Slow-to-fast earthquake nucleation in the lower crust of central Alaska

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Kyle Smith
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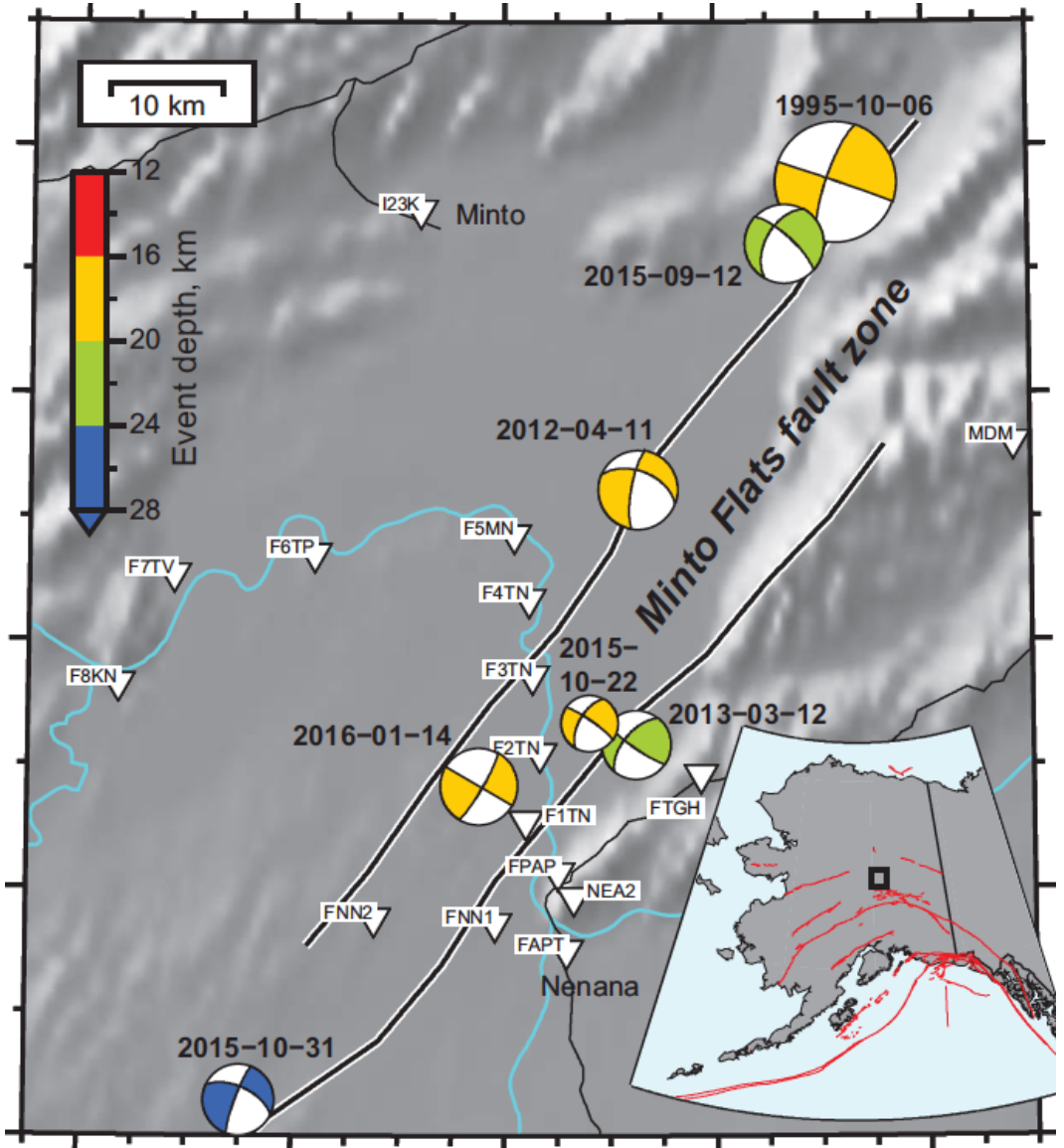
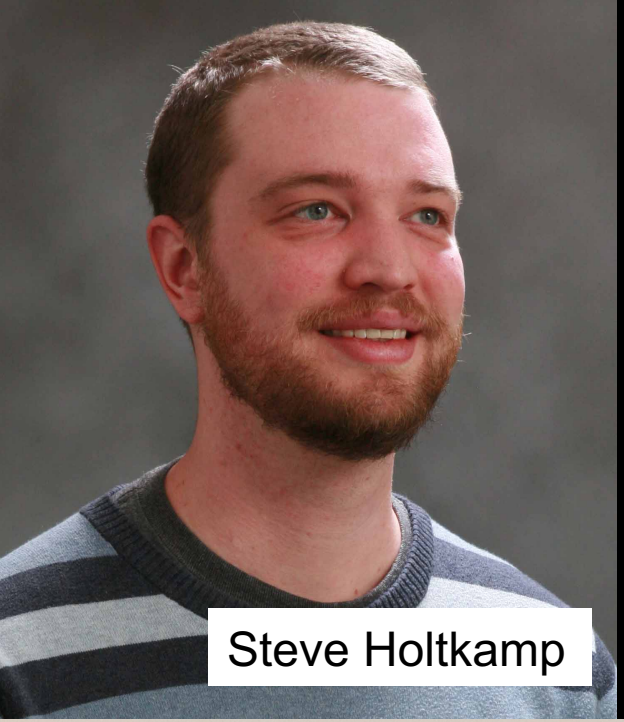
EarthScope National Meeting
Anchorage, Alaska
May 17, 2017




Steve Holtkamp


Vipul Silwal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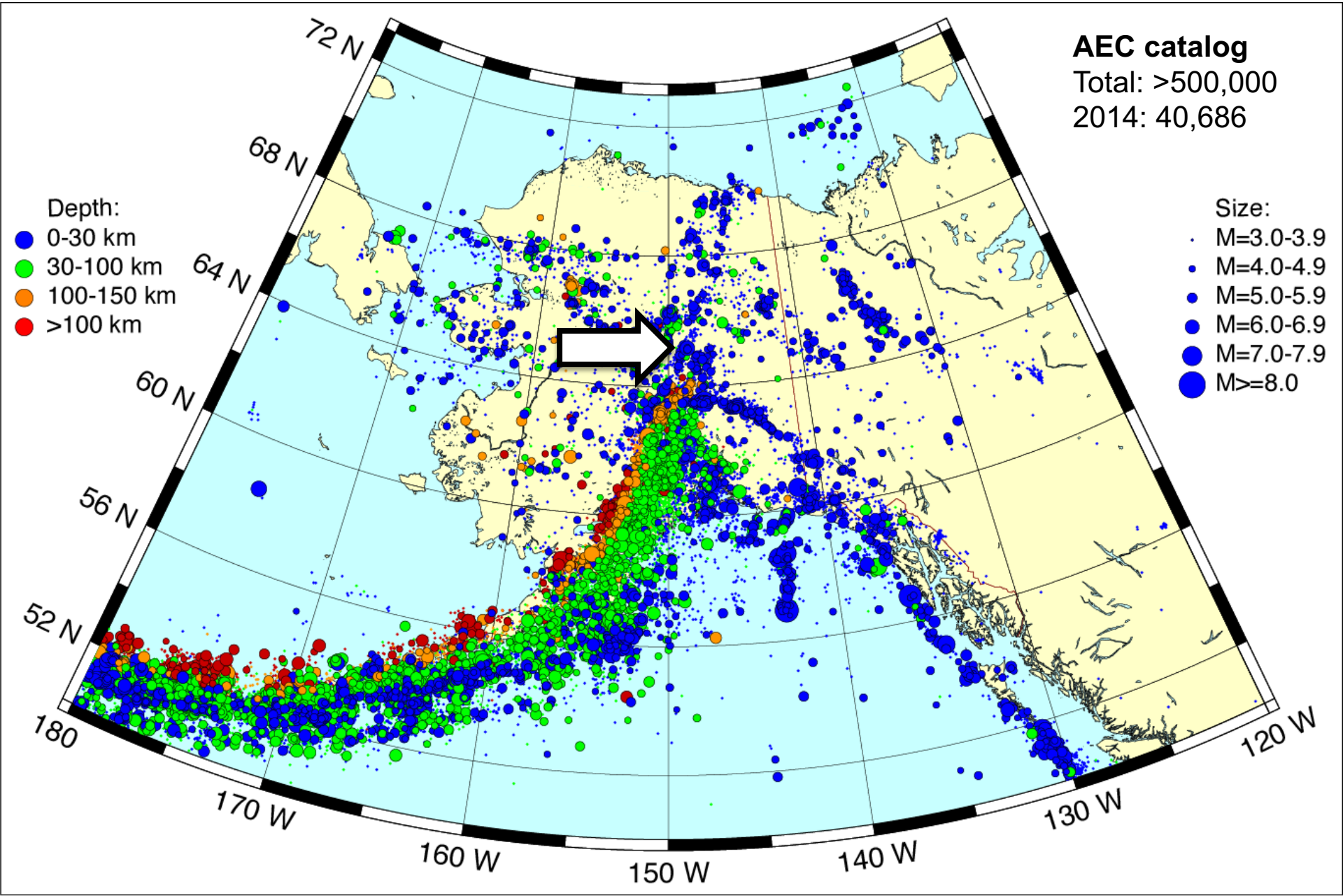
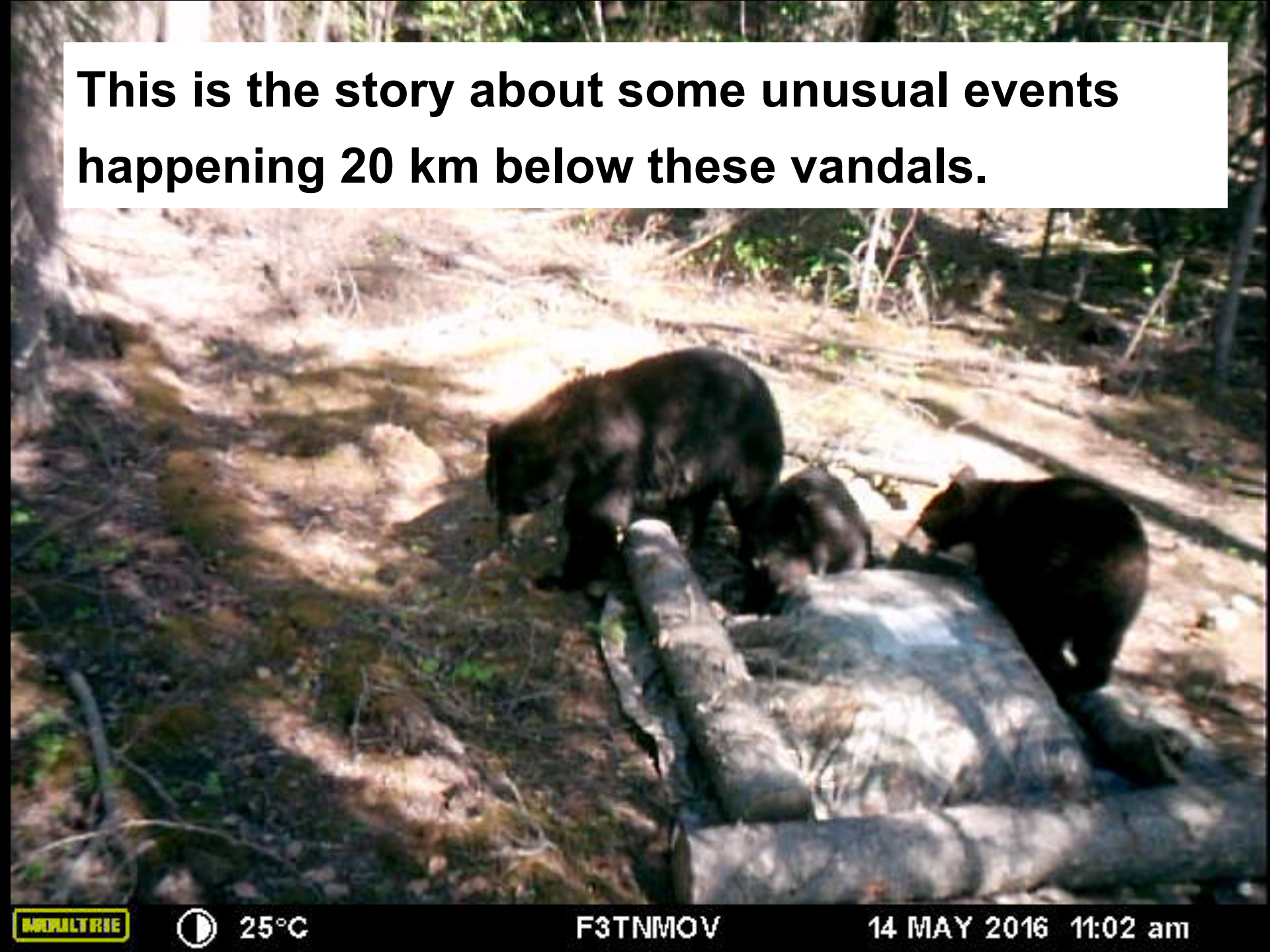
Natalia Ruppert


