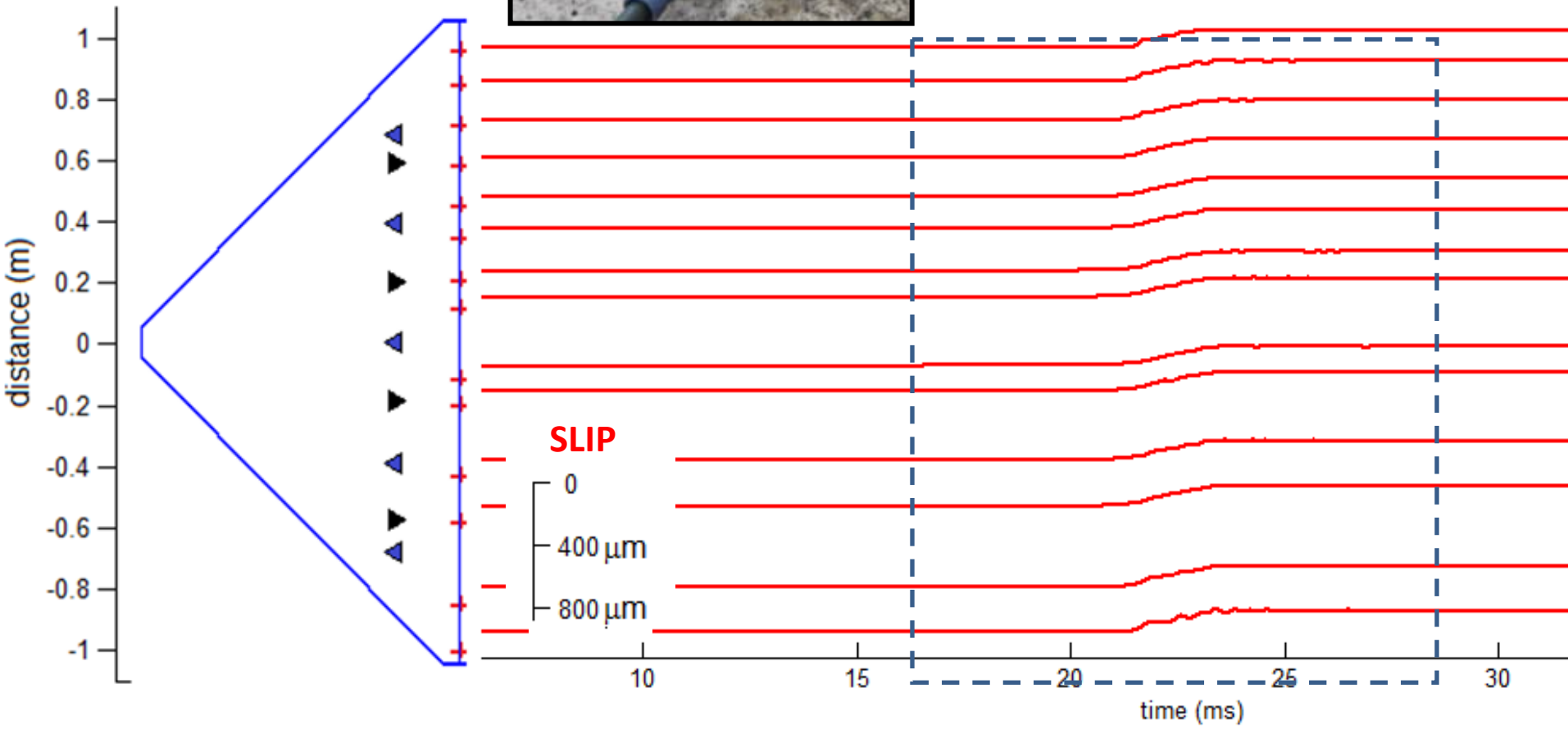
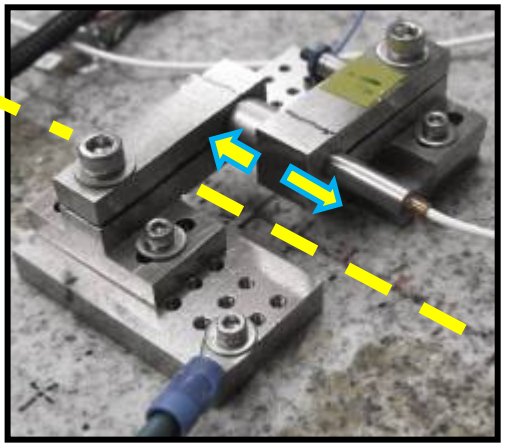
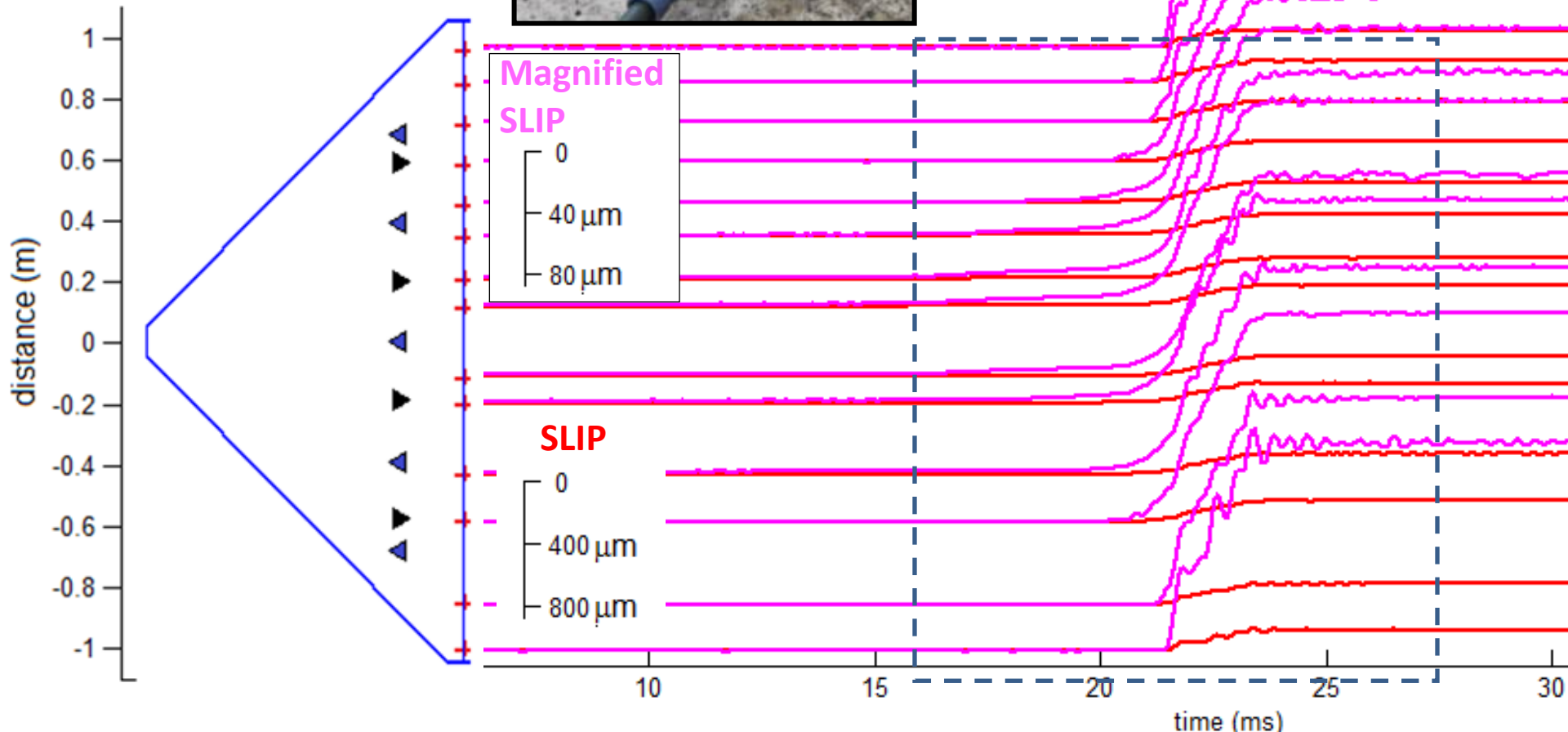




Capacitive slip sensor
(measures fault slip)





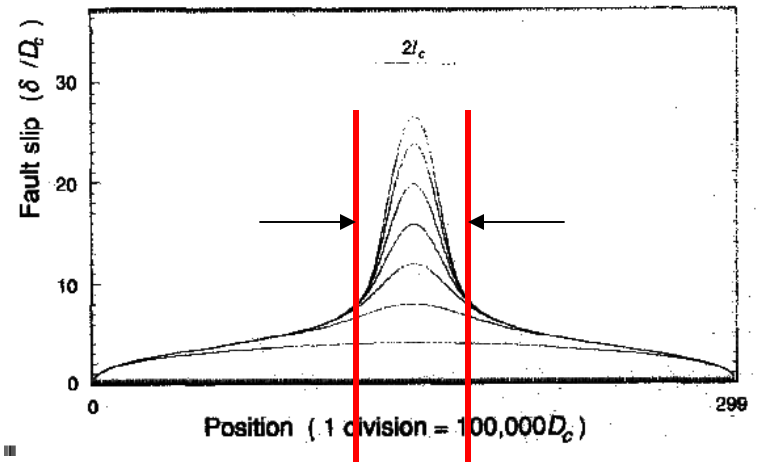
Earthquake nucleation models

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

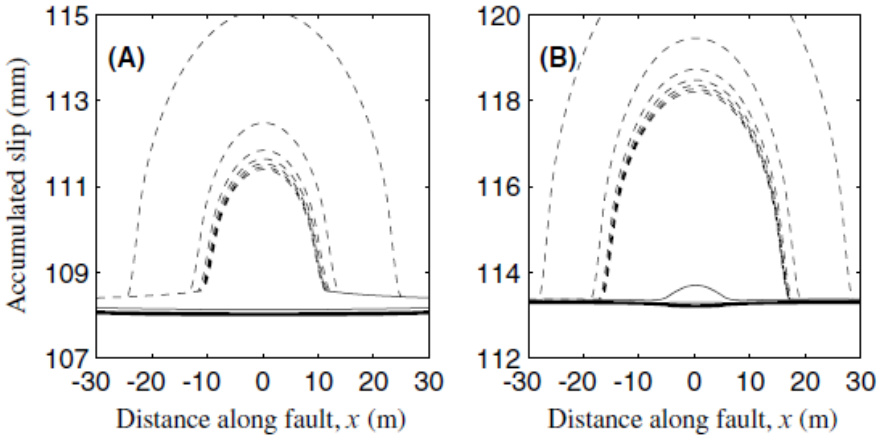
This nucleation zone is ~ 1m – 10m – 100m ? depending on parameters

$$h^* = \frac{\mu \eta D_c}{\sigma_n (b-a)}$$

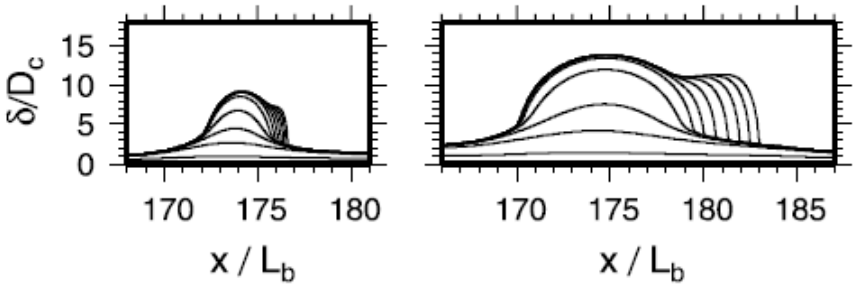
Dieterich 1992



Kaneko and Lapusta 2008



Ampuero and Rubin 2008



Earthquake nucleation models

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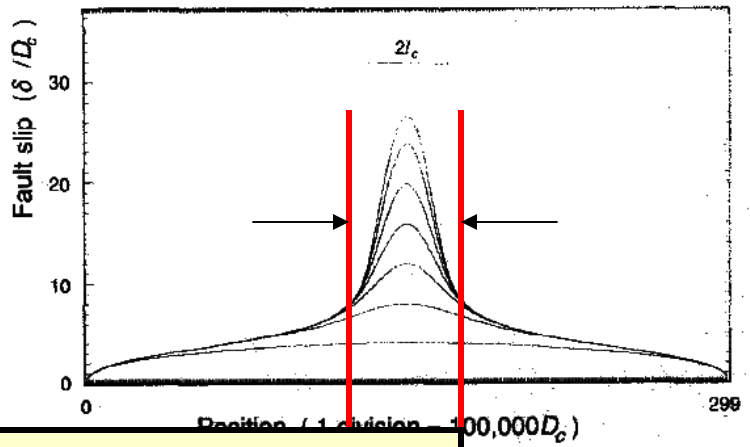
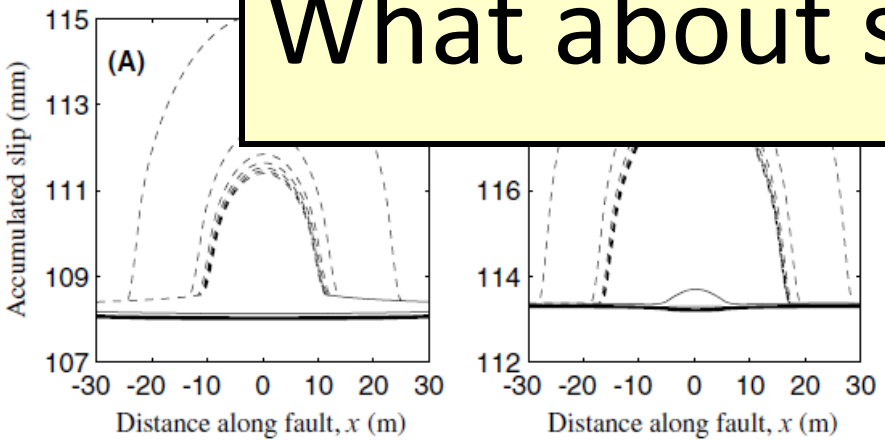
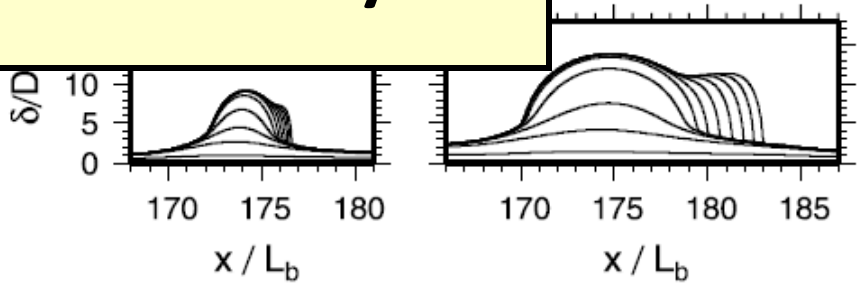


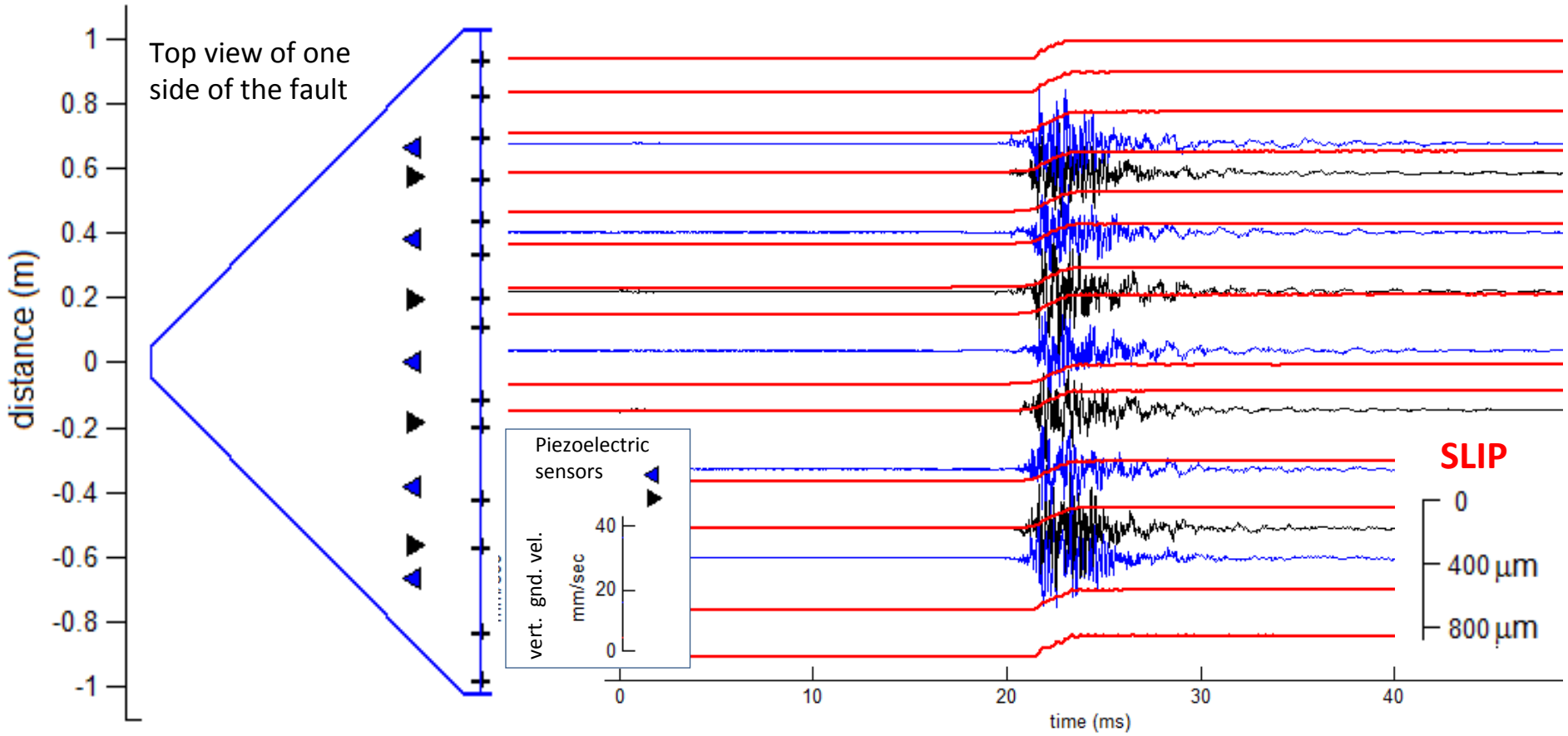
Kar

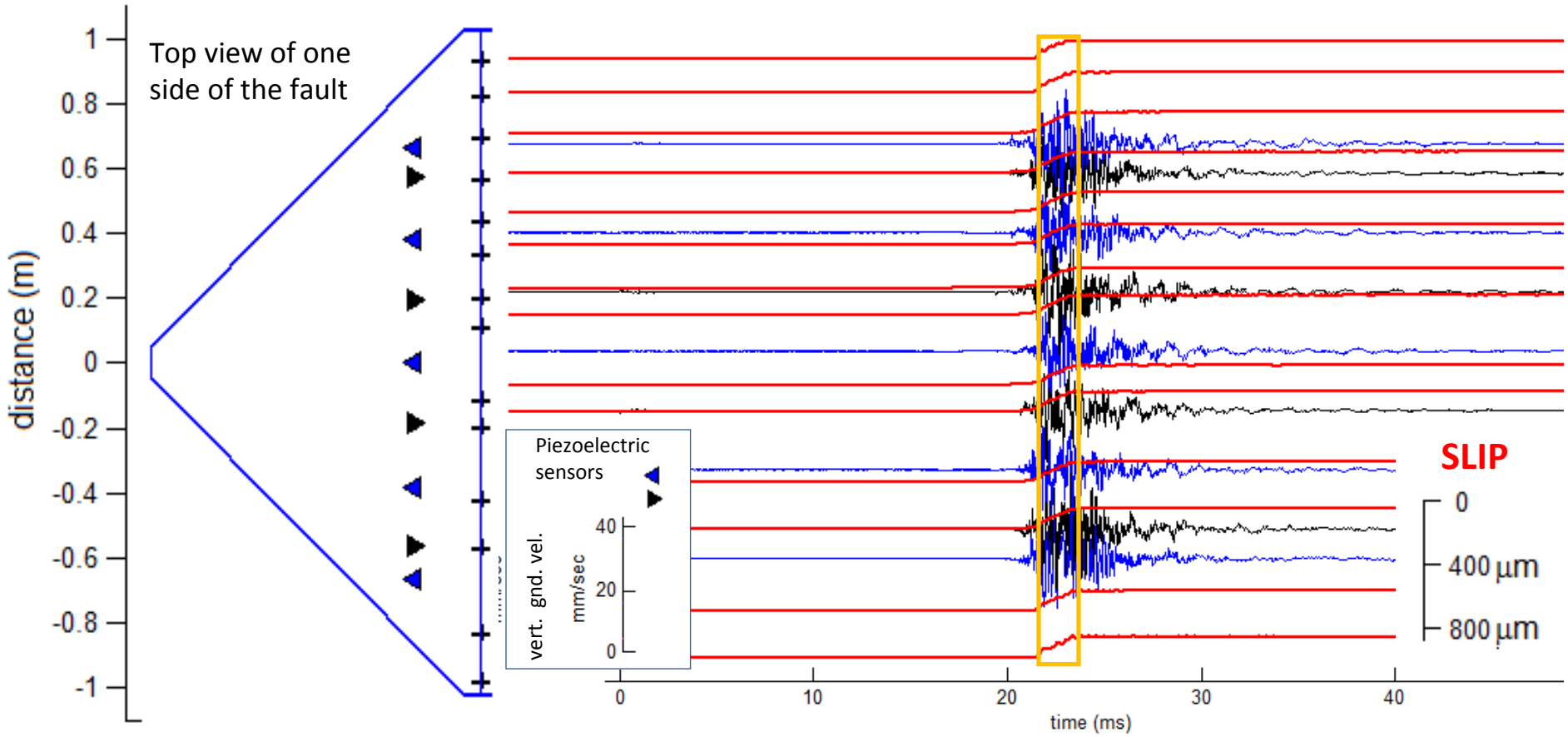


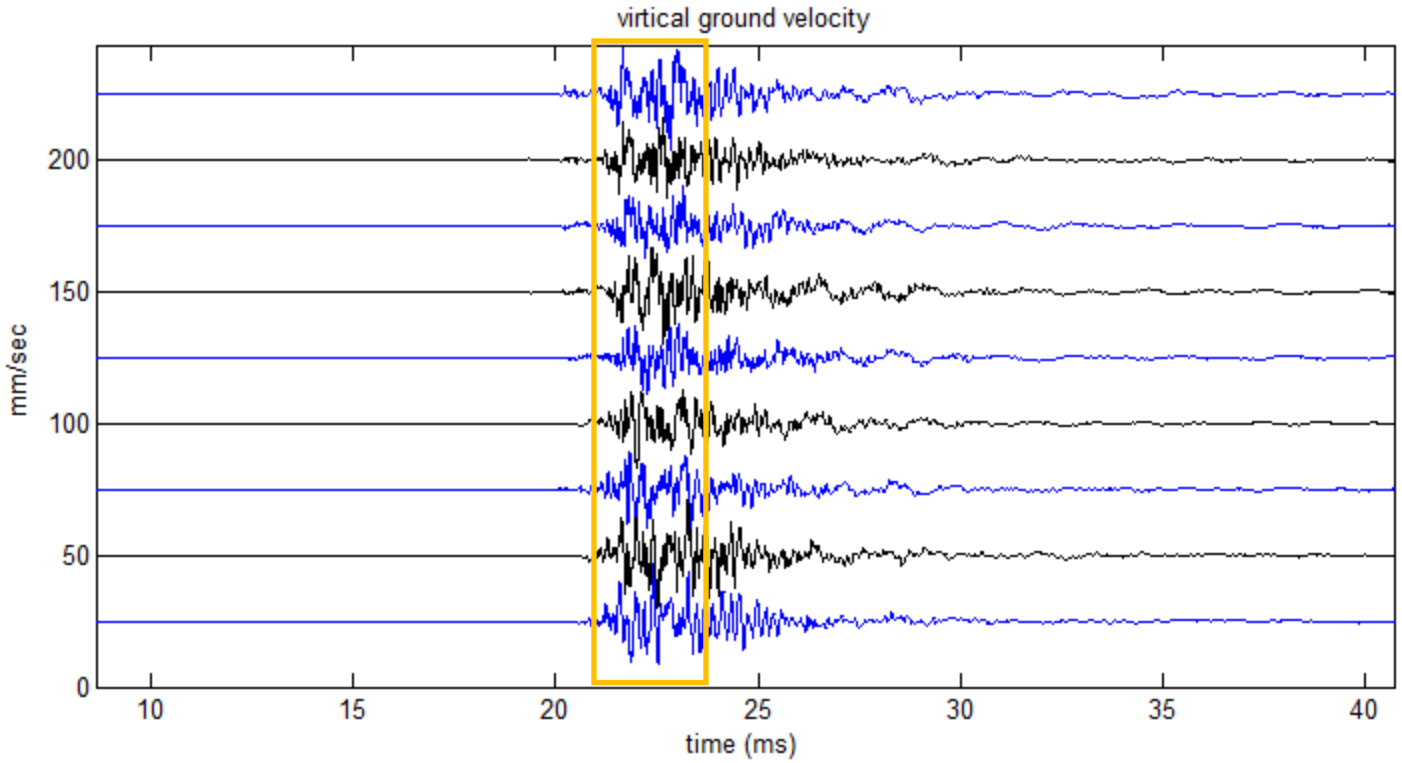
What about seismicity?