Mike West


AEC catalog
Total: >500,000
2014: 40,686
Depth:
0-30 km
30-100 km
100-150 km
>100 km
Size:
M=3.0-3.9
M=4.0-4.9
M=5.0-5.9
M=6.0-6.9
M=7.0-7.9
M>=8.0
72 N
68 N
64 N
60 N
56 N
52 N
180
170 W
160 W
150 W
140 W
130 W
120 W


This is the story about some unusual events happening 20 km below these vandals.
MOULTRIE
25°C
F3TNMOV
14 MAY 2016 11:02 am

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Earthquake nucleation and triggering on an optimally oriented fault

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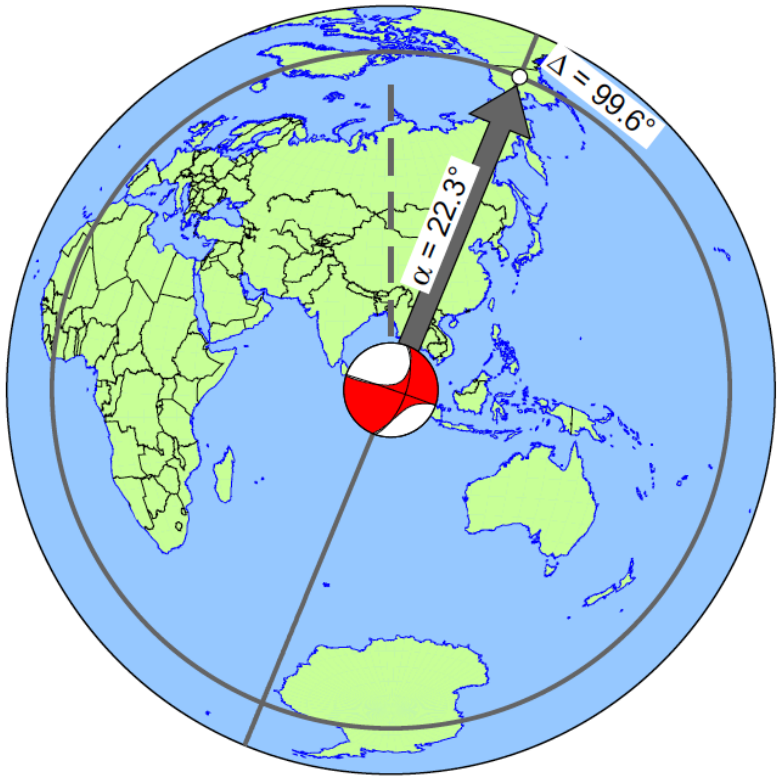
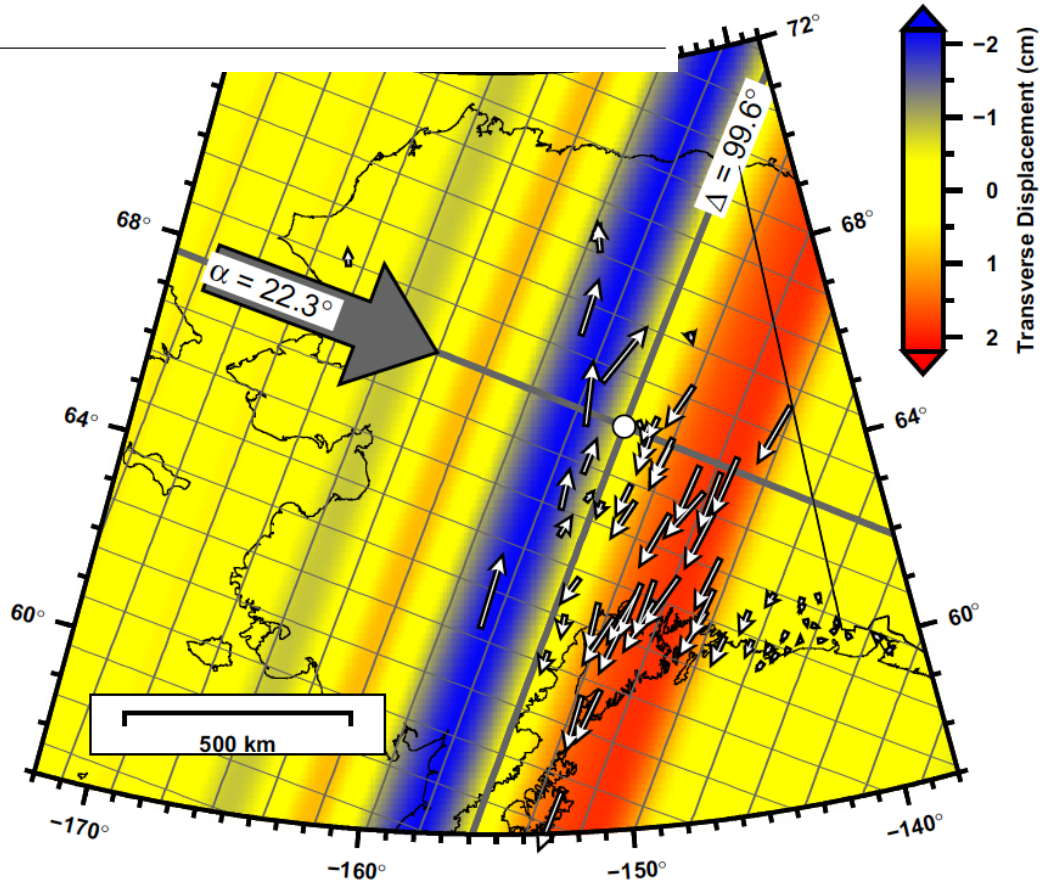
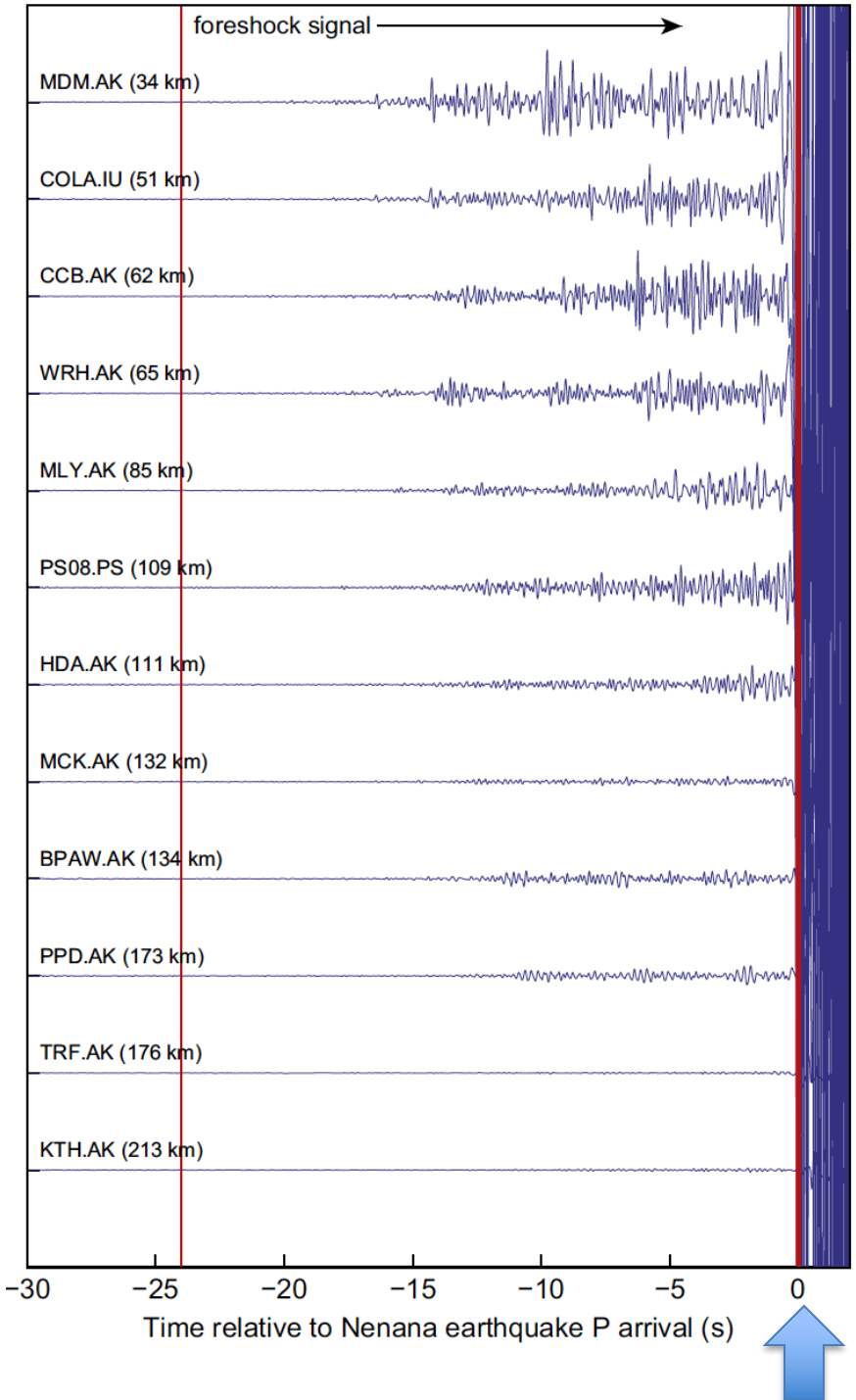
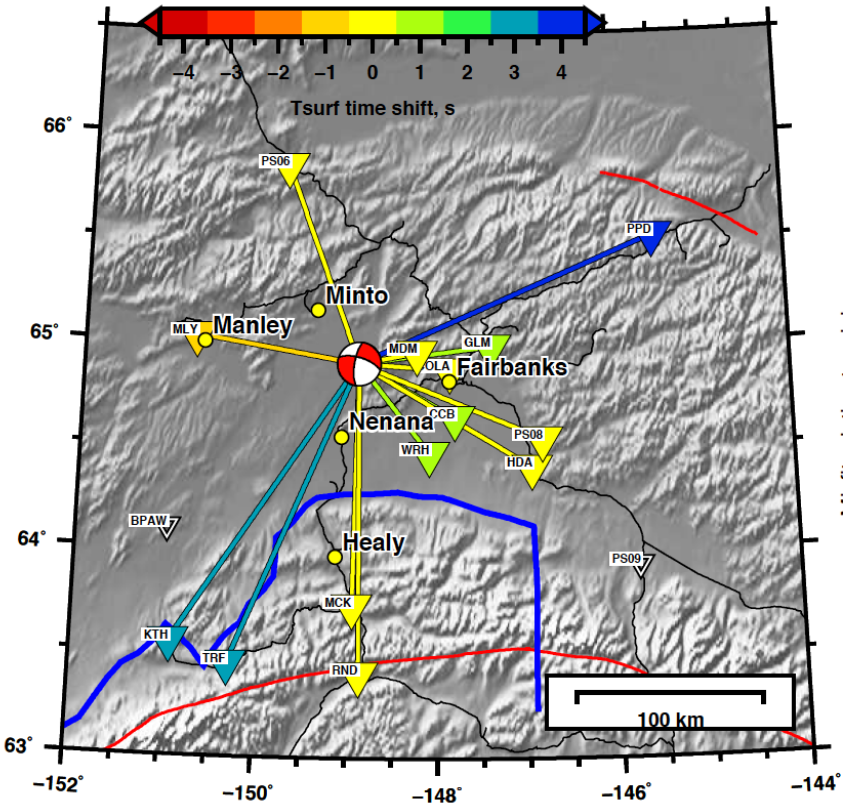
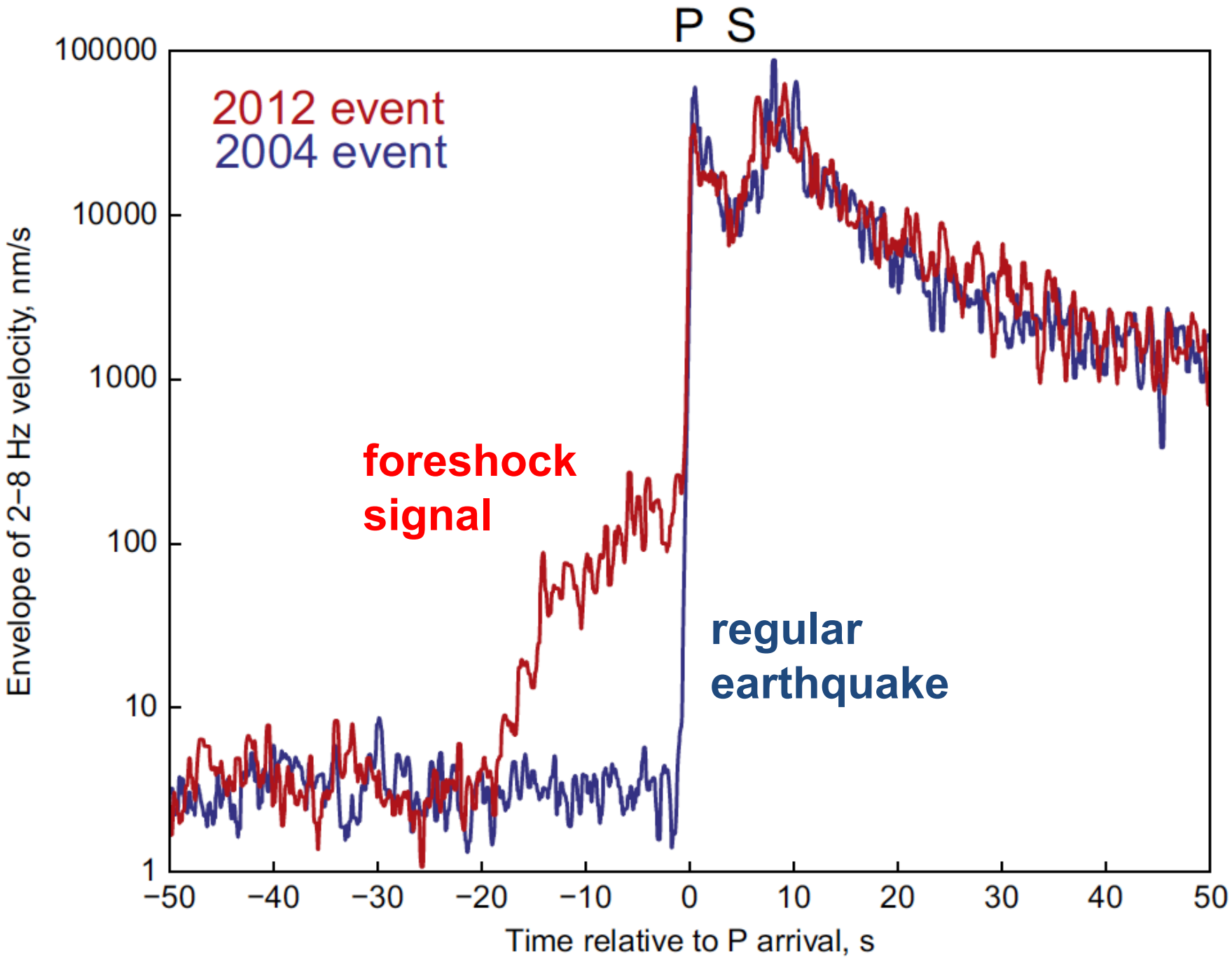


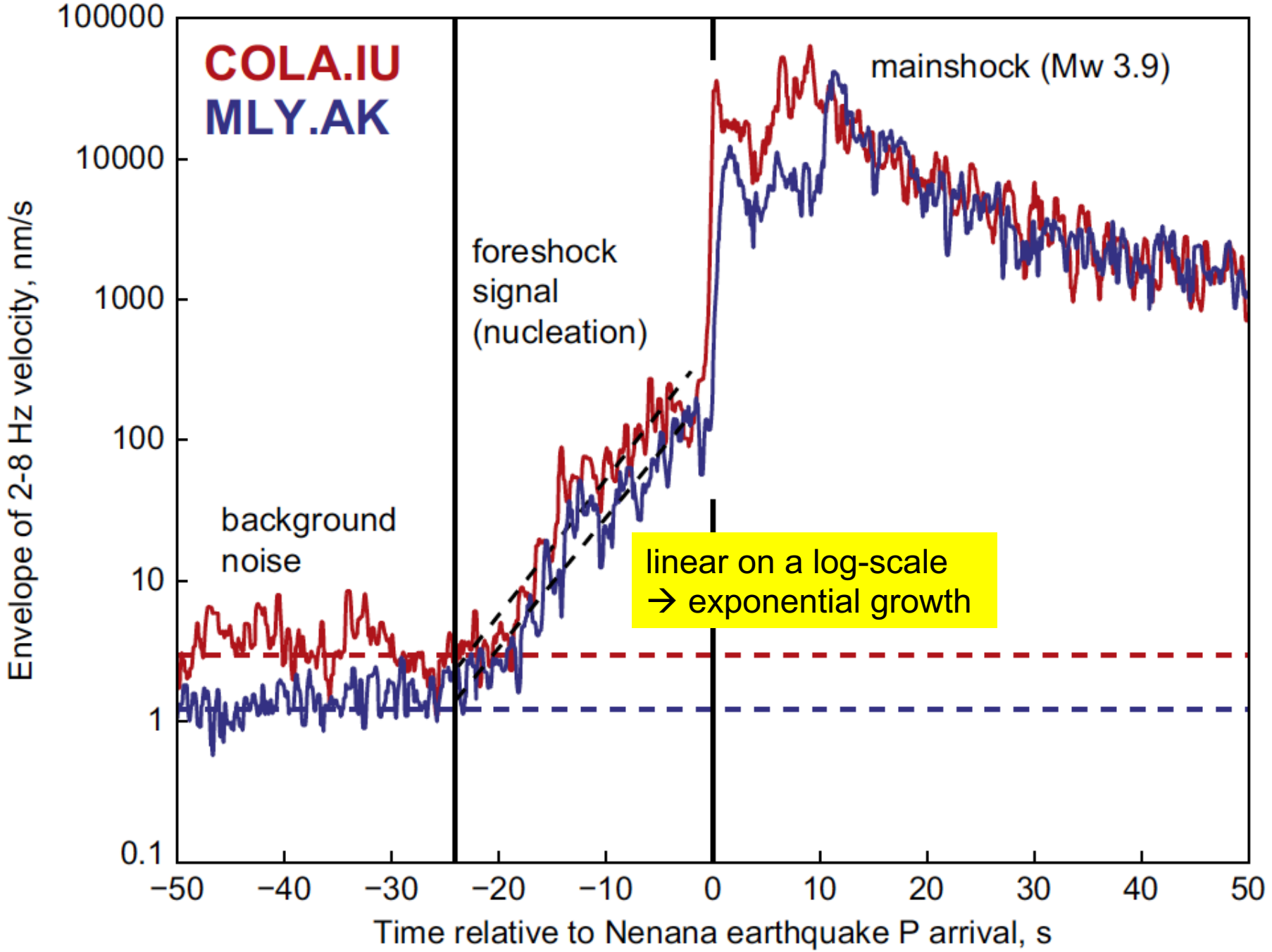






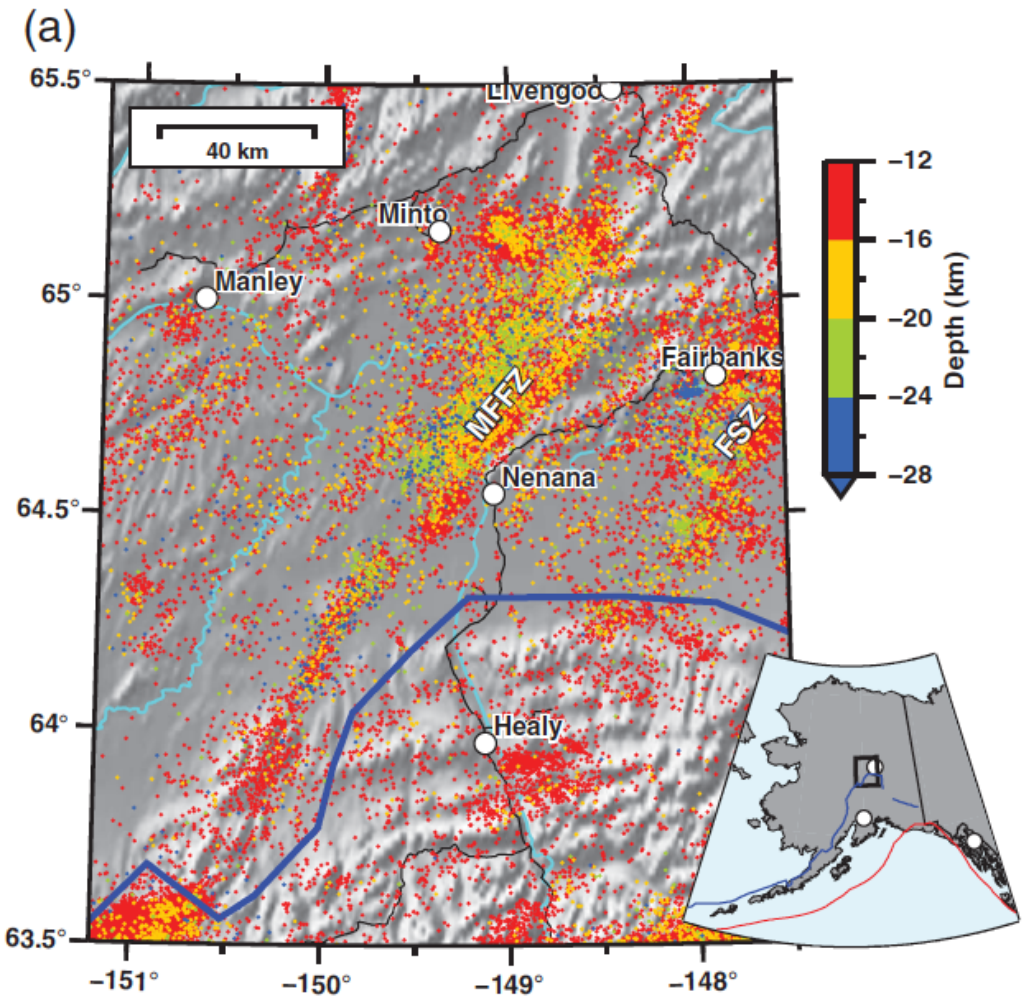
Vipul Silwal

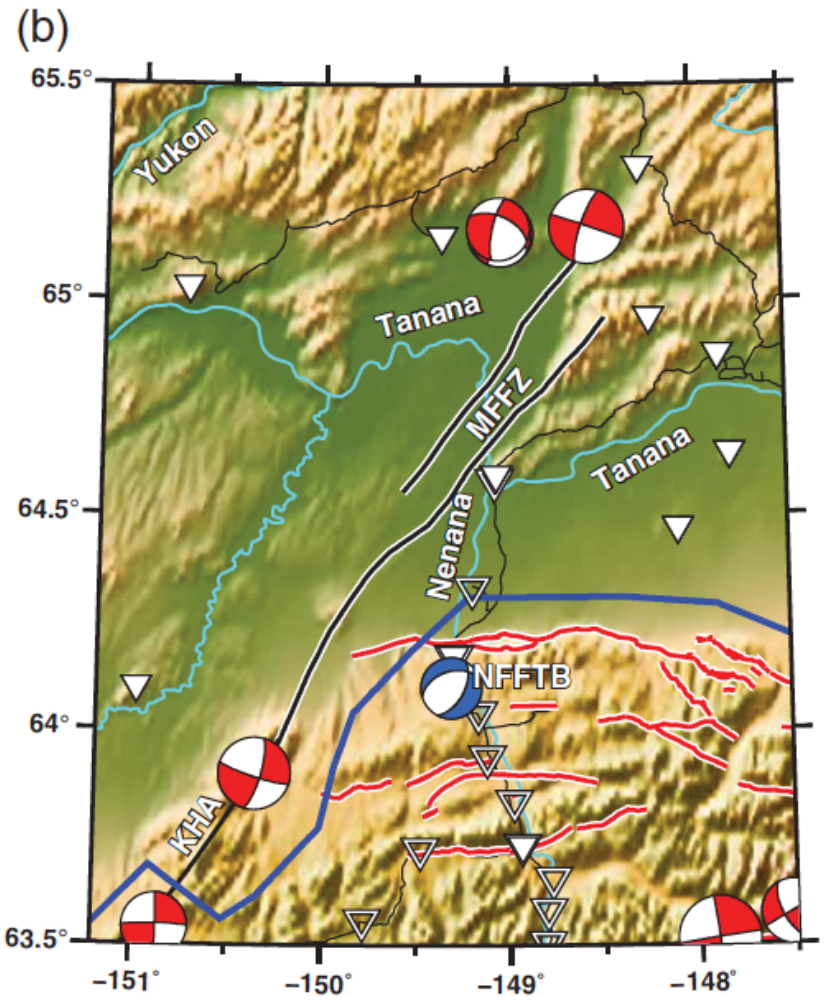

P S
2012 event
2004 event
foreshock signal
regular earthquake
Envelope of 2–8 Hz velocity, nm/s
100000
10000
1000
100
10
1
−50
−40
−30
−20
−10
0
10
20
30
40
50
Time relative to P arrival, s