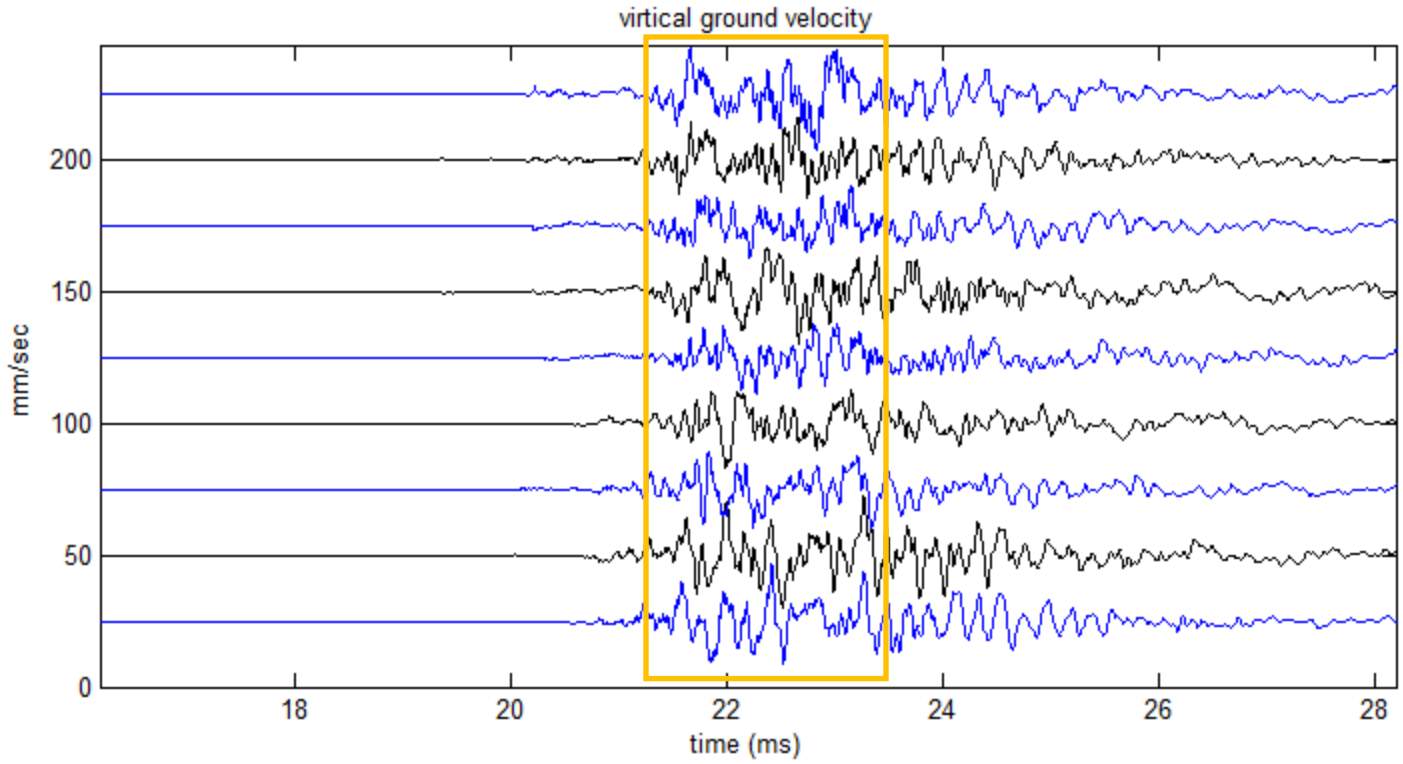
Rubin 2008

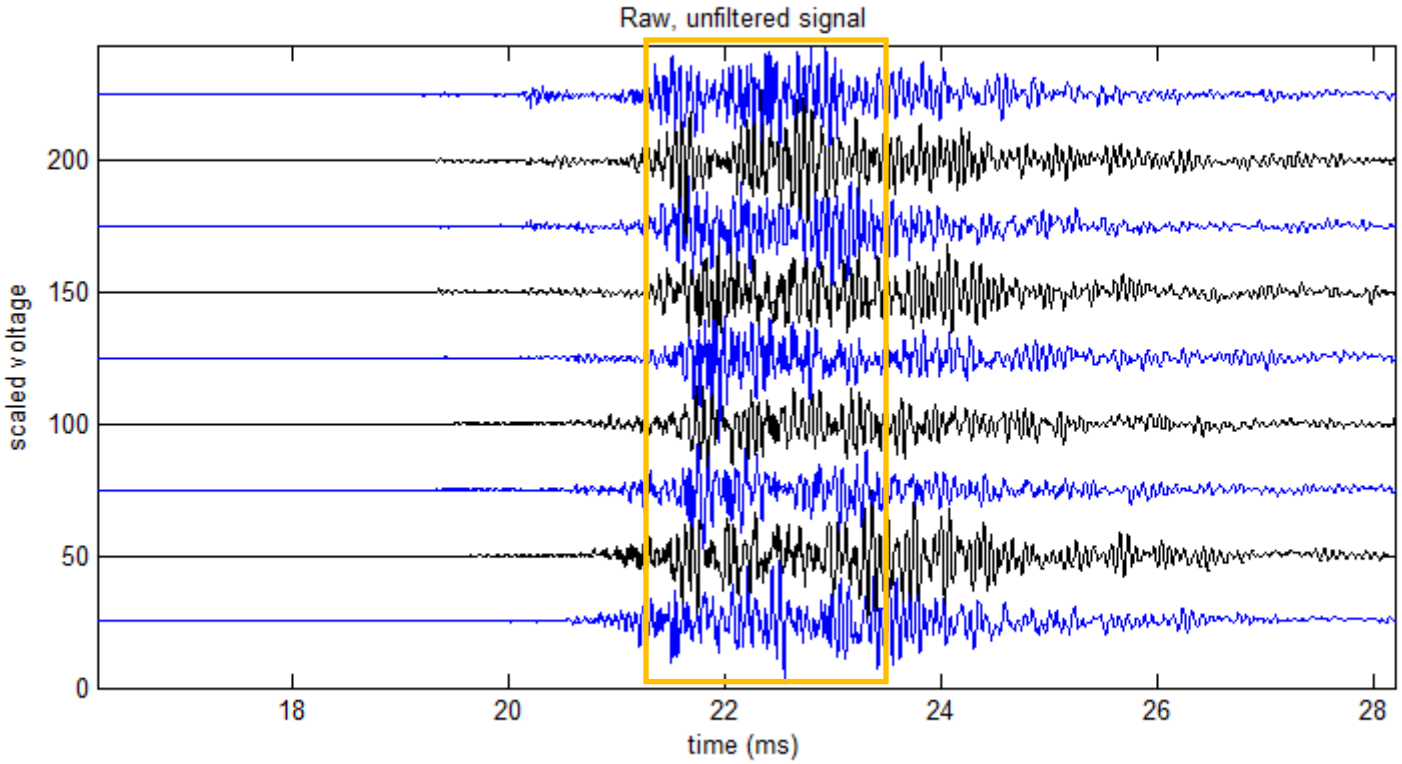


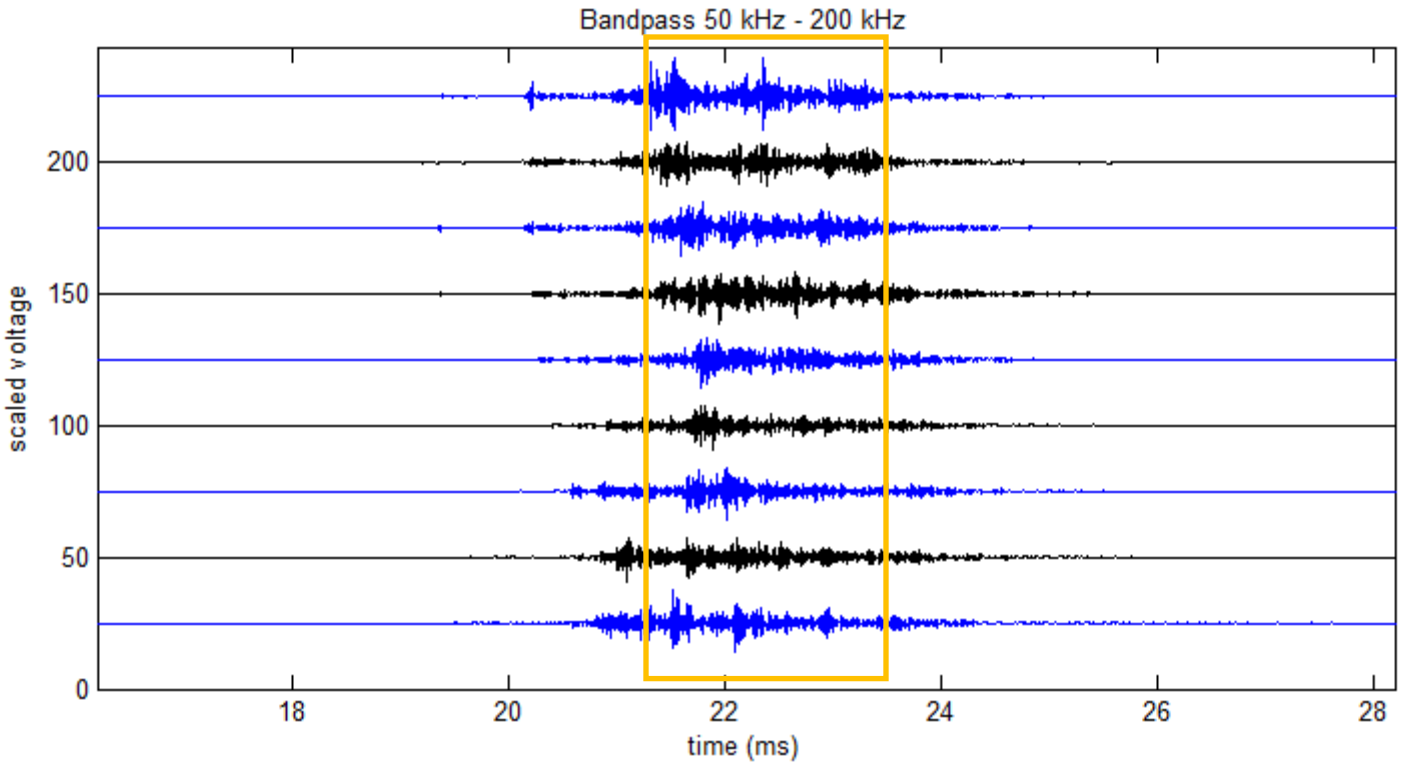

Top view of one side of the fault
distance (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Piezoelectric sensors
vert. gnd. vel.
mm/sec
40
20
0
SLIP
0
400 µm
800 µm
0
10
20
30
40
time (ms)

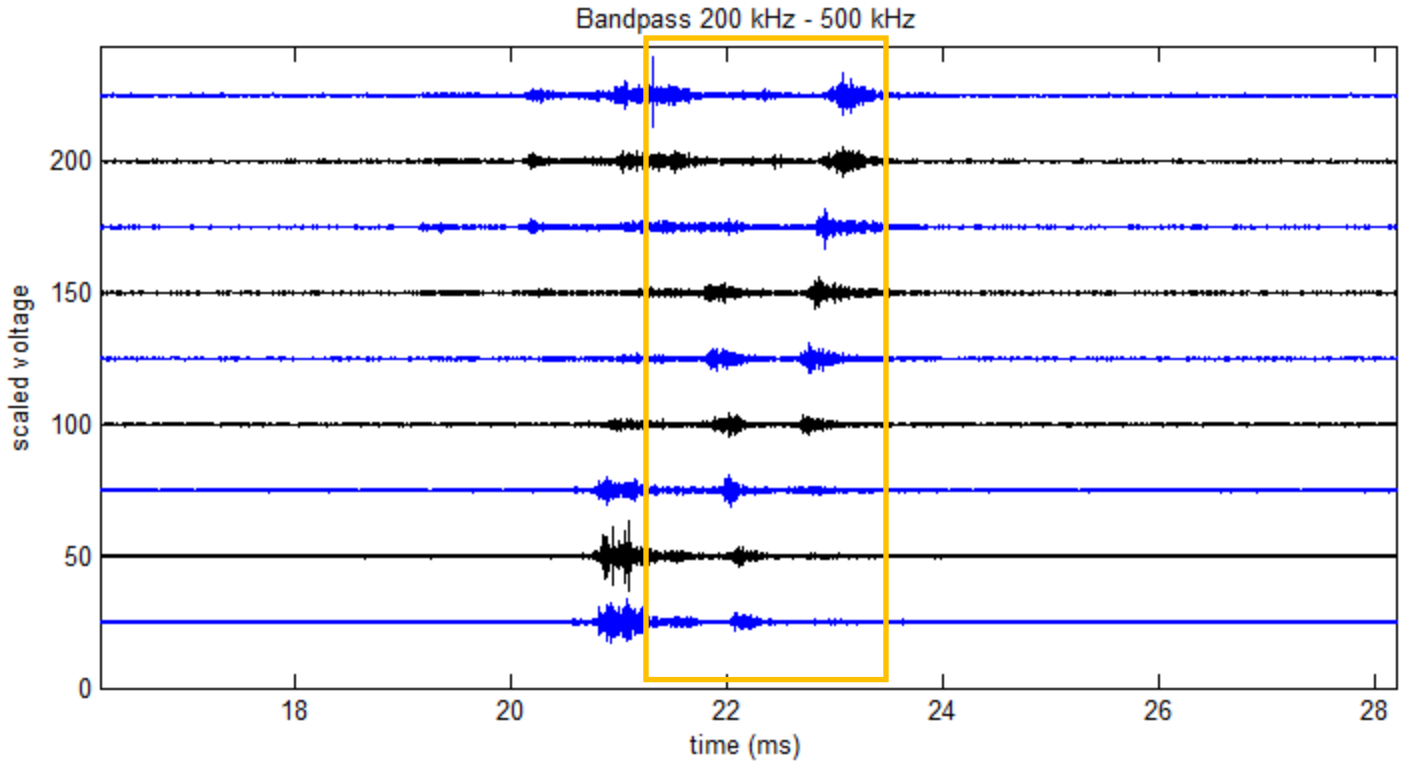

Top view of one side of the fault
distance (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Piezoelectric sensors
vert. gnd. vel.
mm/sec
40
20
0
SLIP
0
400 µm
800 µm
0
10
20
30
40
time (ms)

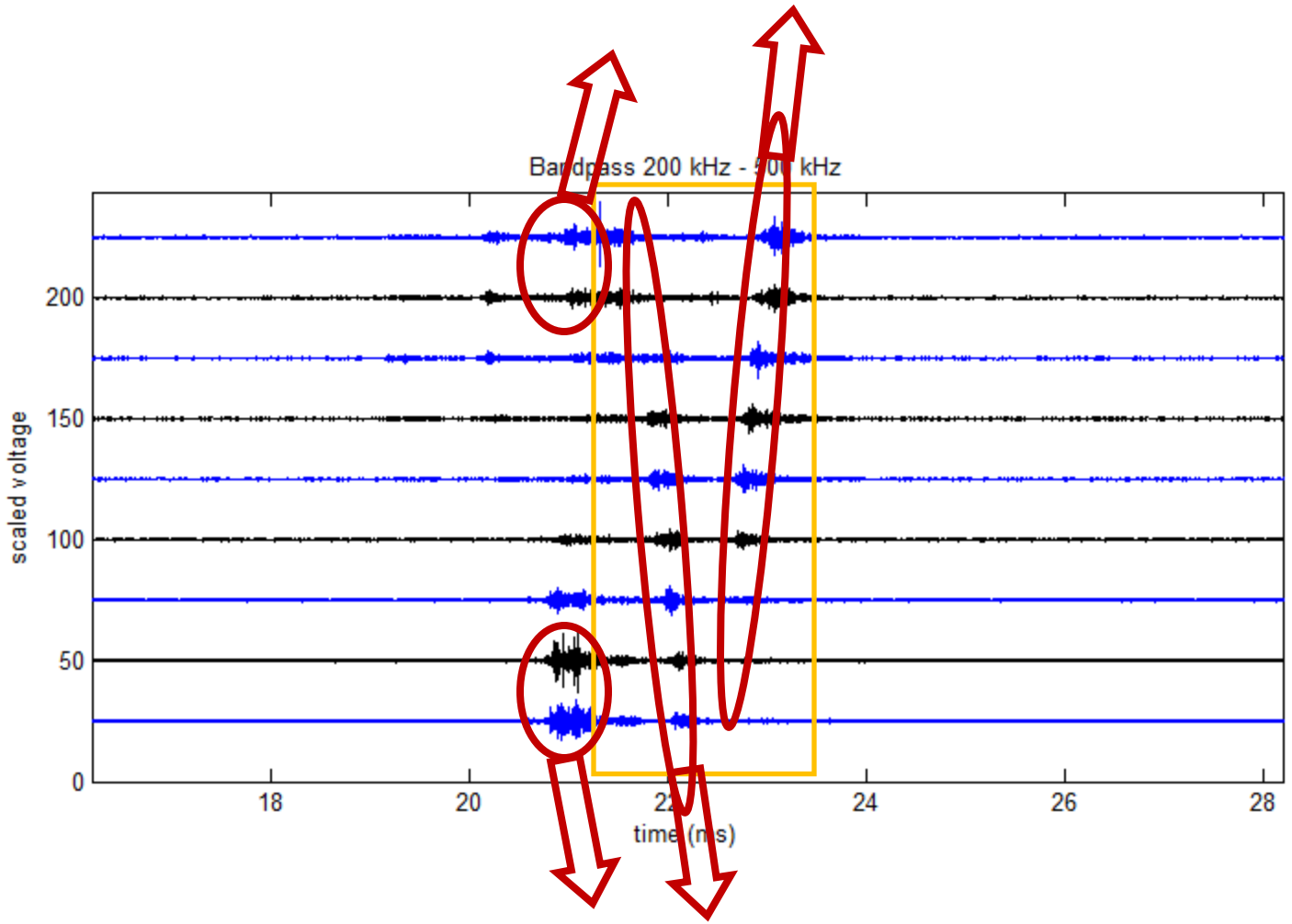

virtical ground velocity
mm/sec
0
50
100
150
200
10
15
20
25
30
35
40
time (ms)

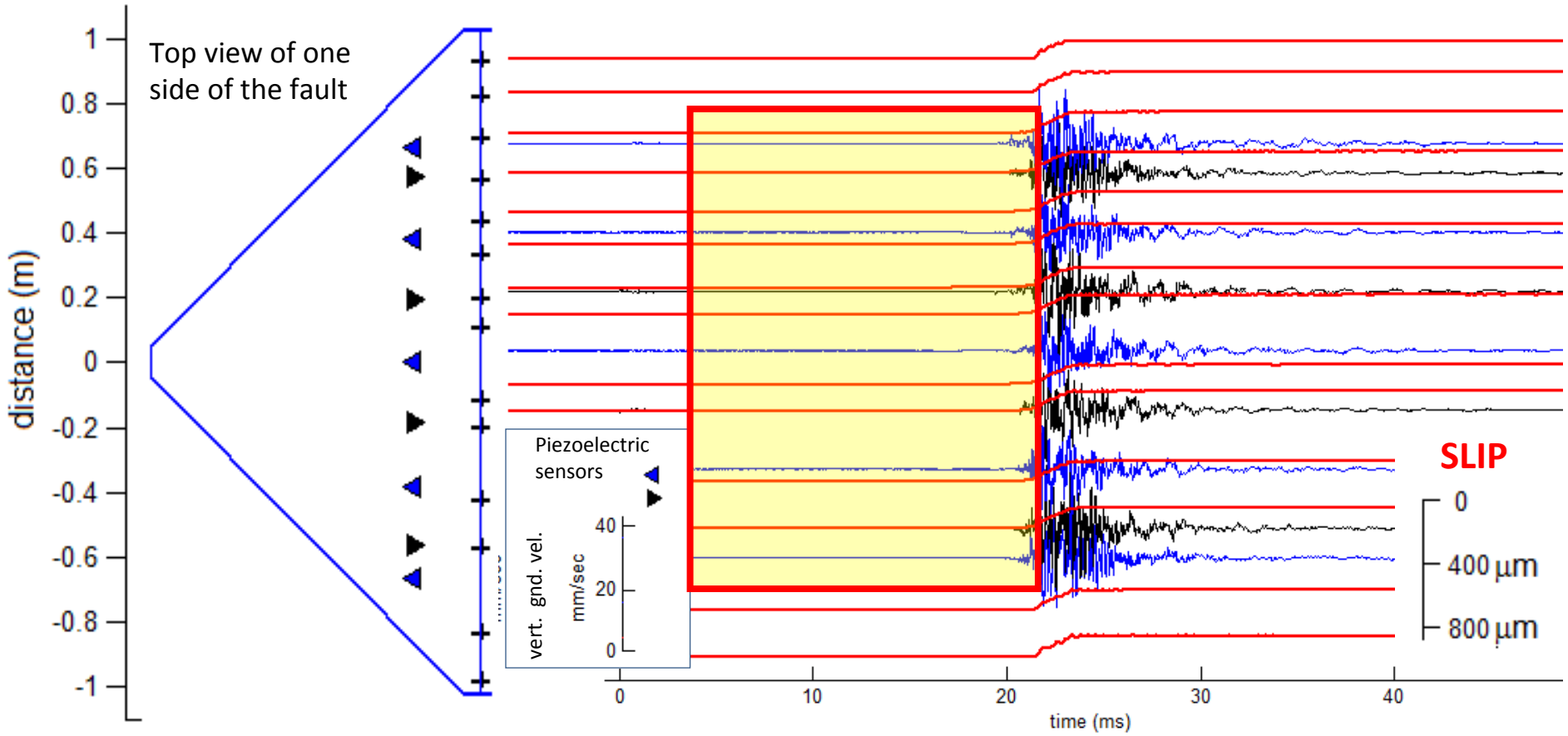

virtical ground velocity
200
150
100
50
0
mm/sec
18
20
22
24
26
28
time (ms)