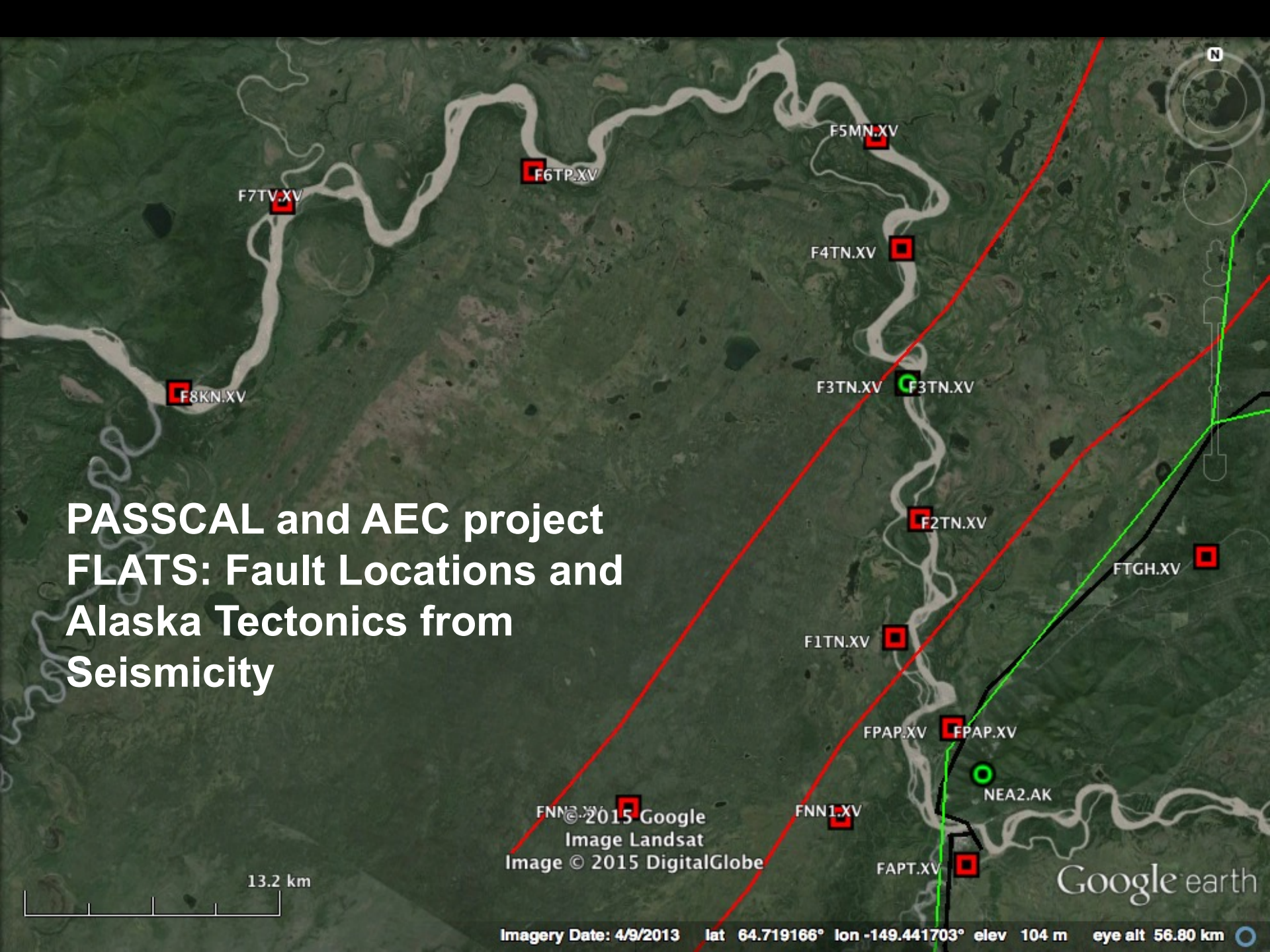

COLA.IU
MLY.AK
mainshock (Mw 3.9)
foreshock
signal
(nucleation)
background
noise
linear on a log-scale
→ exponential growth
Envelope of 2-8 Hz velocity, nm/s
100000
10000
1000
100
10
1
0.1
−50
−40
−30
−20
−10
0
10
20
30
40
50
Time relative to Nenana earthquake P arrival, s

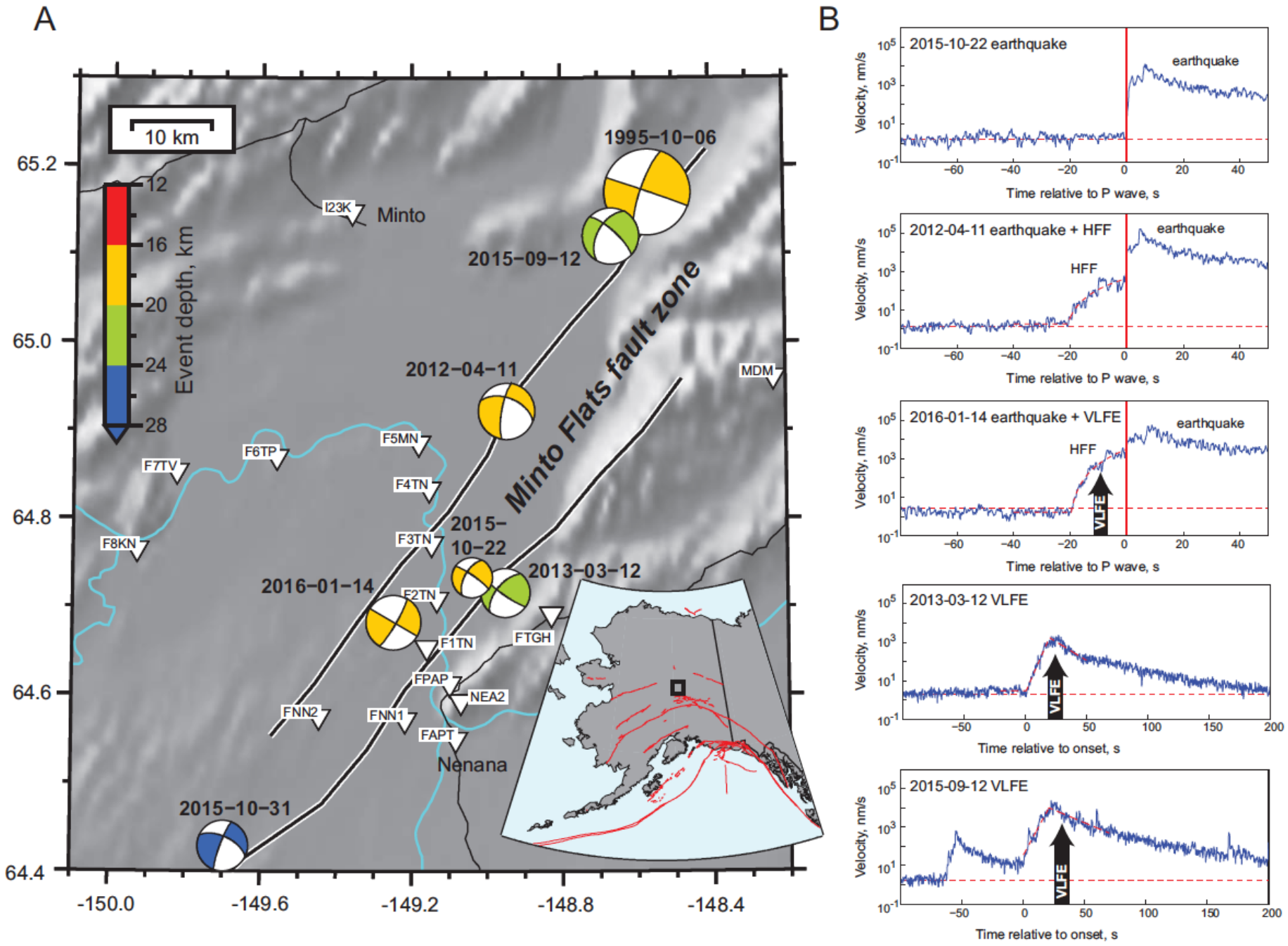
Minto Flats fault zone + Nenana basin

= transtensional tectonic setting



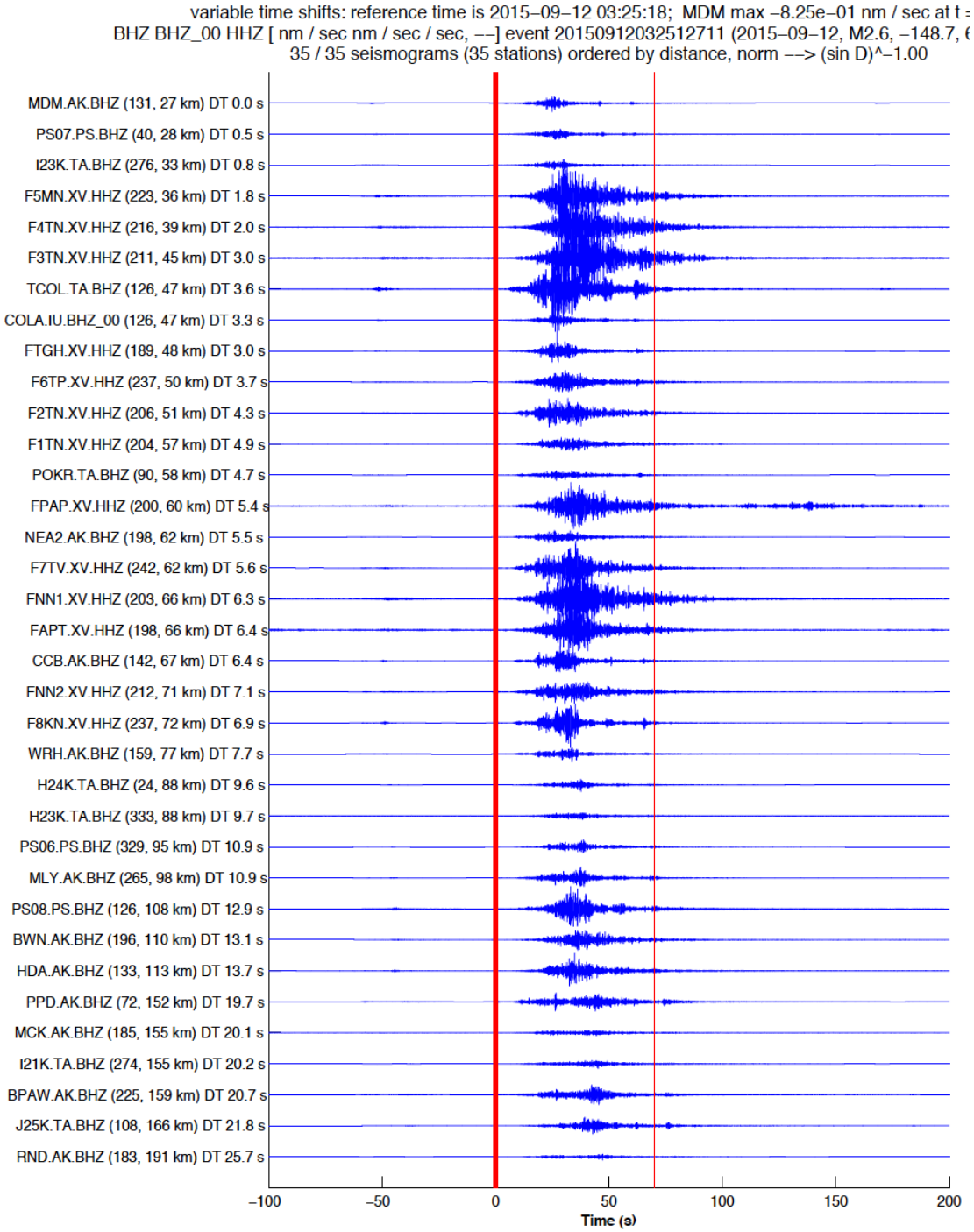



PASSCAL and AEC project FLATS: Fault Locations and Alaska Tectonics from Seismicity
F5MN.XV
F6TP.XV
F7TV.XV
F4TN.XV
F8KN.XV
F3TN.XV
F3TN.XV
F2TN.XV
FTGH.XV
F1TN.XV
FPAP.XV
FPAP.XV
NEA2.AK
FNN1.XV
FAPT.XV
© 2015 Google
Image Landsat
Image © 2015 DigitalGlobe
13.2 km
Google earth
Imagery Date: 4/9/2013 lat 64.719166° lon -149.441703° elev 104 m eye alt 56.80 km


A
B
10 km
Event depth, km
12
16
20
24
28
65.2
65.0
64.8
64.6
64.4
-150.0
-149.6
-149.2
-148.8
-148.4
I23K
Minto
1995–10–06
2015–09–12
2012–04–11
Minto Flats fault zone
MDM
F5MN
F6TP
F7TV
F4TN
F8KN
F3TN
2015–
10–22
2013–03–12
2016–01–14
F2TN
FTGH
F1TN
FPAP
NEA2
FNN2
FNN1
FAPT
Nenana
2015–10–31
2015-10-22 earthquake
earthquake
Velocity, nm/s
Time relative to P wave, s
2012-04-11 earthquake + HFF
HFF
2016-01-14 earthquake + VLFE
VLFE
2013-03-12 VLFE
Time relative to onset, s
2015-09-12 VLFE

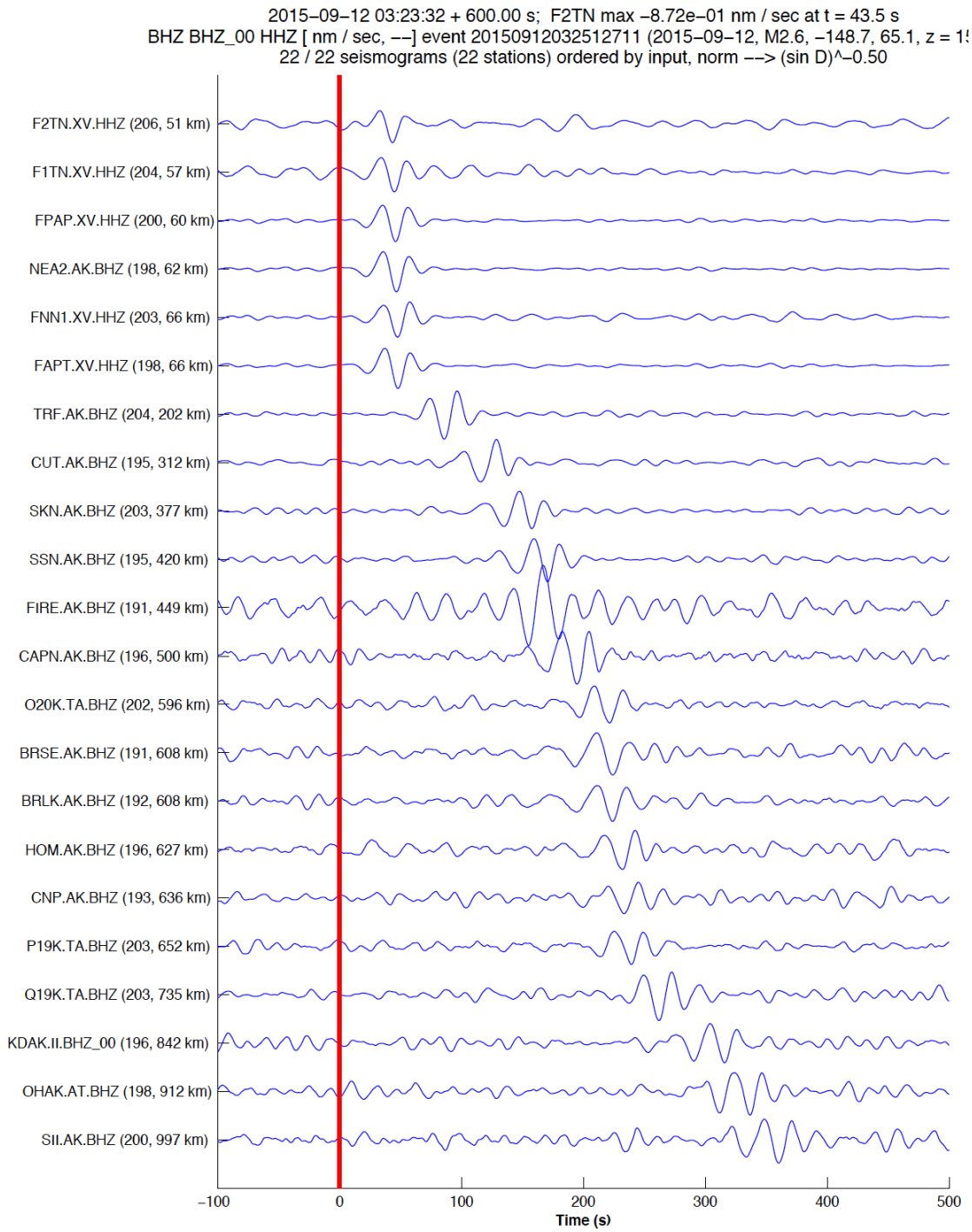
2015 very low frequency earthquake (VLFE)

Mw 3.8

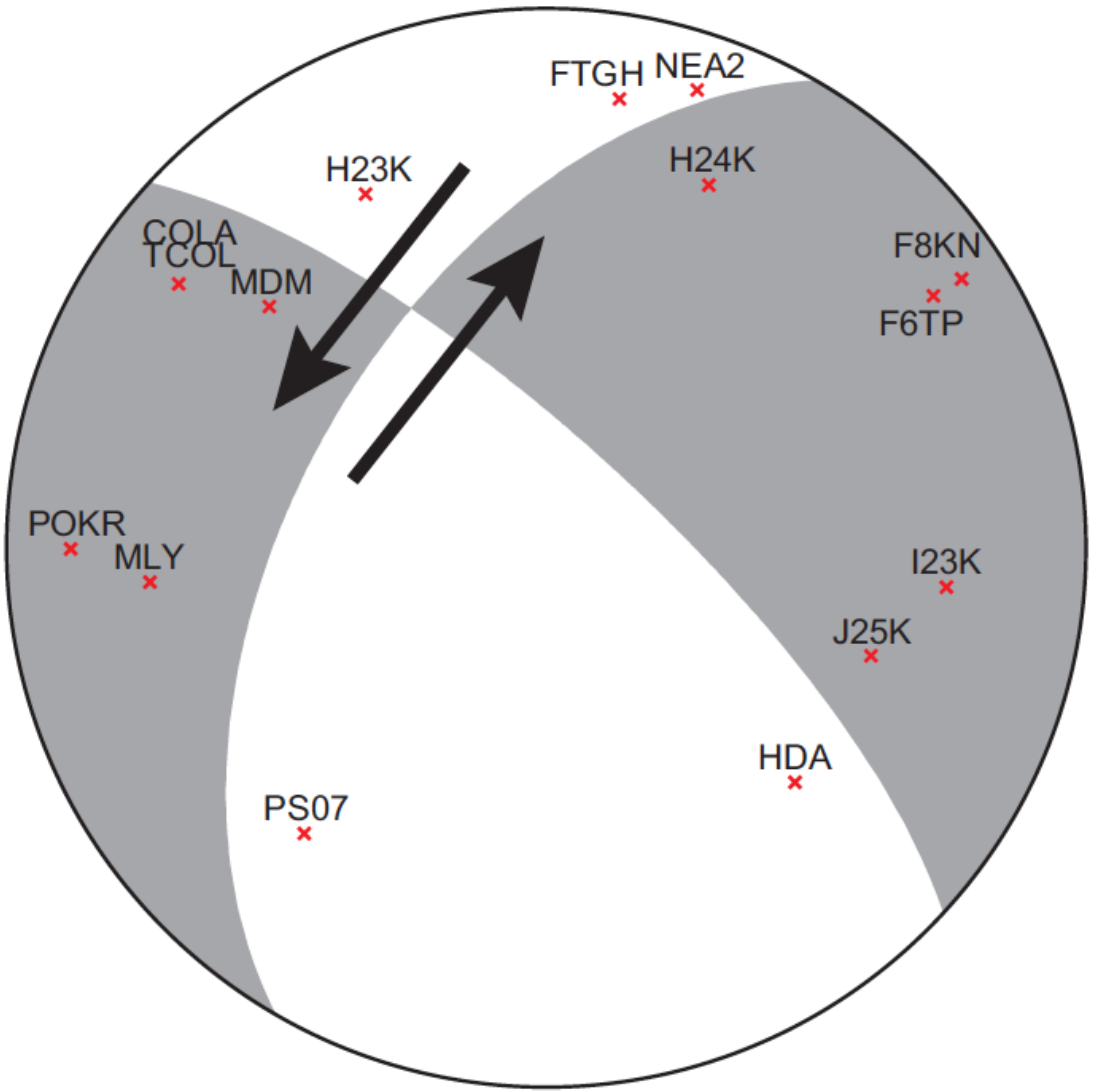

variable time shifts: reference time is 2015–09–12 03:25:18; MDM max –8.25e–01 nm / sec at t =
BHZ BHZ_00 HHZ [nm / sec nm / sec / sec, ––] event 20150912032512711 (2015–09–12, M2.6, –148.7, 6
35 / 35 seismograms (35 stations) ordered by distance, norm ––> (sin D)^–1.00
MDM.AK.BHZ (131, 27 km) DT 0.0 s
PS07.PS.BHZ (40, 28 km) DT 0.5 s
I23K.TA.BHZ (276, 33 km) DT 0.8 s
F5MN.XV.HHZ (223, 36 km) DT 1.8 s
F4TN.XV.HHZ (216, 39 km) DT 2.0 s
F3TN.XV.HHZ (211, 45 km) DT 3.0 s
TCOL.TA.BHZ (126, 47 km) DT 3.6 s
COLA.IU.BHZ_00 (126, 47 km) DT 3.3 s
FTGH.XV.HHZ (189, 48 km) DT 3.0 s
F6TP.XV.HHZ (237, 50 km) DT 3.7 s
F2TN.XV.HHZ (206, 51 km) DT 4.3 s
F1TN.XV.HHZ (204, 57 km) DT 4.9 s
POKR.TA.BHZ (90, 58 km) DT 4.7 s
FPAP.XV.HHZ (200, 60 km) DT 5.4 s
NEA2.AK.BHZ (198, 62 km) DT 5.5 s
F7TV.XV.HHZ (242, 62 km) DT 5.6 s
FNN1.XV.HHZ (203, 66 km) DT 6.3 s
FAPT.XV.HHZ (198, 66 km) DT 6.4 s
CCB.AK.BHZ (142, 67 km) DT 6.4 s
FNN2.XV.HHZ (212, 71 km) DT 7.1 s
F8KN.XV.HHZ (237, 72 km) DT 6.9 s
WRH.AK.BHZ (159, 77 km) DT 7.7 s
H24K.TA.BHZ (24, 88 km) DT 9.6 s
H23K.TA.BHZ (333, 88 km) DT 9.7 s
PS06.PS.BHZ (329, 95 km) DT 10.9 s
MLY.AK.BHZ (265, 98 km) DT 10.9 s
PS08.PS.BHZ (126, 108 km) DT 12.9 s
BWN.AK.BHZ (196, 110 km) DT 13.1 s
HDA.AK.BHZ (133, 113 km) DT 13.7 s
PPD.AK.BHZ (72, 152 km) DT 19.7 s
MCK.AK.BHZ (185, 155 km) DT 20.1 s
I21K.TA.BHZ (274, 155 km) DT 20.2 s
BPAW.AK.BHZ (225, 159 km) DT 20.7 s
J25K.TA.BHZ (108, 166 km) DT 21.8 s
RND.AK.BHZ (183, 191 km) DT 25.7 s
–100
–50
0
50
100
150
200
Time (s)