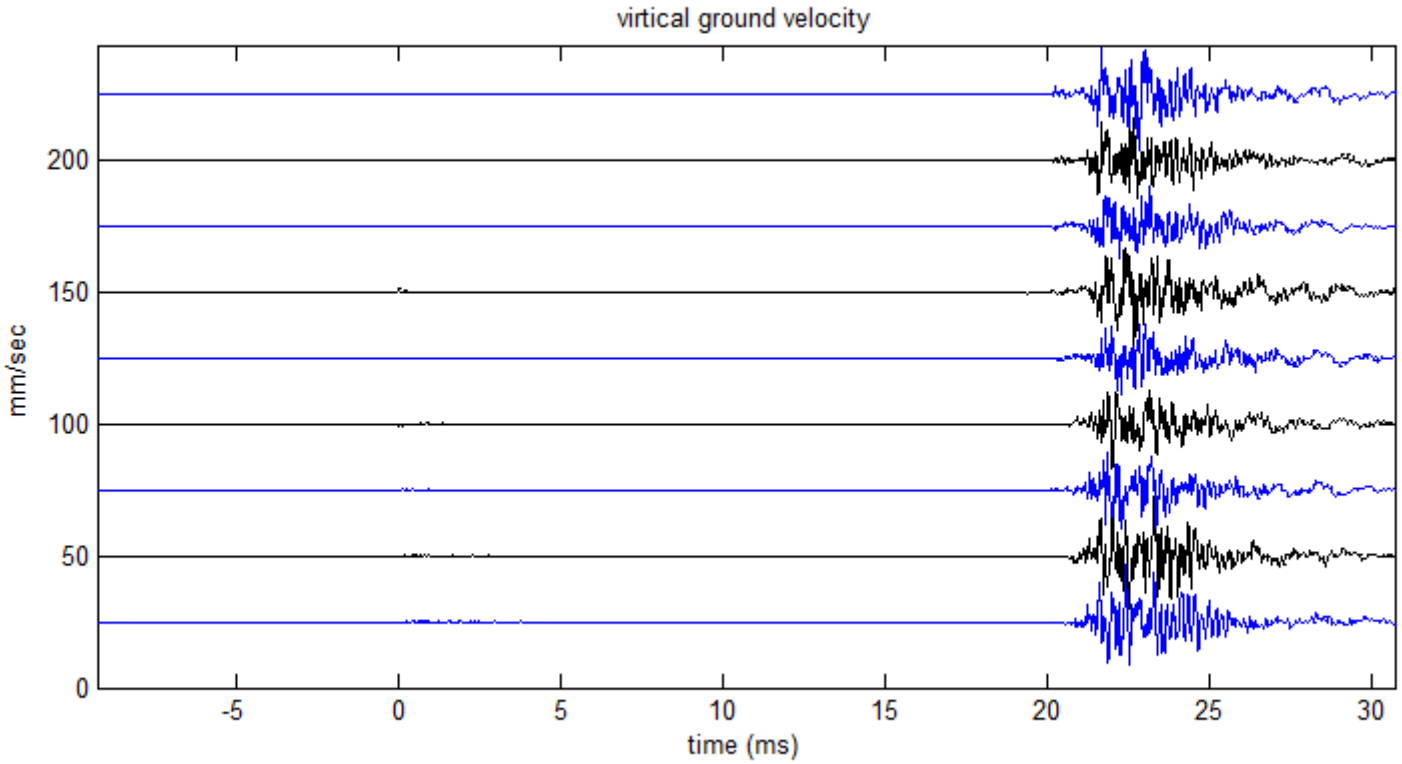

Raw, unfiltered signal
scaled voltage
0
50
100
150
200
18
20
22
24
26
28
time (ms)

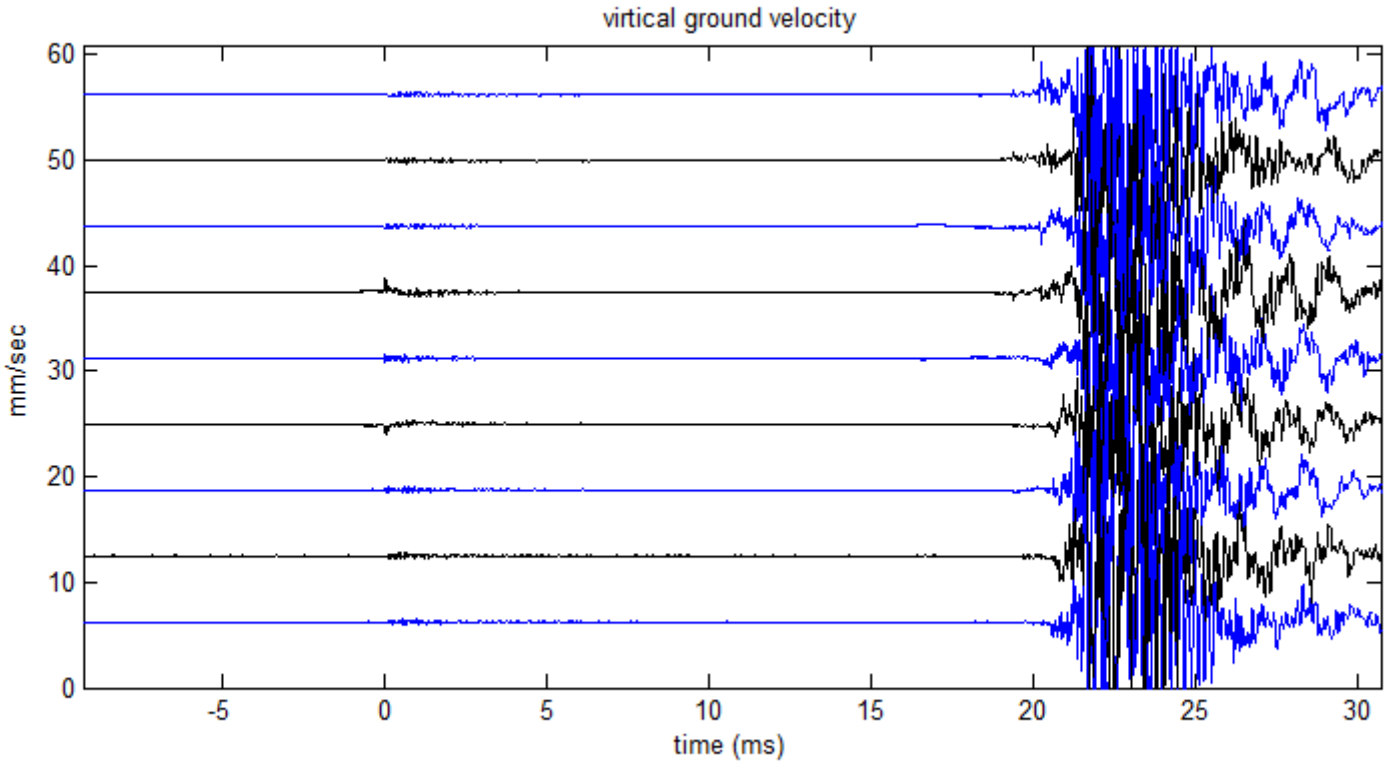

Bandpass 50 kHz - 200 kHz
scaled voltage
0
50
100
150
200
18
20
22
24
26
28
time (ms)

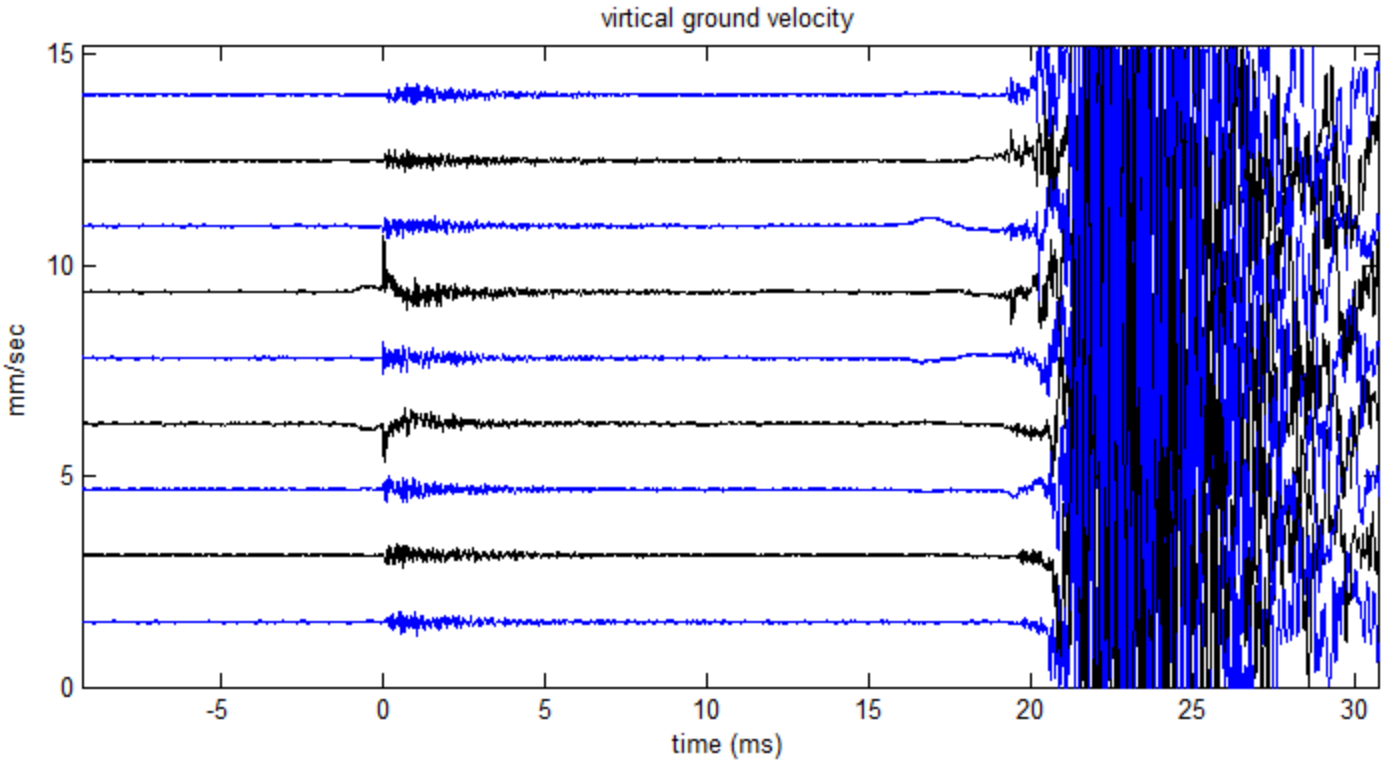

Bandpass 200 kHz - 500 kHz
scaled voltage
200
150
100
50
0
18
20
22
24
26
28
time (ms)

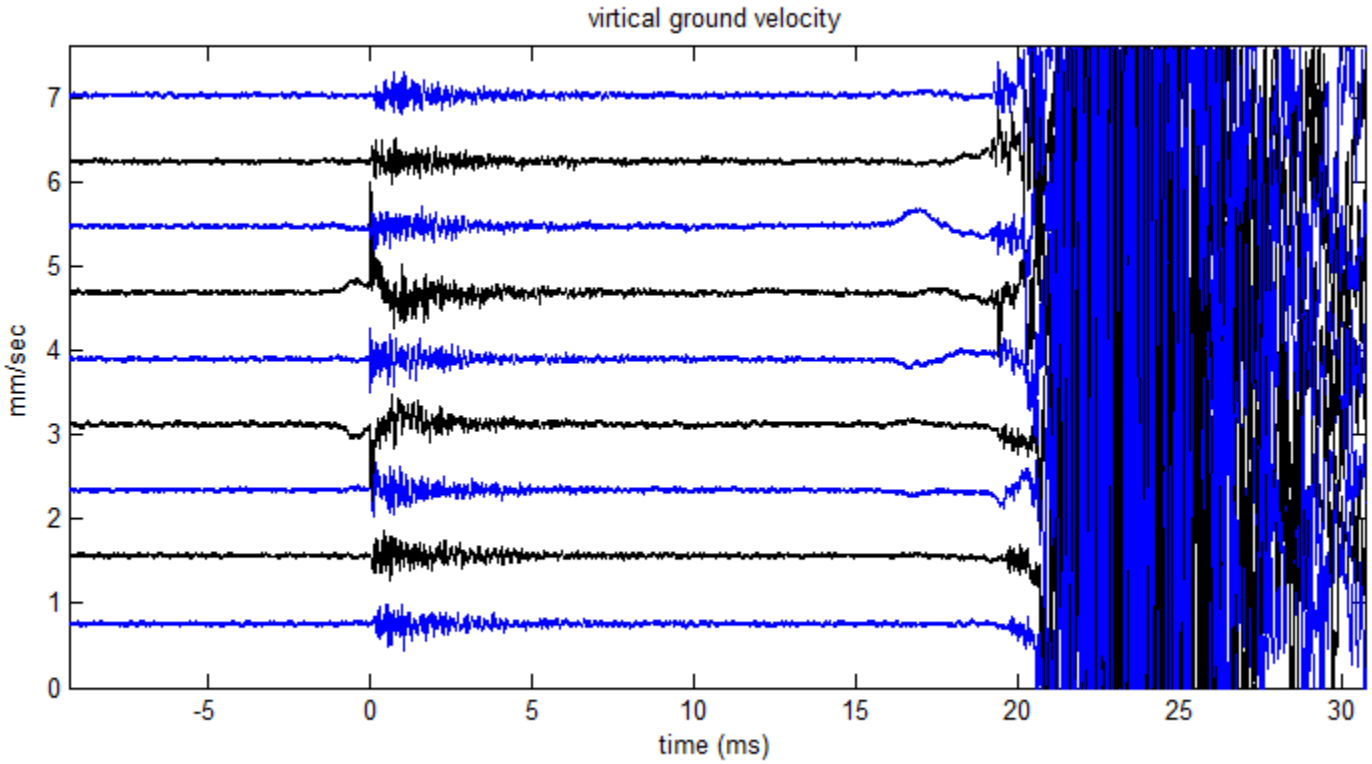

Bandpass 200 kHz - 900 kHz
scaled voltage
0
50
100
150
200
18
20
22
24
26
28
time (ms)

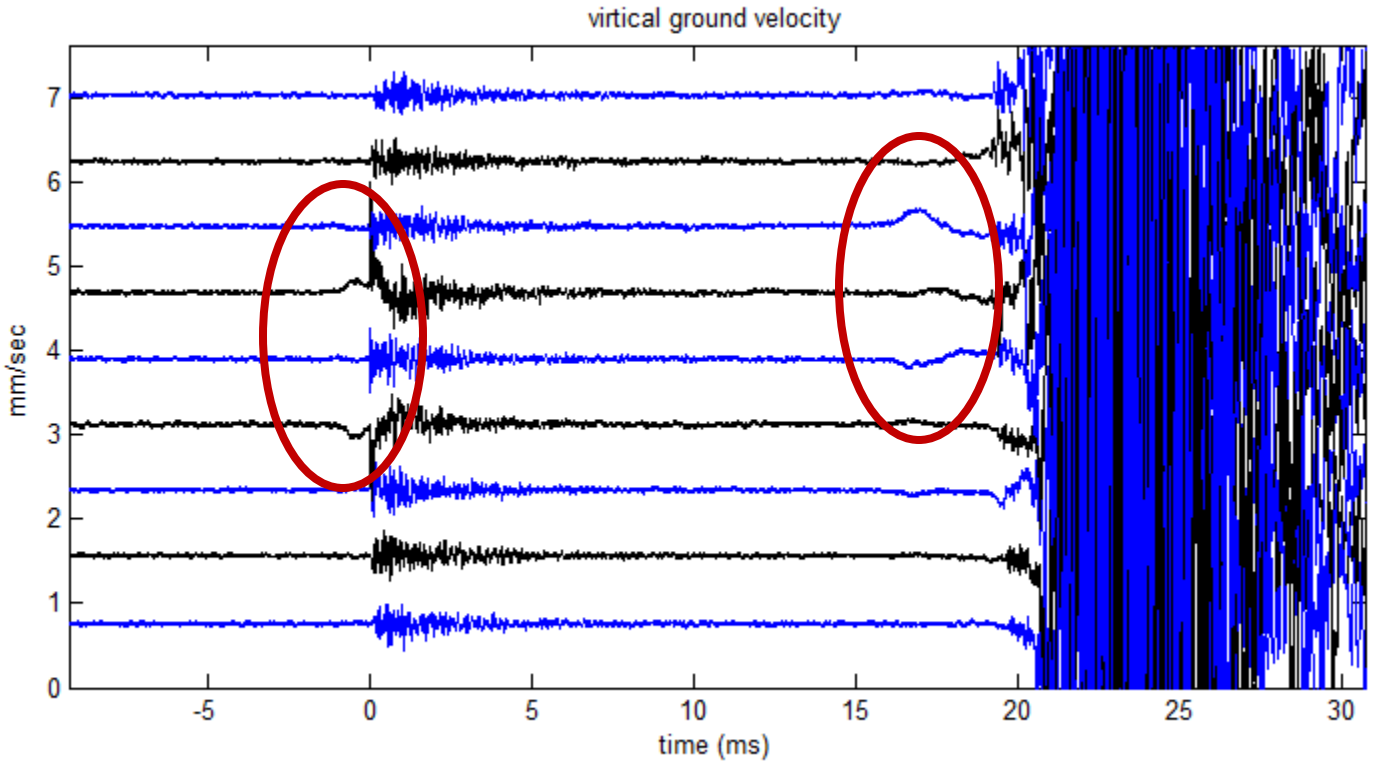

Top view of one side of the fault
distance (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
Piezoelectric sensors
vert. gnd. vel.
mm/sec
40
20
0
SLIP
0
400 µm
800 µm
0
10
20
30
40
time (ms)

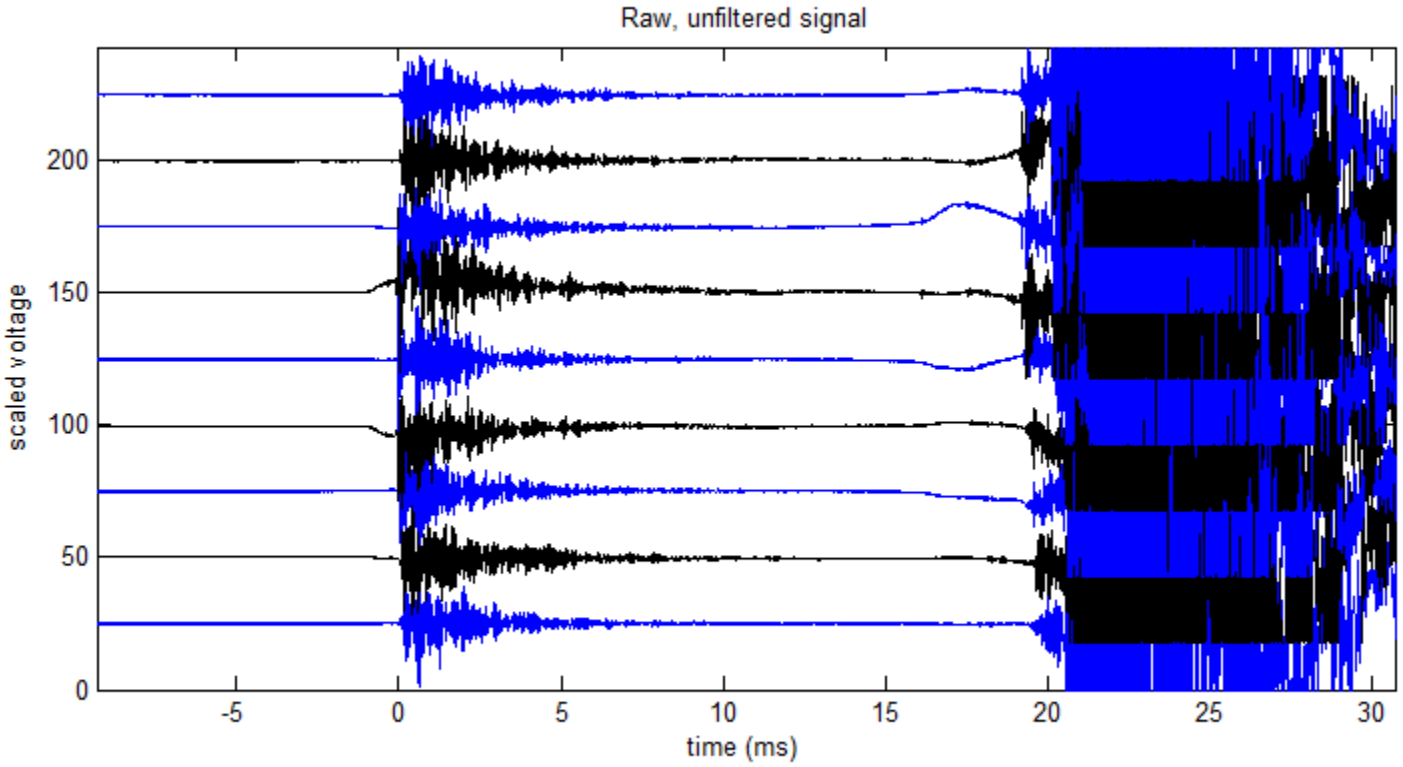

virtical ground velocity
mm/sec
0
50
100
150
200
-5
0
5
10
15
20
25
30
time (ms)

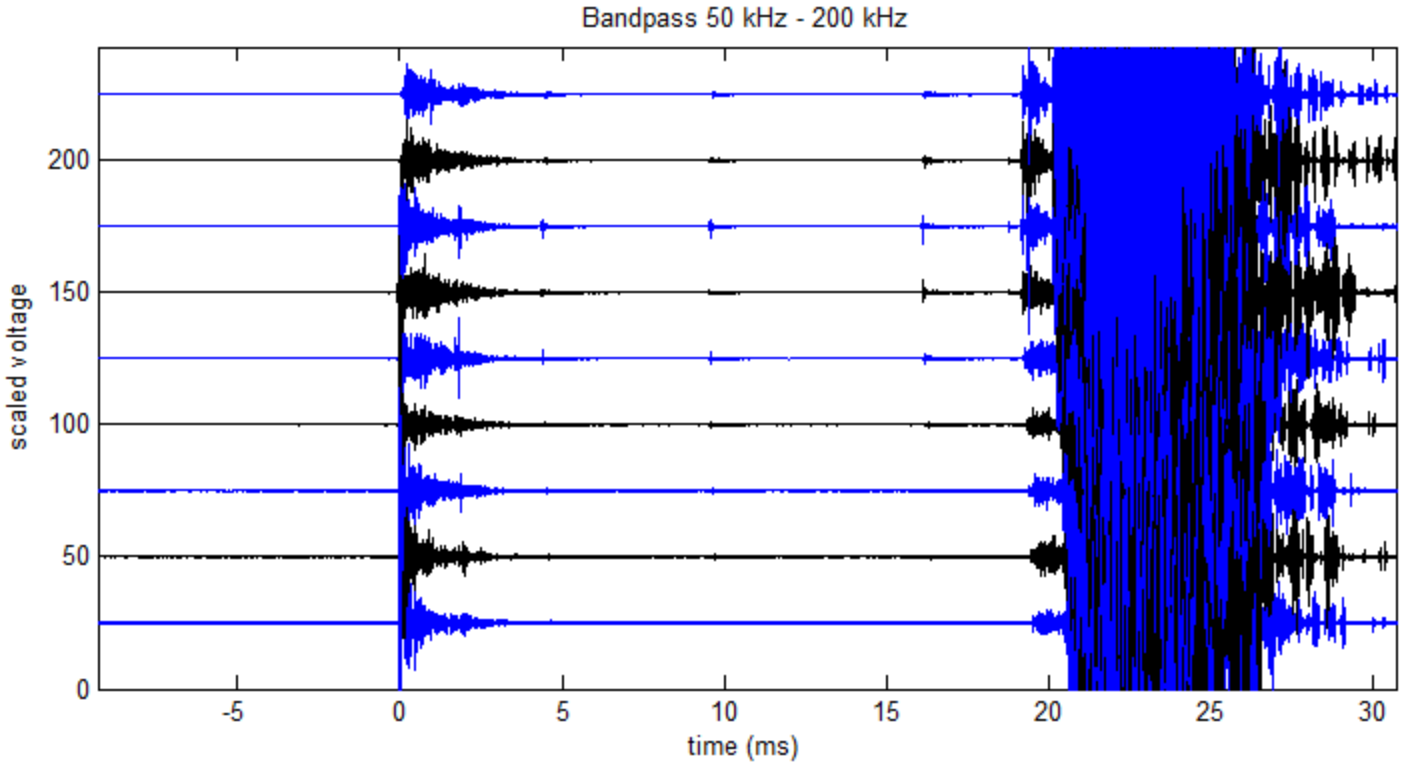

virtical ground velocity
mm/sec
60
50
40
30
20
10
0
-5
0
5
10
15
20
25
30
time (ms)

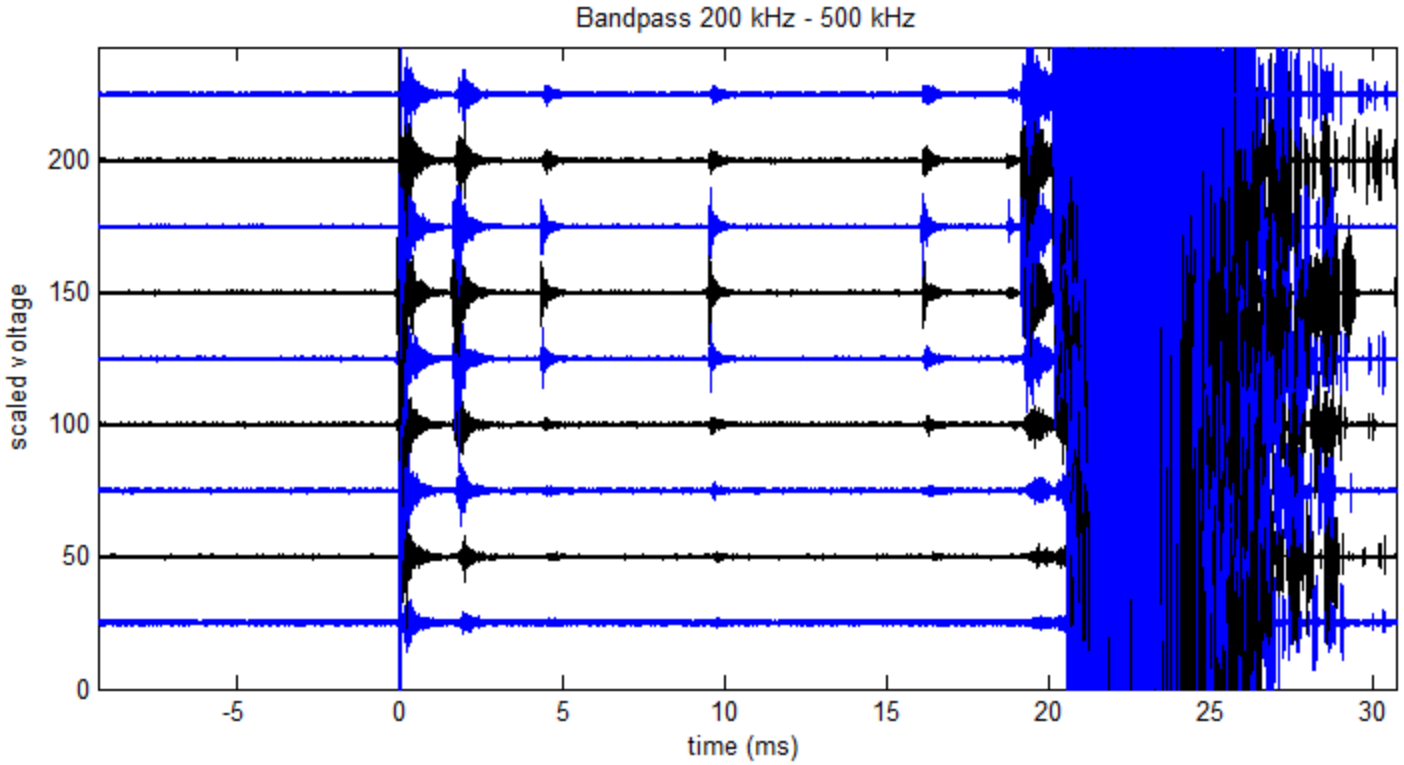

virtical ground velocity
15
10
5
0
mm/sec
-5
0
5
10
15
20
25
30
time (ms)

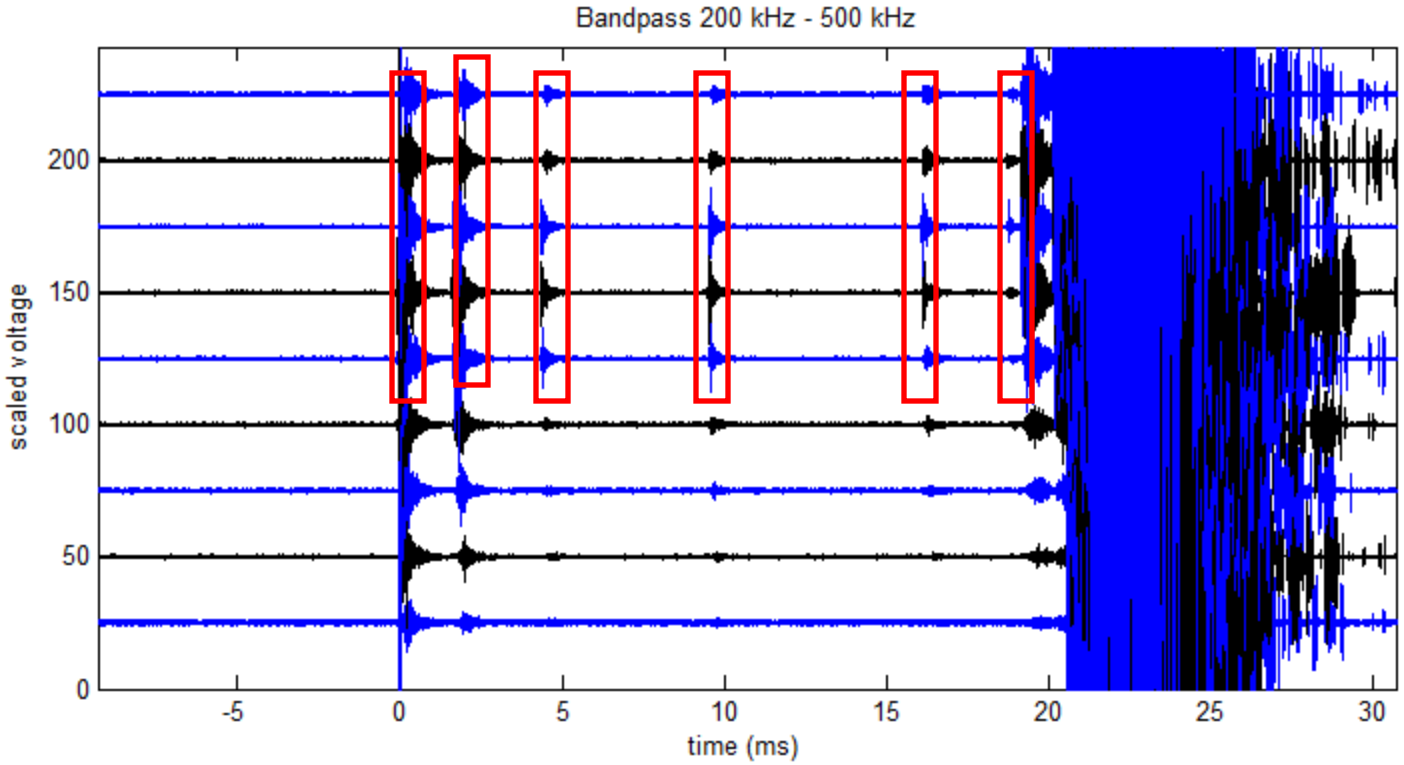

virtical ground velocity
mm/sec
0
1
2
3
4
5
6
7
-5
0
5
10
15
20
25
30
time (ms)