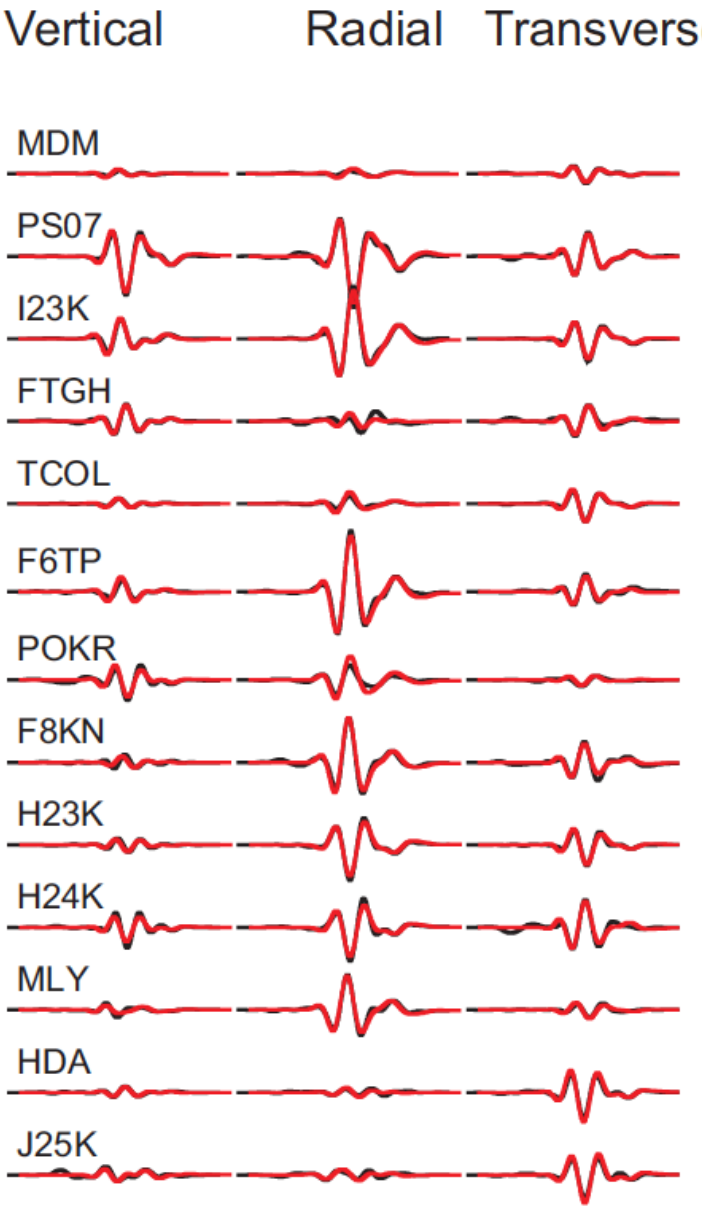
Mw 3.8 event clearly visible at 1000 km!

(bandpass 20-50 s)

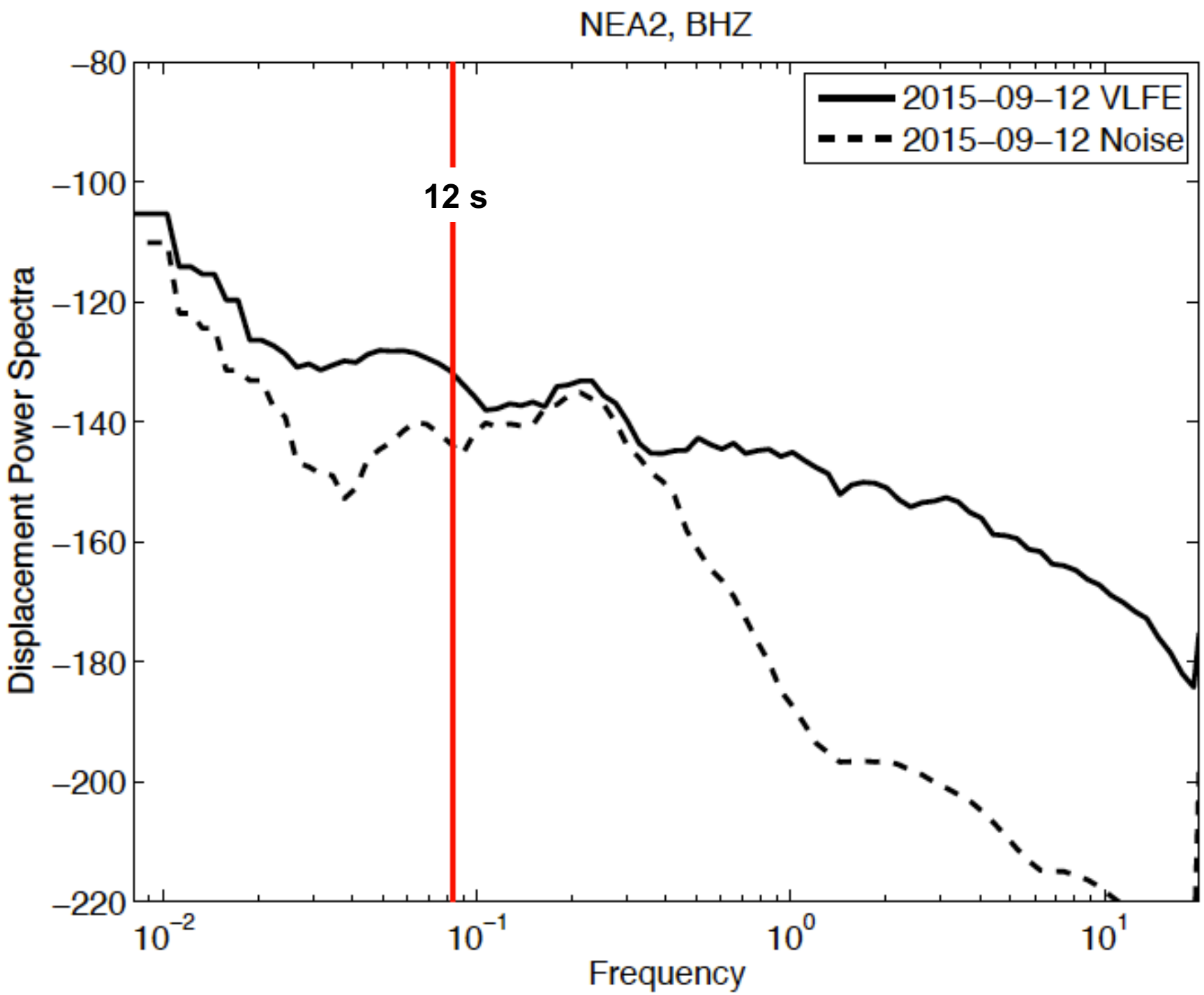


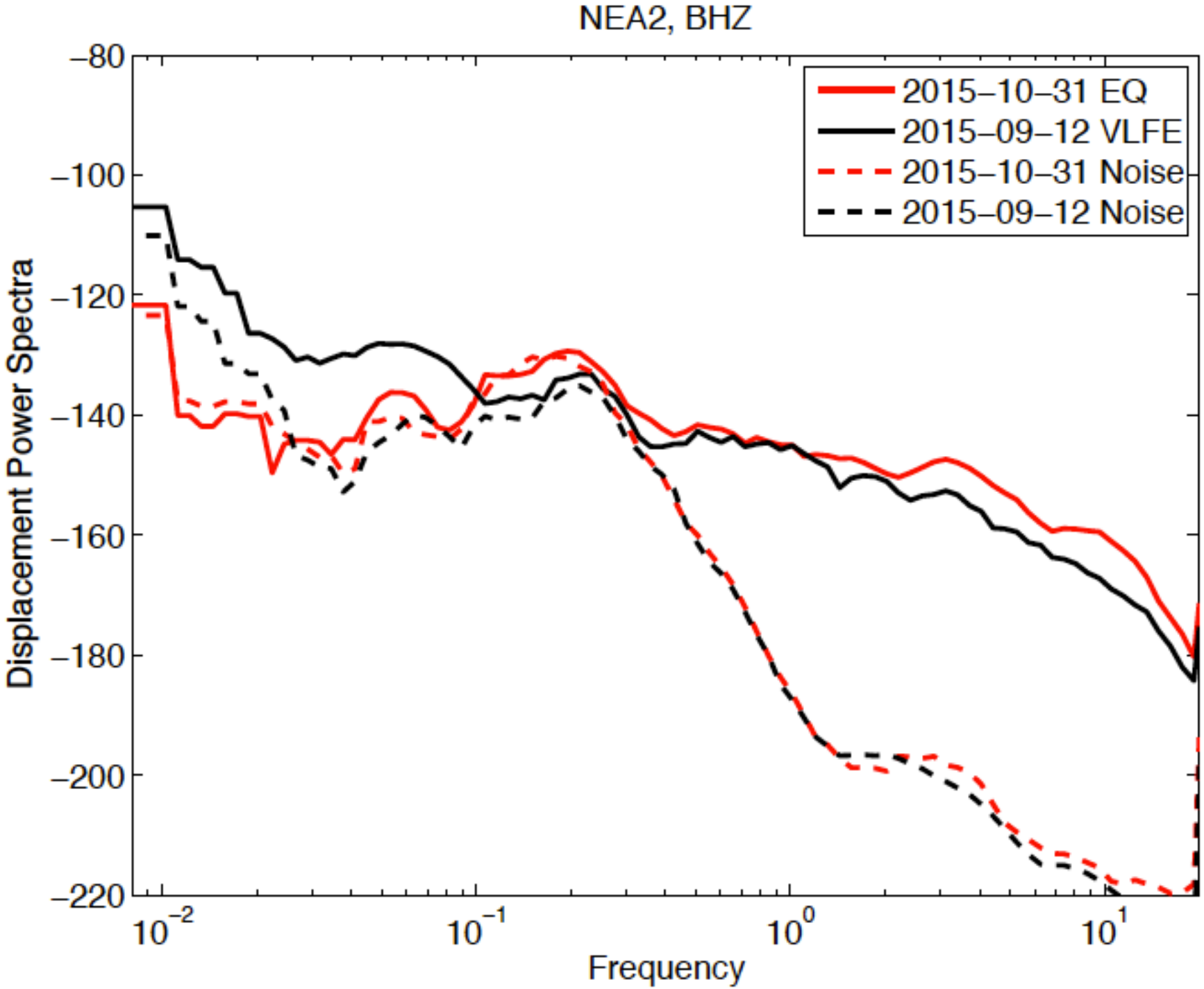
A 2015-09-12 very low frequency earthquake (VLFE)