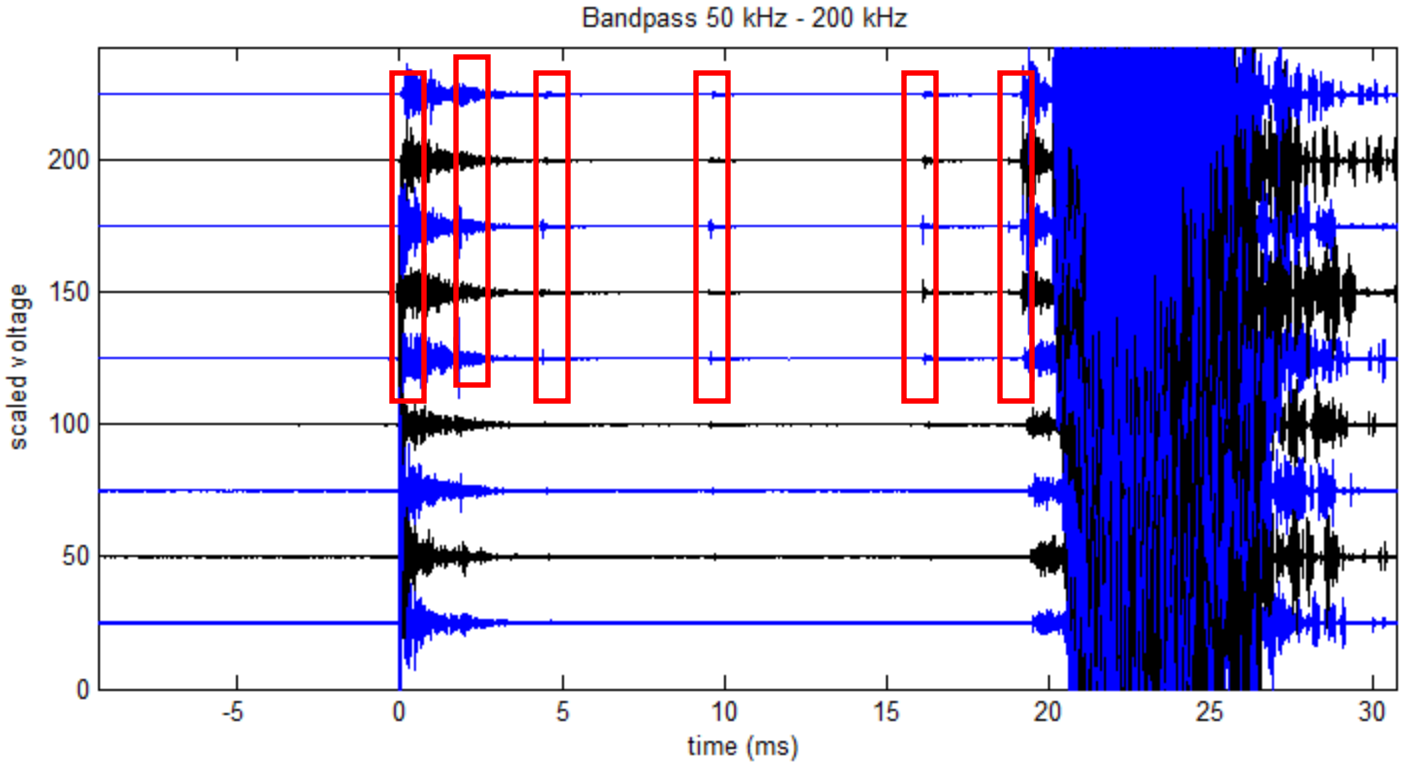

virtical ground velocity
mm/sec
7
6
5
4
3
2
1
0
-5
0
5
10
15
20
25
30
time (ms)

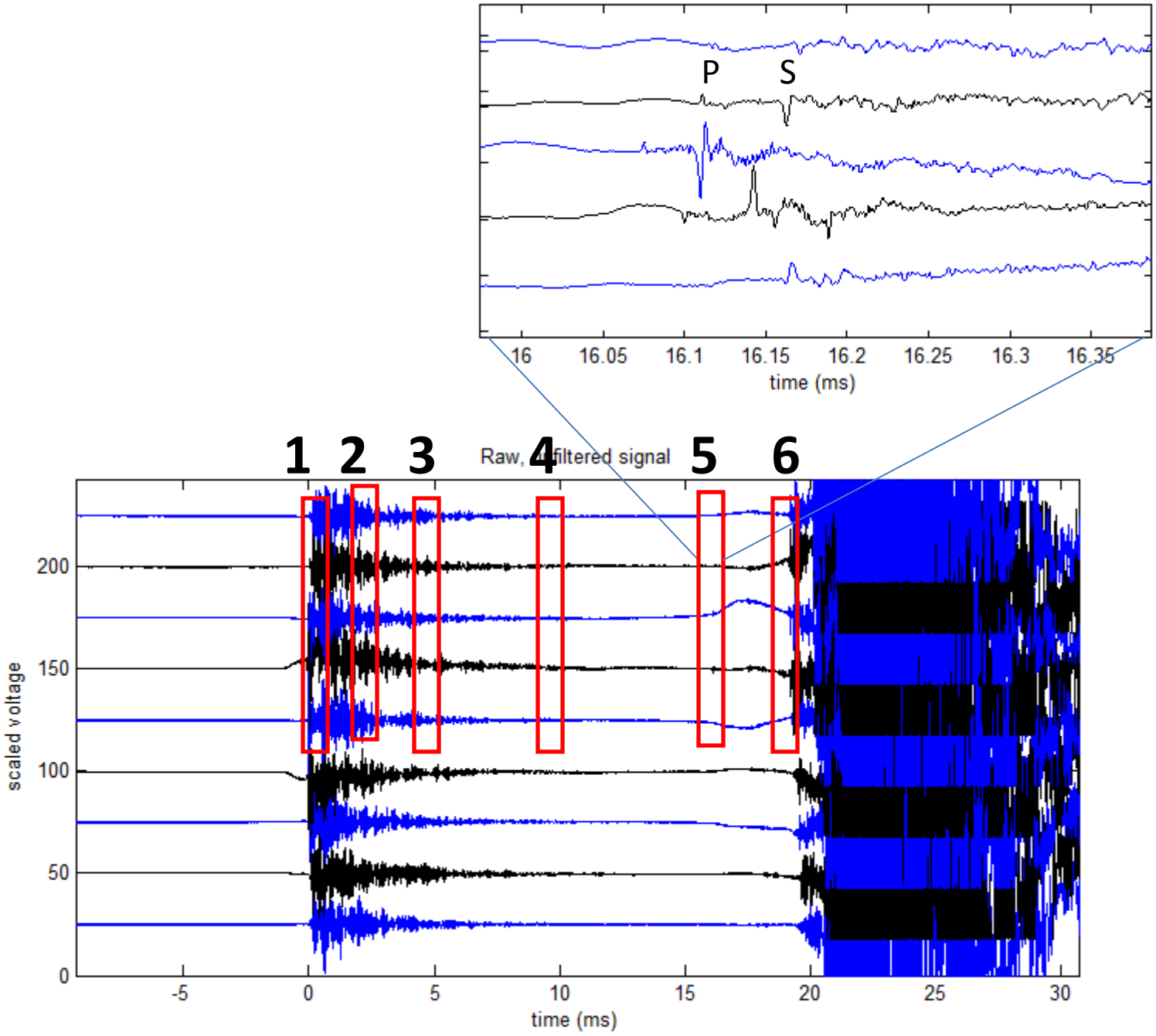

Raw, unfiltered signal
scaled voltage
0
50
100
150
200
-5
0
5
10
15
20
25
30
time (ms)


Bandpass 50 kHz - 200 kHz
scaled voltage
0
50
100
150
200
-5
0
5
10
15
20
25
30
time (ms)


Bandpass 200 kHz - 500 kHz
scaled voltage
0
50
100
150
200
-5
0
5
10
15
20
25
30
time (ms)

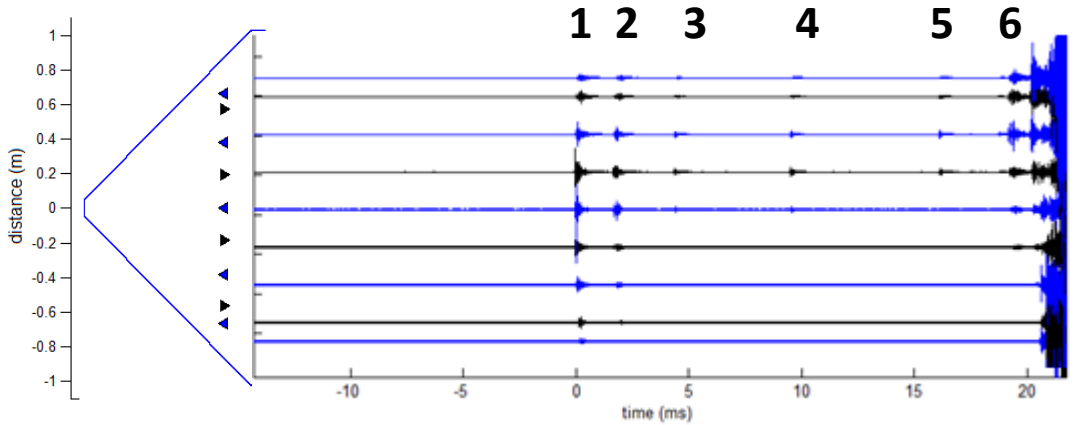

Bandpass 200 kHz - 500 kHz
scaled voltage
200
150
100
50
0
-5
0
5
10
15
20
25
30
time (ms)

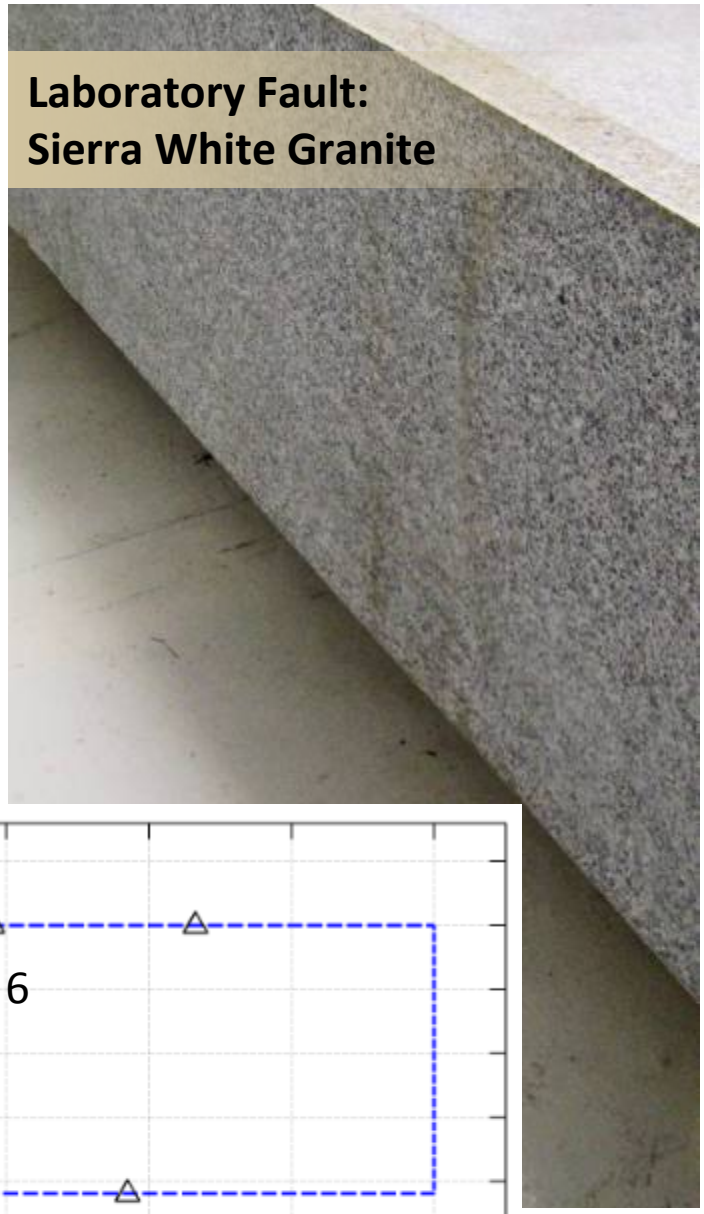

Bandpass 50 kHz - 200 kHz
scaled voltage
0
50
100
150
200
-5
0
5
10
15
20
25
30
time (ms)

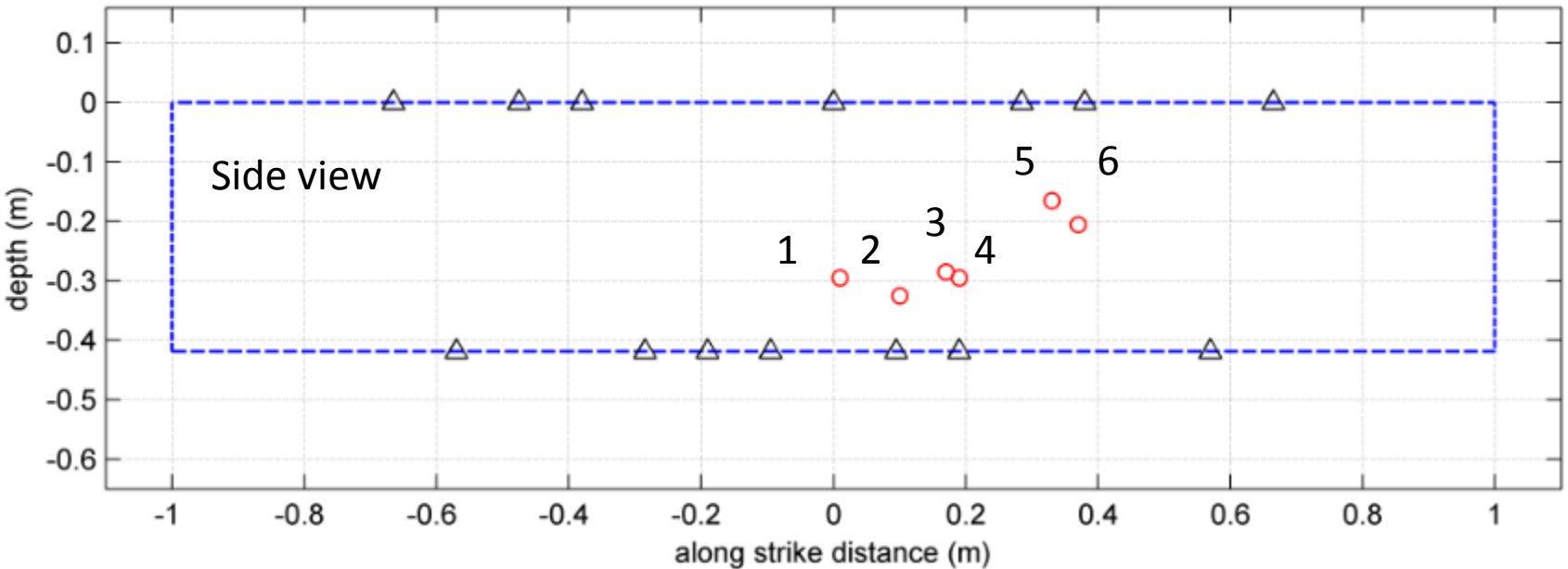

P
S
16
16.05
16.1
16.15
16.2
16.25
16.3
16.35
time (ms)
1
2
3
4
5
6
Raw, unfiltered signal
scaled voltage
200
150
100
50
0
-5
0
5
10
15
20
25
30
time (ms)

Foreshock locations:
along strike and depth

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

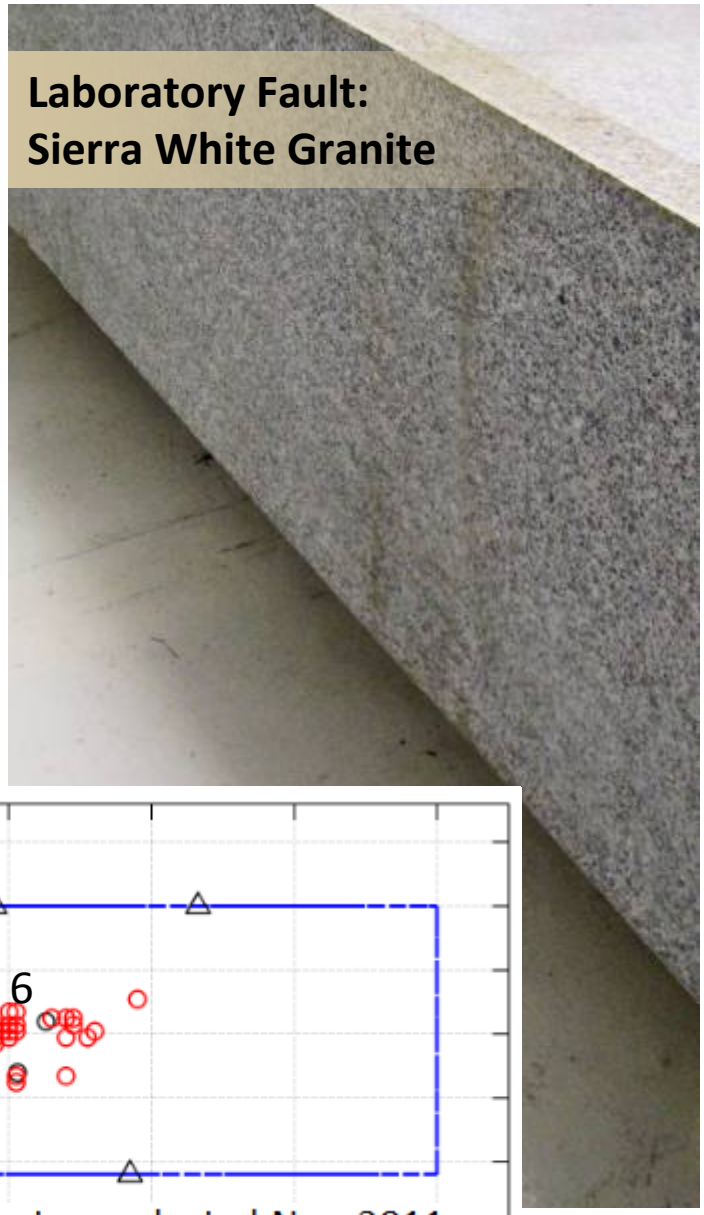


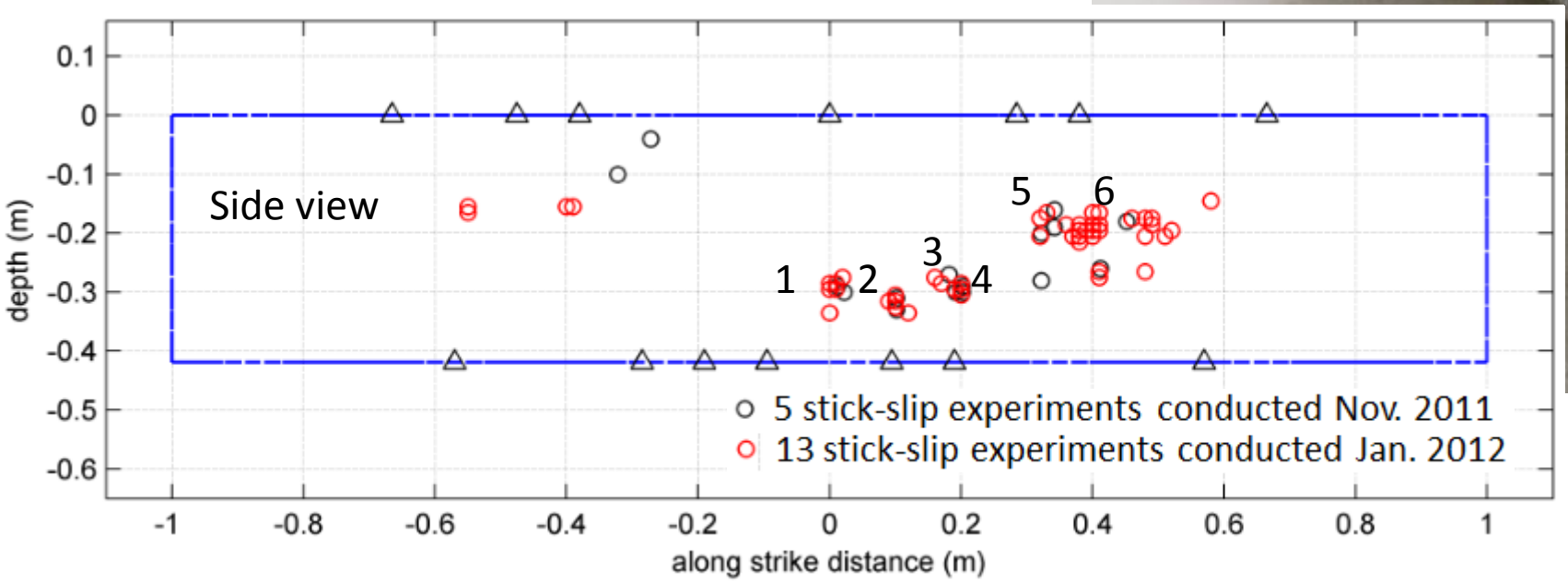




Foreshock locations:
along strike and depth

- Foreshocks tend to cluster on 2-70 mm patches
- Patches comprise only a small % of total fault area
- Migration of foreshocks follows the expansion of slow slip during earthquake nucleation
- Locations persist for more than 1mm cumulative fault slip





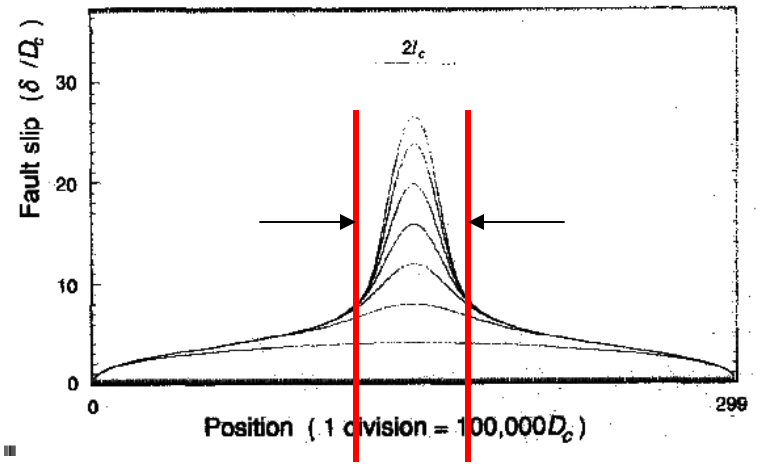
How such a small earthquake?

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

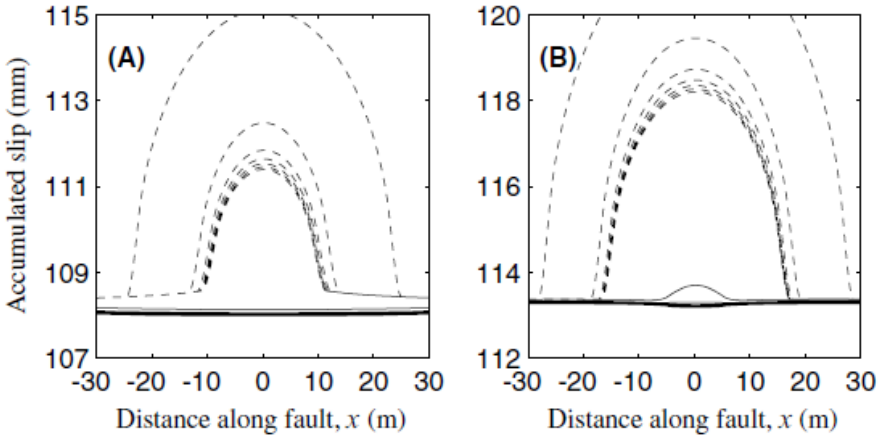
This nucleation zone is ~ 1m – 10m – 100m ? depending on parameters

$$h^* = \frac{\mu \eta D_c}{\sigma_n (b-a)}$$

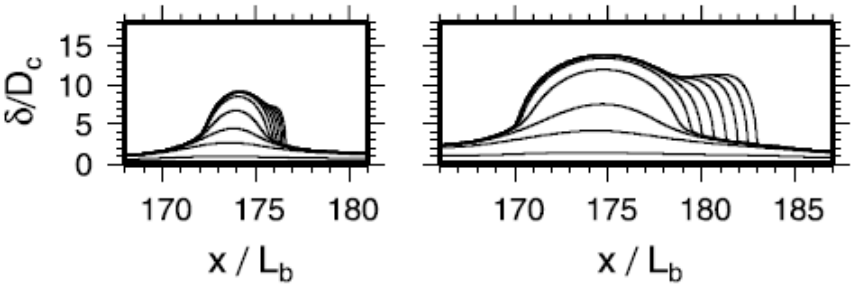
Dieterich 1992



Kaneko and Lapusta 2008



Ampuero and Rubin 2008



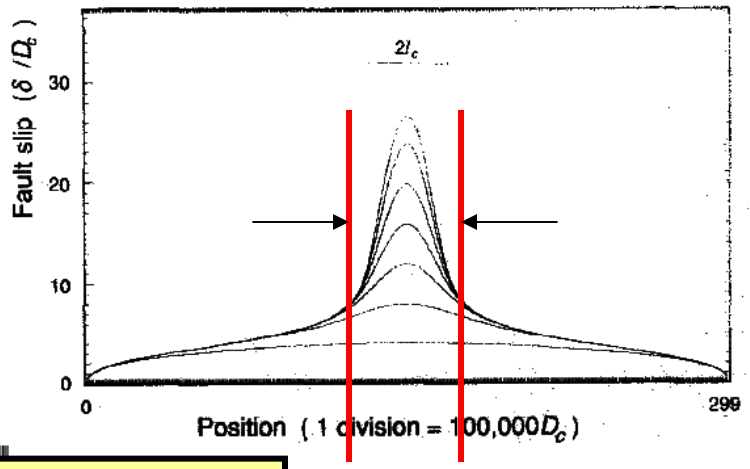
How such a small earthquake?

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

This nucleation zone is ~ 1m – 10m – 100m ? depending on parameters

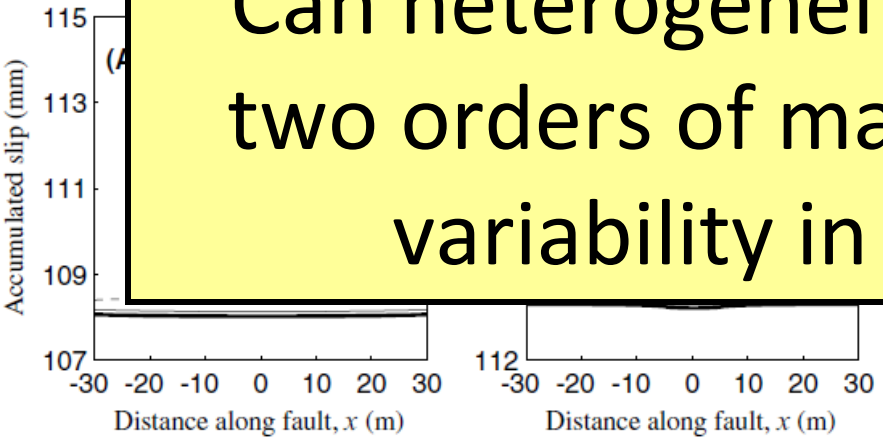
$$h^* = \frac{\mu \eta D_c}{\sigma_n (b-a)}$$

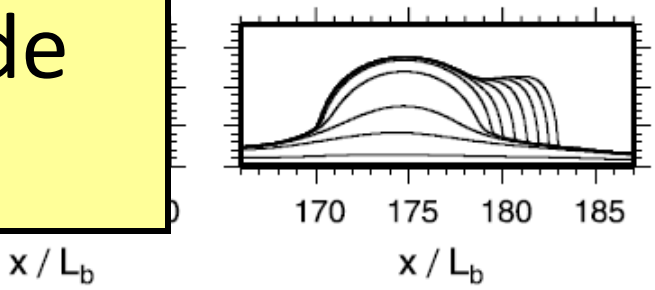
Dieterich 1992



Can heterogeneity cause two orders of magnitude variability in h*?