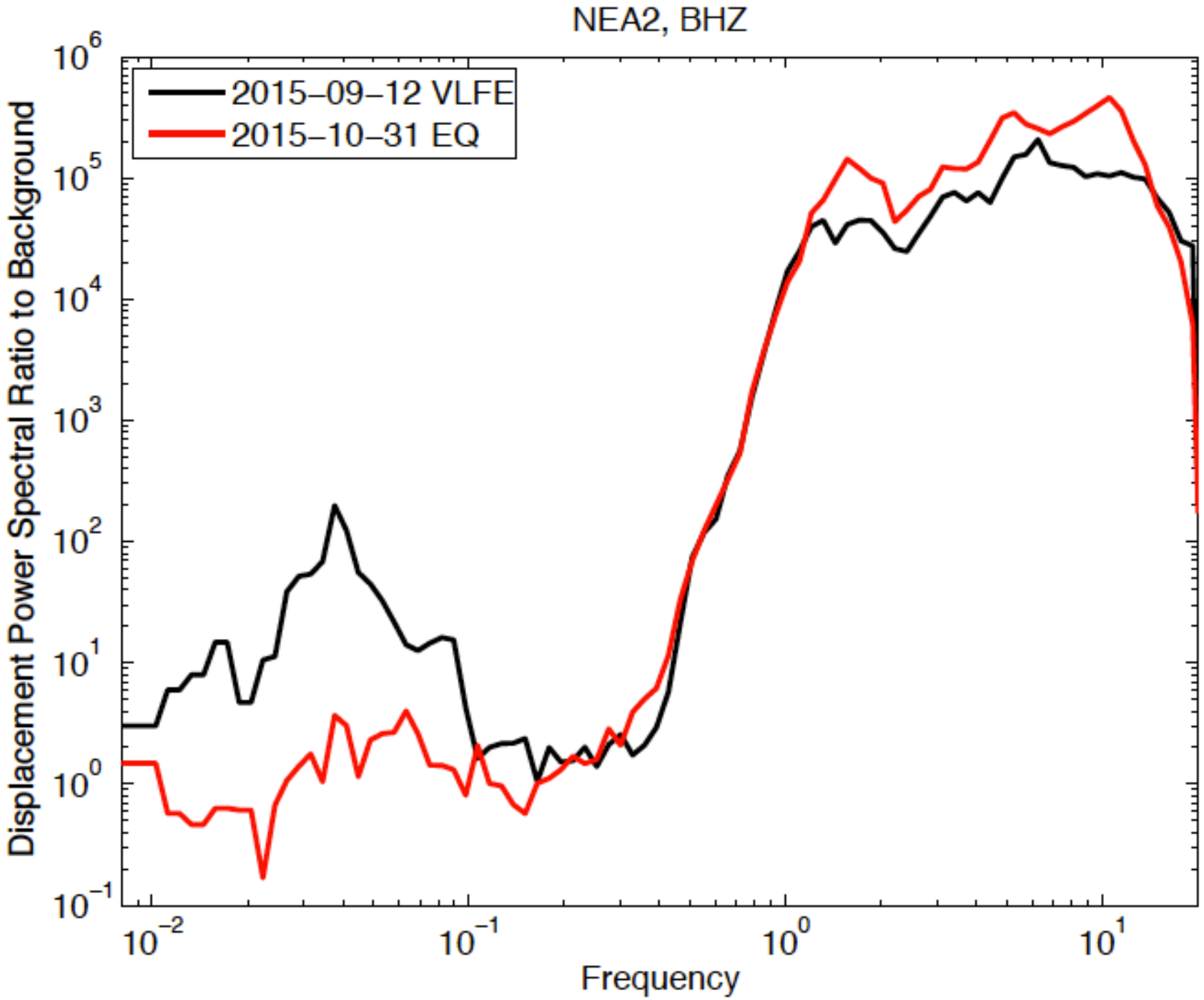


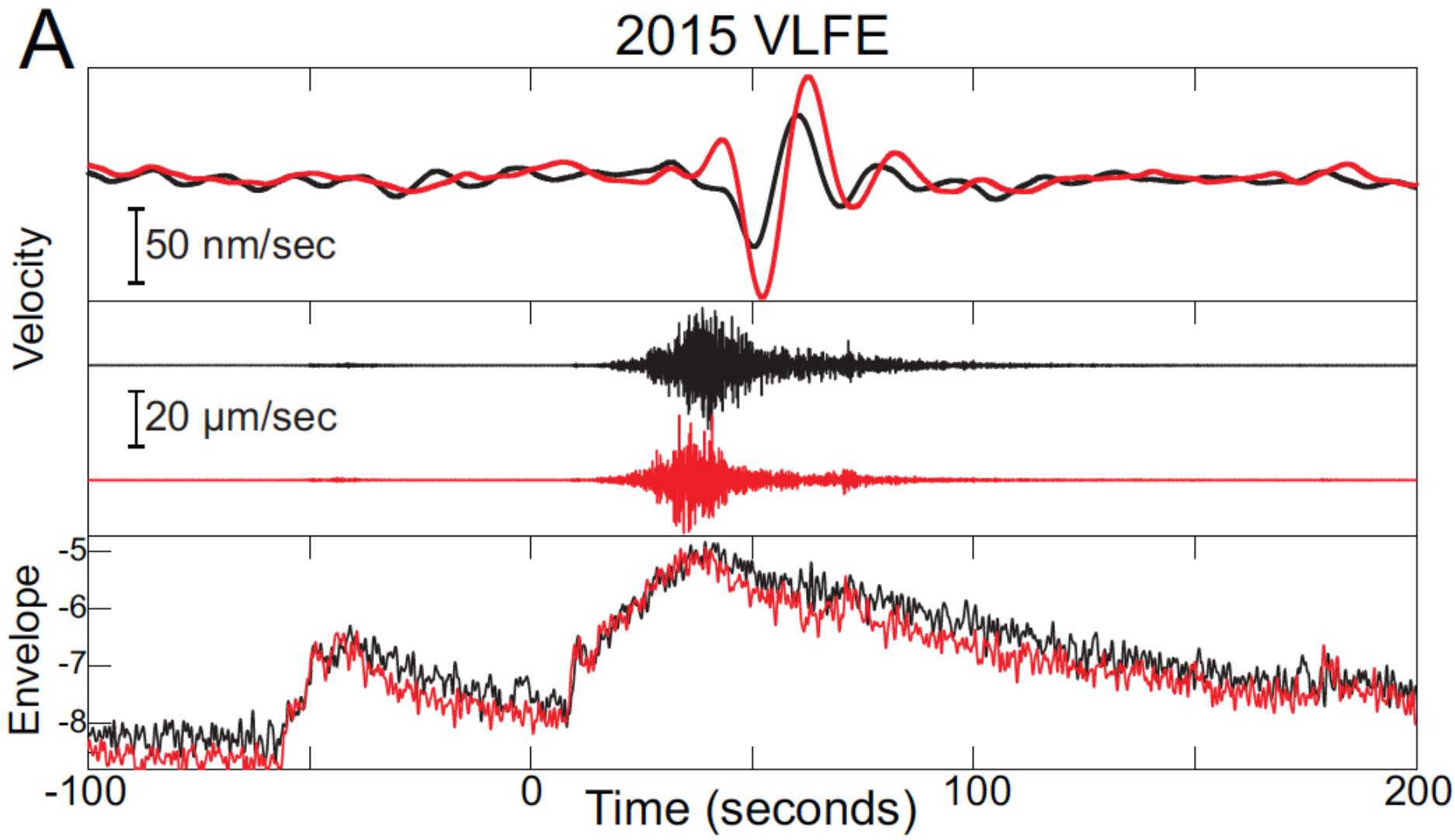


Vipul Silwal


NEA2, BHZ
2015–09–12 VLFE
2015–09–12 Noise
12 s
Displacement Power Spectra
Frequency
–80
–100
–120
–140
–160
–180
–200
–220
10^{-2}
10^{-1}
10^{0}
10^{1}

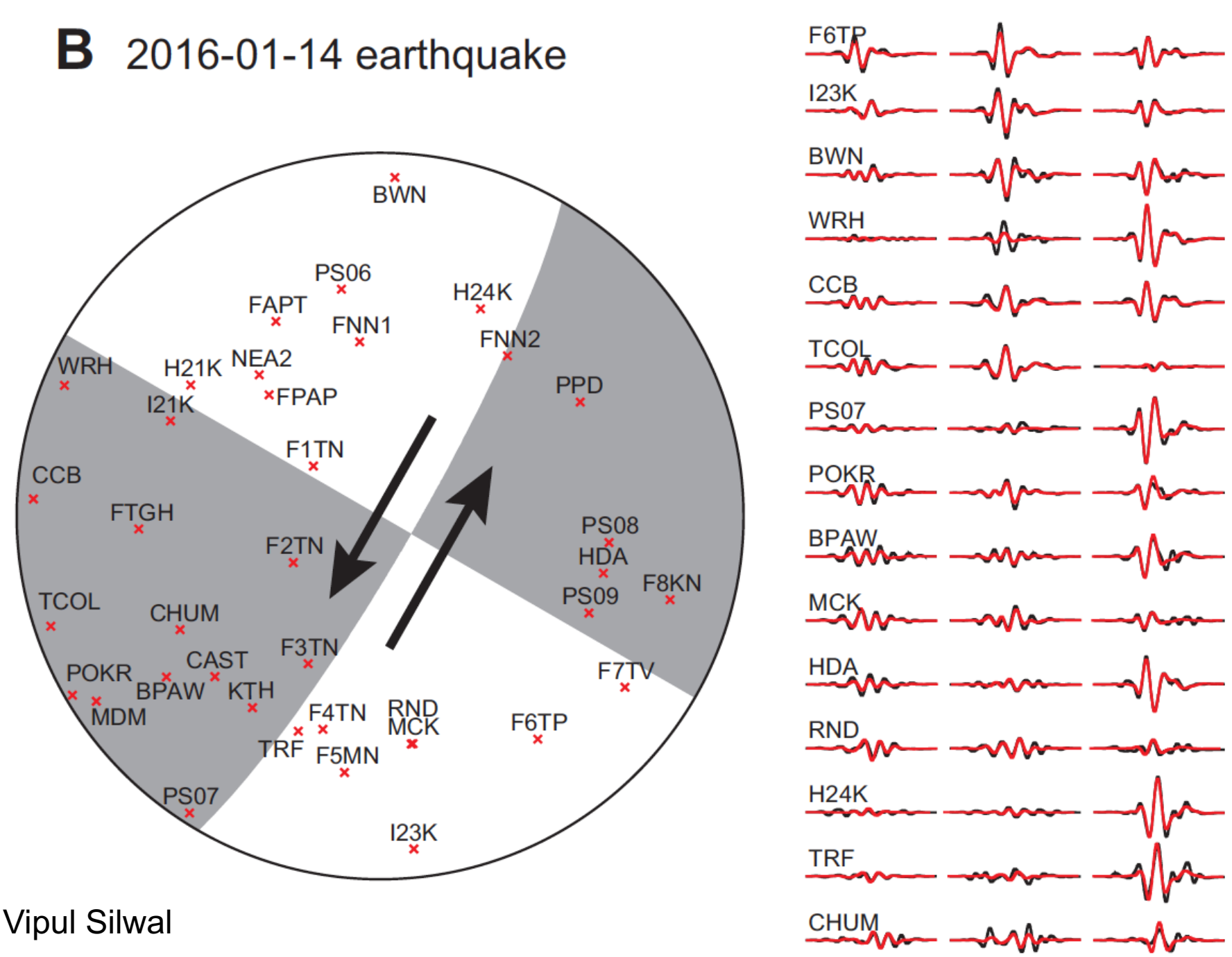

NEA2, BHZ
2015–10–31 EQ
2015–09–12 VLFE
2015–10–31 Noise
2015–09–12 Noise
Displacement Power Spectra
Frequency
–80
–100
–120
–140
–160
–180
–200
–220
10^{-2}
10^{-1}
10^{0}
10^{1}


NEA2, BHZ
2015–09–12 VLFE
2015–10–31 EQ
Displacement Power Spectral Ratio to Background
Frequency
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-1}
10^{0}
10^{1}

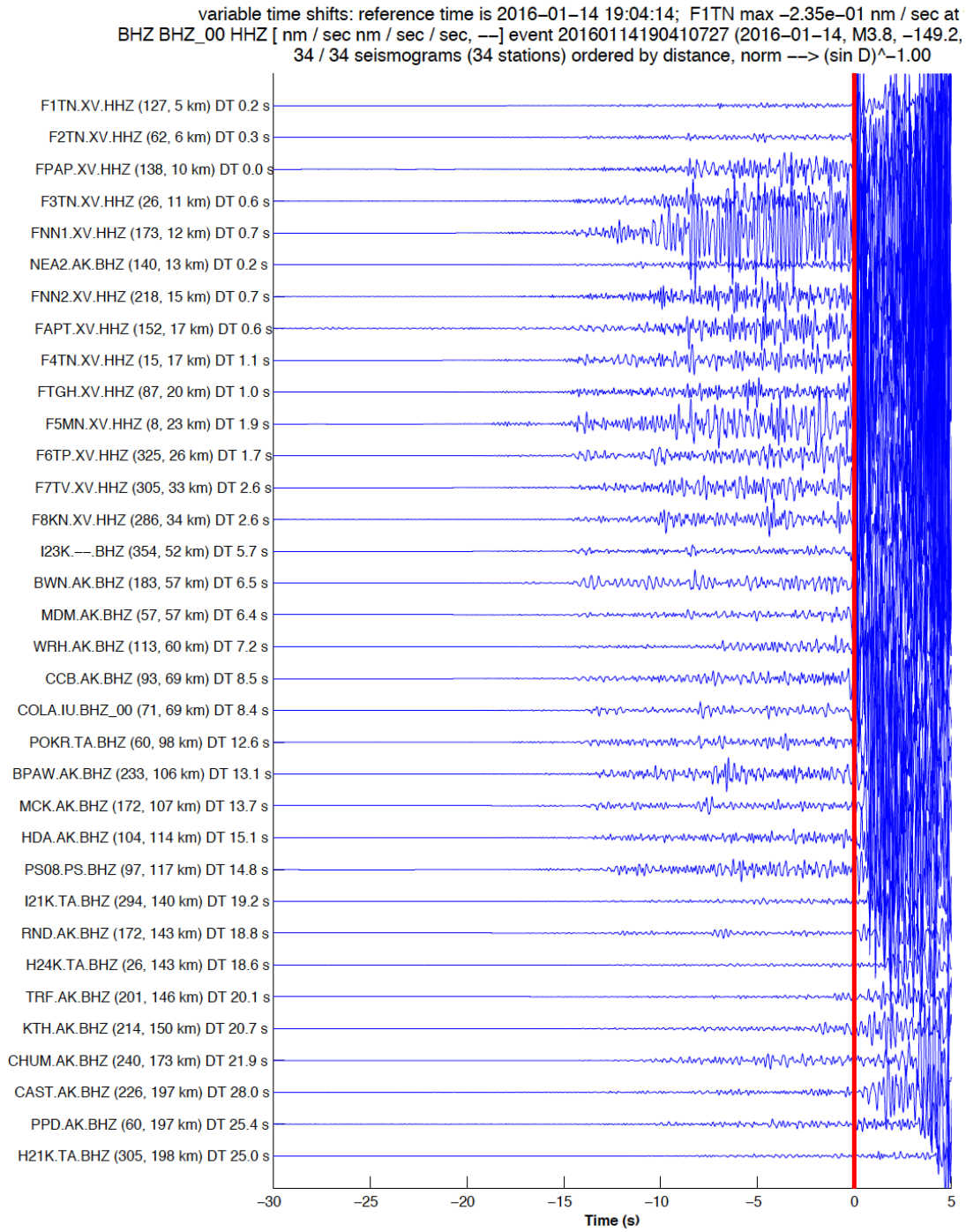

A
2015 VLFE
Velocity
50 nm/sec
20 μm/sec
Envelope
-5
-6
-7
-8
-100
0
100
200
Time (seconds)