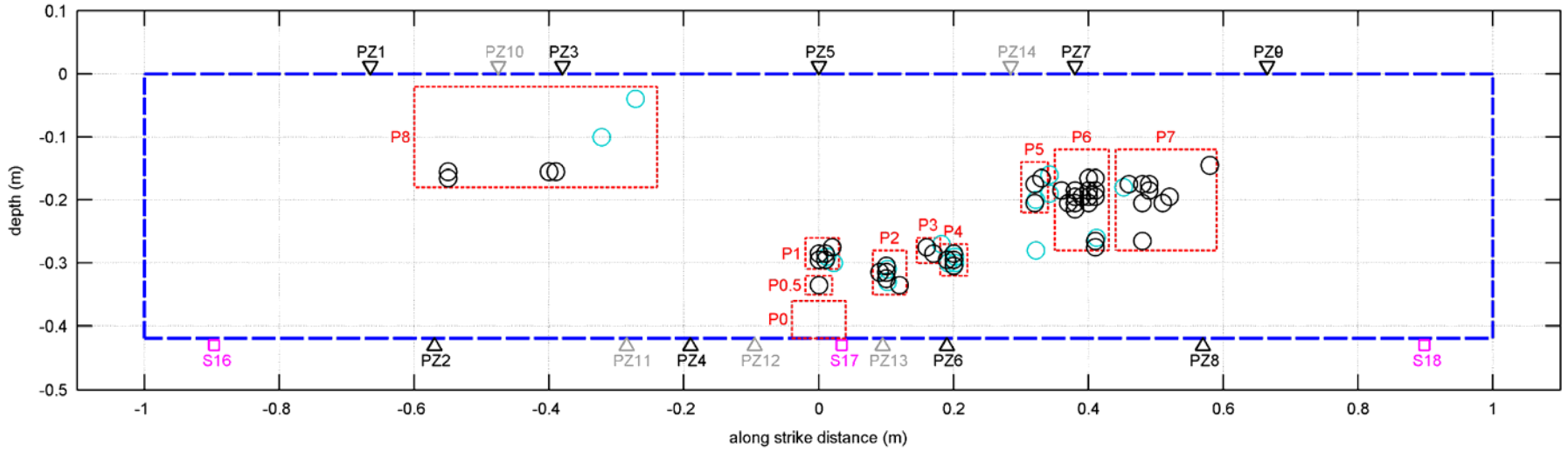
ero and Rubin 2008

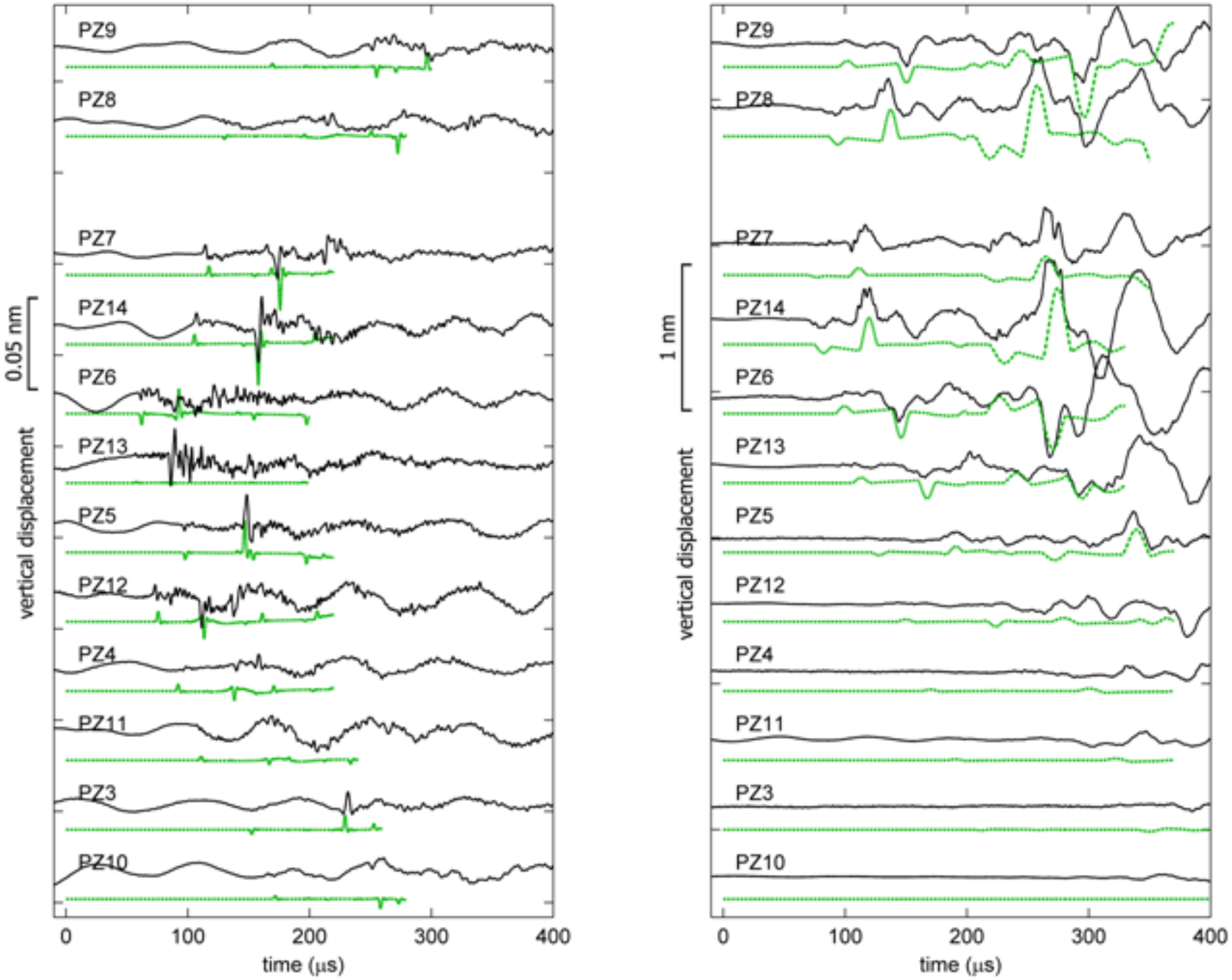




How such a small earthquake?

- Maybe the constitutive law (i.e. rate-state friction) is not valid?
  - Foreshock characteristics do not change as fault friction evolves over cumulative slip
  - Foreshocks persist over at least 10 stick-slip cycles and > 1 mm cumulative slip
  - Shear-type focal mechanisms




PZ9
PZ8
PZ7
PZ14
PZ6
PZ13
PZ5
PZ12
PZ4
PZ11
PZ3
PZ10
0.05 nm
vertical displacement
0
100
200
300
400
time (μs)
1 nm
vertical displacement
time (μs)

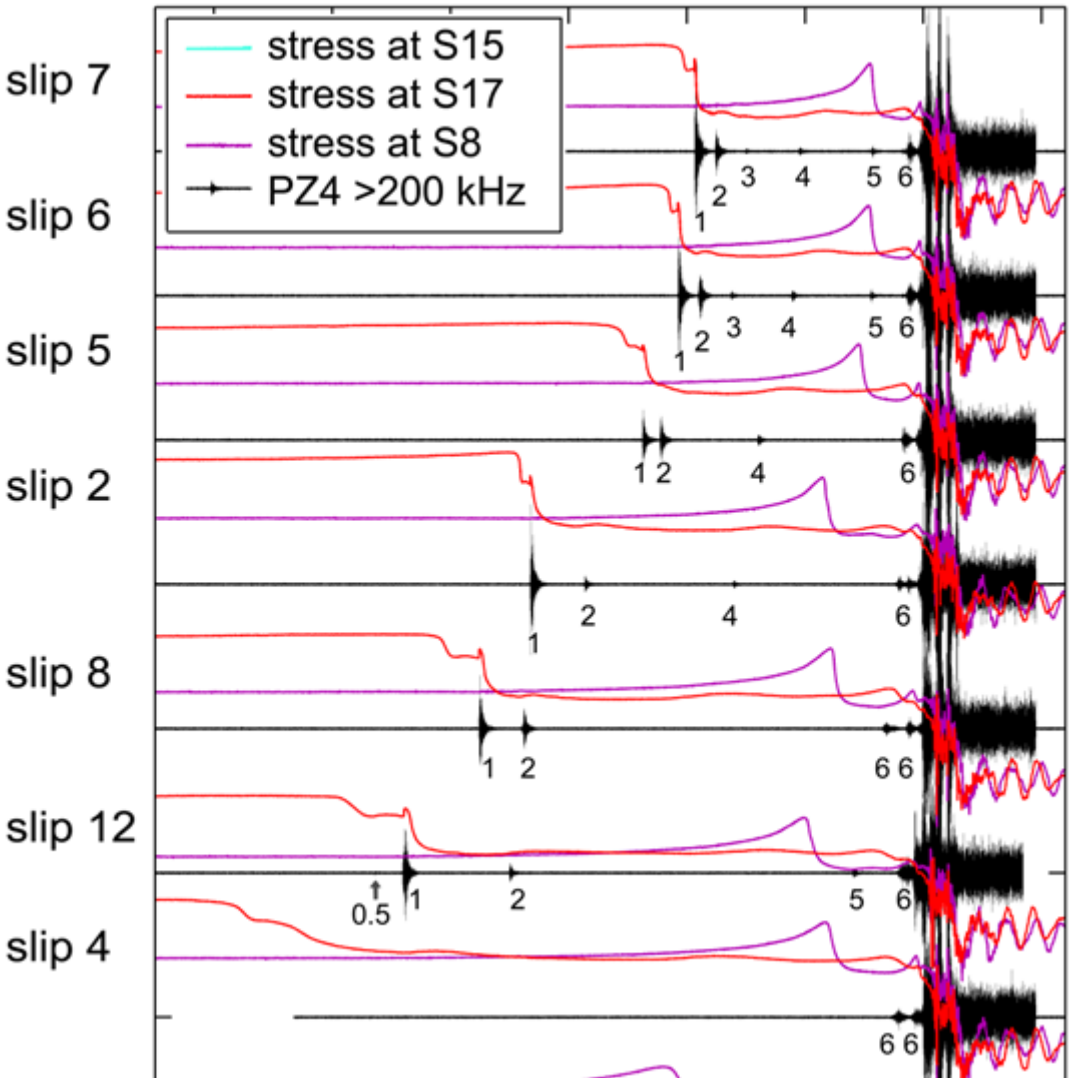
Loading rate / stressing rate effect

- We only observe tiny “foreshocks” 5-50 ms before stick-slip, never at other times

The tiny (Mw = -6) events cannot nucleate on their own!

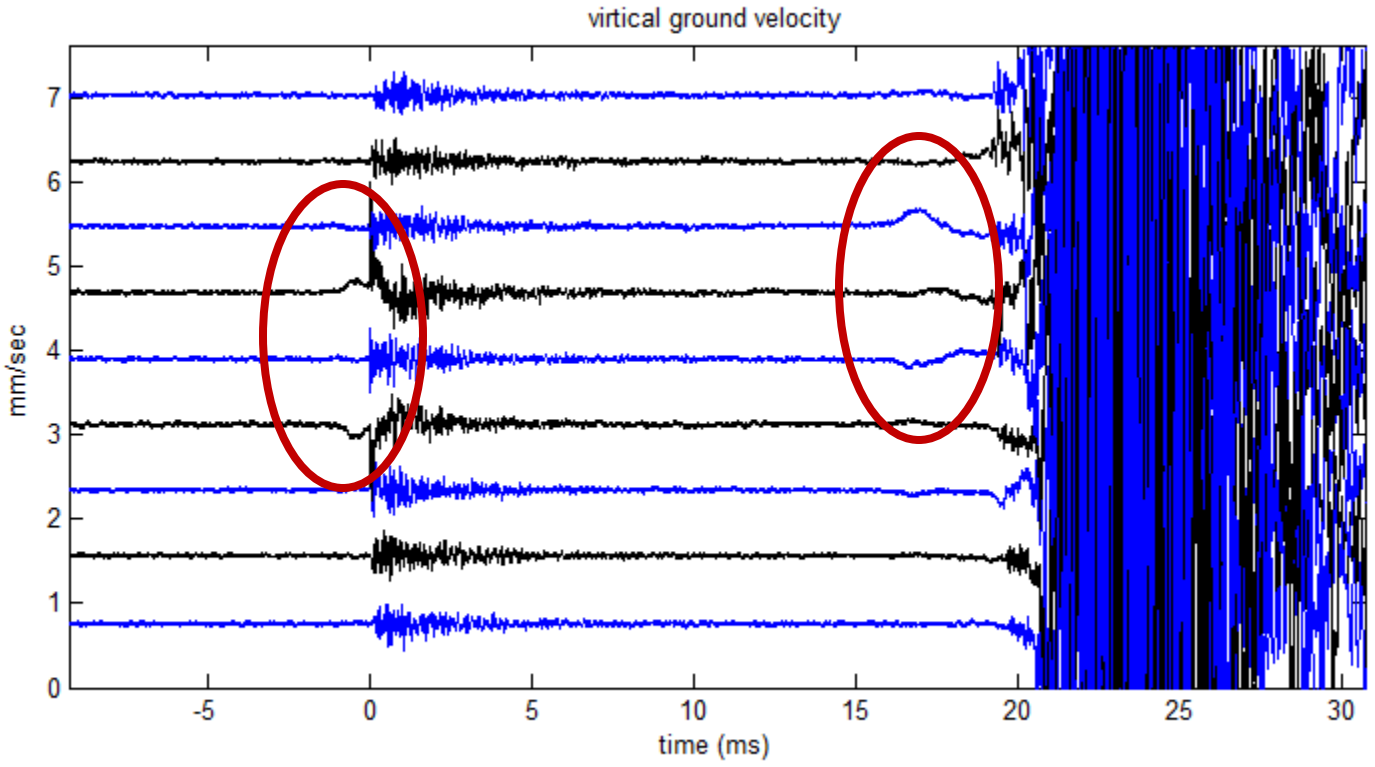
- sometimes the foreshock sequence is not detected.

i.e. the foreshock patches slip aseismically if driven more slowly!

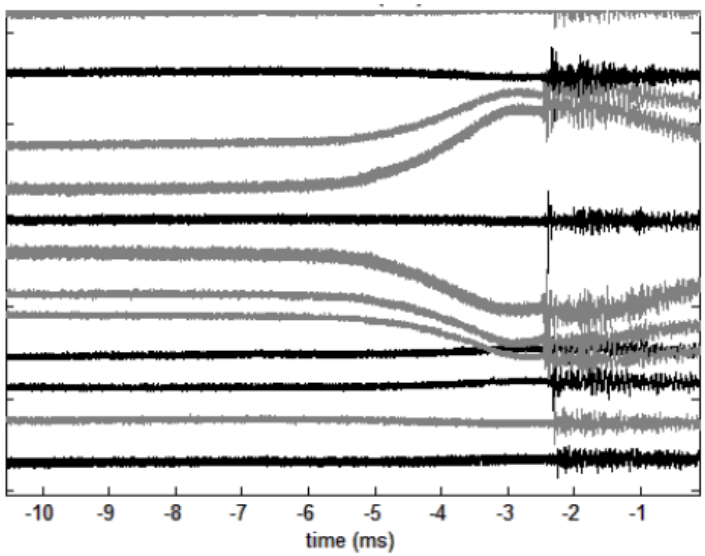


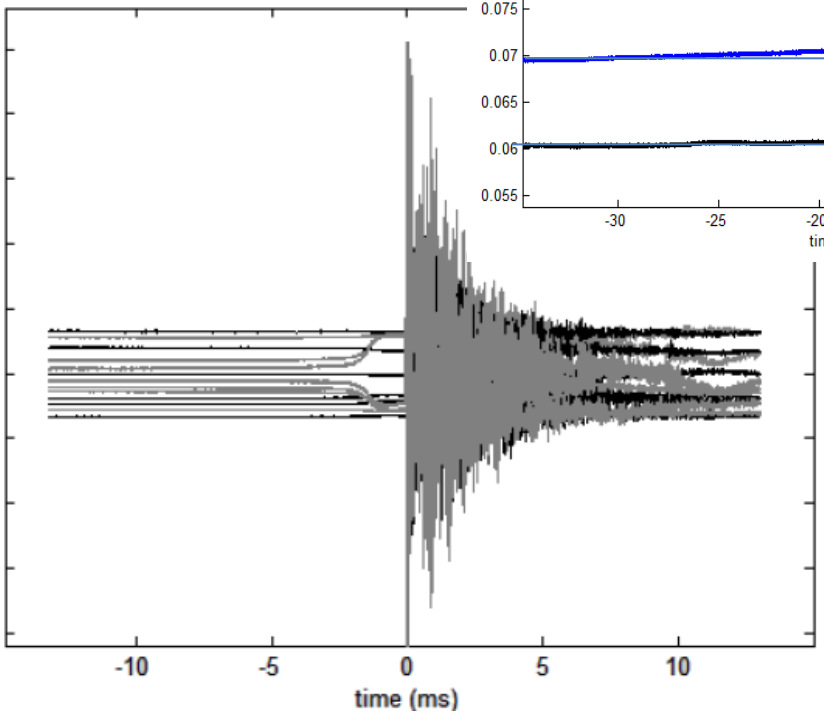
Aseismic slip transients

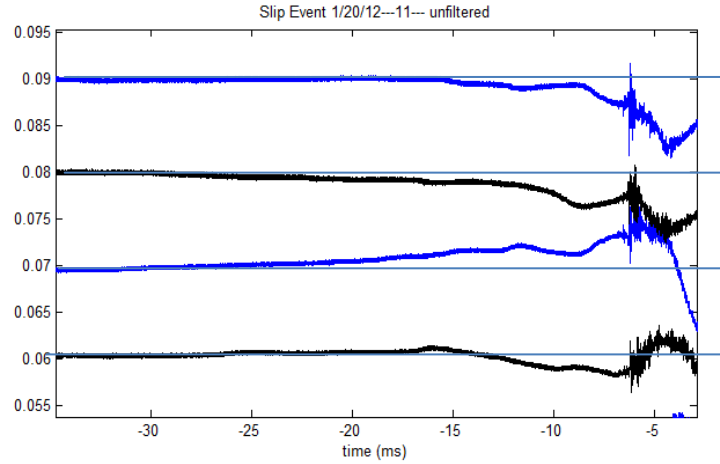
- Collocated with and preceeding foreshocks



- Slow and aseismic slip is always detected before the foreshocks,
- The fault cannot instantaneously transition from locked and aseismic to slipping and radiating seismic waves, slip has to accelerate.







- The foreshocks we record are a by product of the nucleation of the larger stick-slip instability.

Observations

- Small part of the fault radiates seismically even though much of it is slipping up to 10 μm
- Low frequency ground deformations (i.e. aseismic slip transients) preceed collocated high frequency foreshocks
- Fault slip appears to be smoothly accelerating even though seismicity occurs in sparse bursts.
- Foreshocks only occur in the final 10s of ms before stick slip and do not occur if nucleation proceeds at a slower rate.

Conclusions

- Foreshocks are caused by fault strength heterogeneity and are a by product of the nucleation of a larger event.
- The tiny events cannot spontaneously nucleate on their own, they must be driven by aseismic slip of neighboring fault sections.