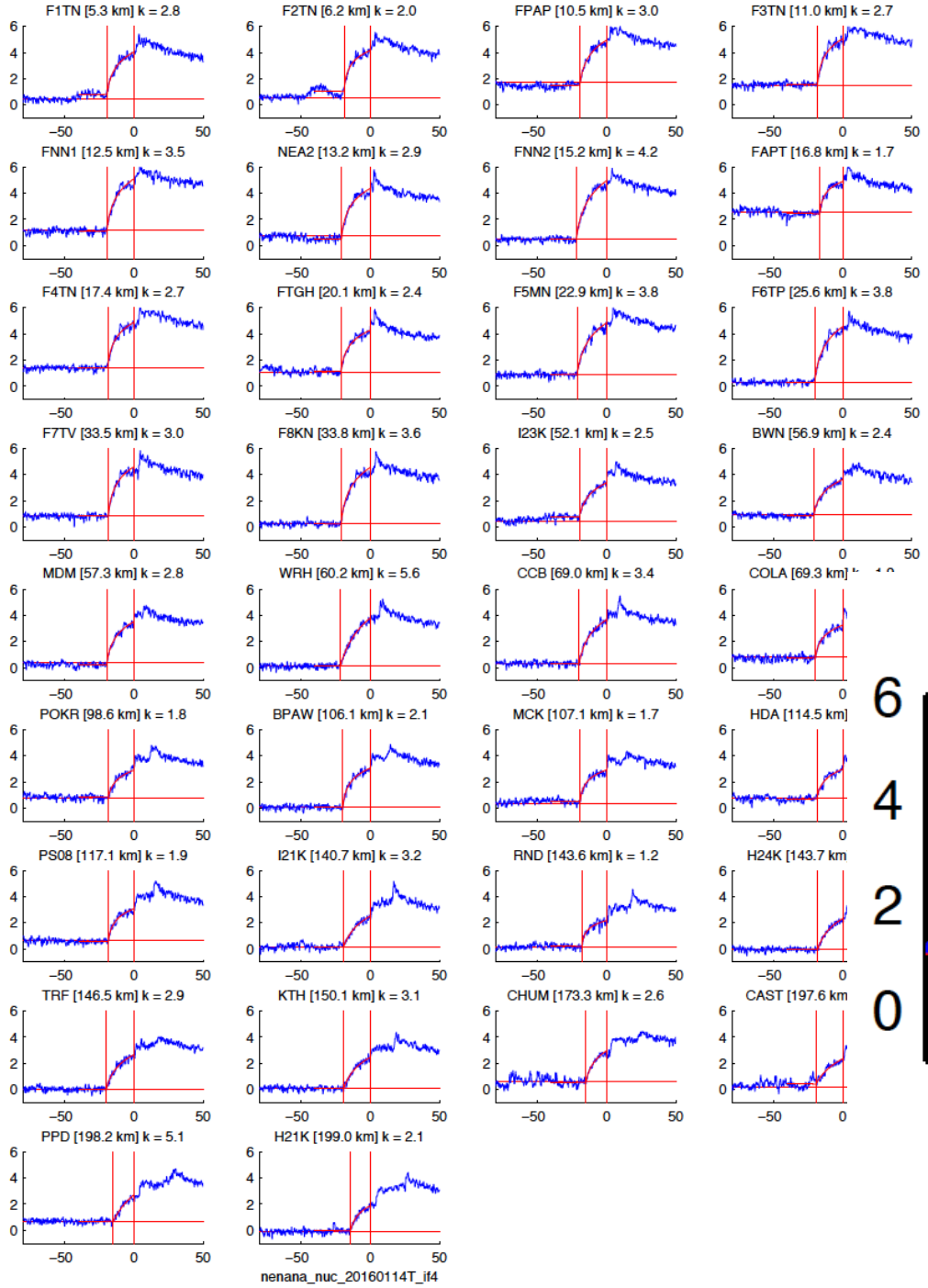
2016 earthquake

Mw 3.8



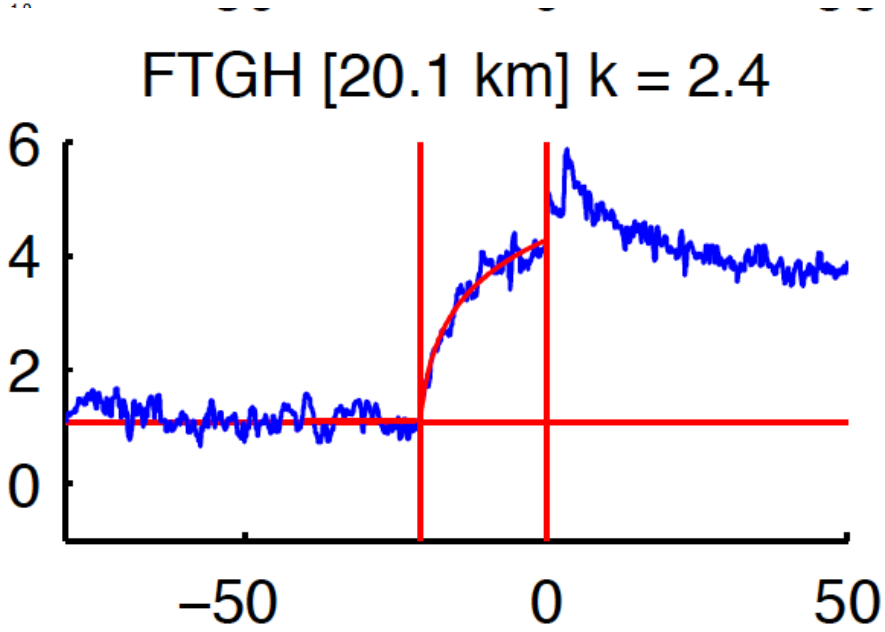
Vipul Silwal

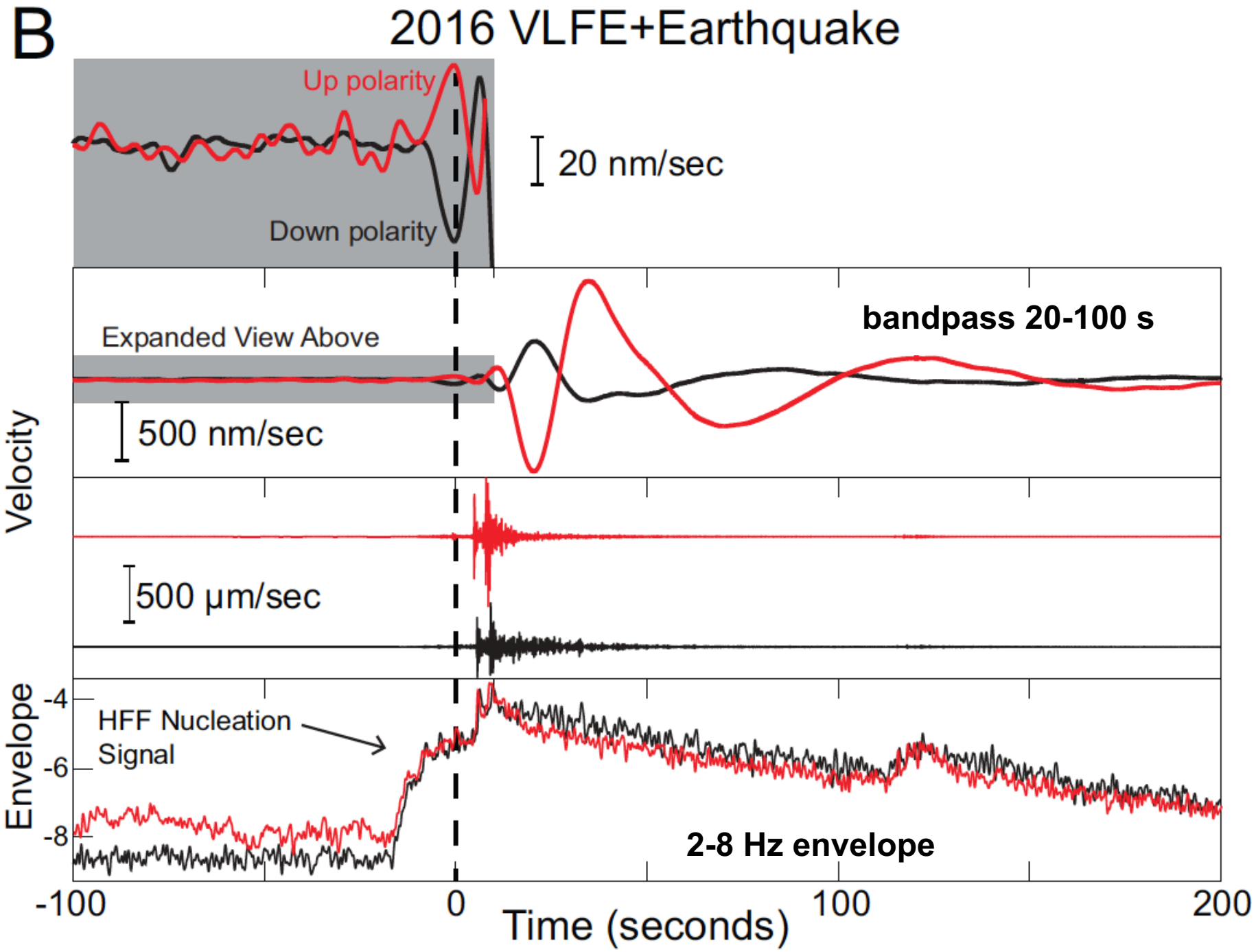

variable time shifts: reference time is 2016–01–14 19:04:14; F1TN max –2.35e–01 nm / sec at
BHZ BHZ_00 HHZ [nm / sec nm / sec / sec, ––] event 20160114190410727 (2016–01–14, M3.8, –149.2,
34 / 34 seismograms (34 stations) ordered by distance, norm –––> (sin D)^–1.00
F1TN.XV.HHZ (127, 5 km) DT 0.2 s
F2TN.XV.HHZ (62, 6 km) DT 0.3 s
FPAP.XV.HHZ (138, 10 km) DT 0.0 s
F3TN.XV.HHZ (26, 11 km) DT 0.6 s
FNN1.XV.HHZ (173, 12 km) DT 0.7 s
NEA2.AK.BHZ (140, 13 km) DT 0.2 s
FNN2.XV.HHZ (218, 15 km) DT 0.7 s
FAPT.XV.HHZ (152, 17 km) DT 0.6 s
F4TN.XV.HHZ (15, 17 km) DT 1.1 s
FTGH.XV.HHZ (87, 20 km) DT 1.0 s
F5MN.XV.HHZ (8, 23 km) DT 1.9 s
F6TP.XV.HHZ (325, 26 km) DT 1.7 s
F7TV.XV.HHZ (305, 33 km) DT 2.6 s
F8KN.XV.HHZ (286, 34 km) DT 2.6 s
I23K.––.BHZ (354, 52 km) DT 5.7 s
BWN.AK.BHZ (183, 57 km) DT 6.5 s
MDM.AK.BHZ (57, 57 km) DT 6.4 s
WRH.AK.BHZ (113, 60 km) DT 7.2 s
CCB.AK.BHZ (93, 69 km) DT 8.5 s
COLA.IU.BHZ_00 (71, 69 km) DT 8.4 s
POKR.TA.BHZ (60, 98 km) DT 12.6 s
BPAW.AK.BHZ (233, 106 km) DT 13.1 s
MCK.AK.BHZ (172, 107 km) DT 13.7 s
HDA.AK.BHZ (104, 114 km) DT 15.1 s
PS08.PS.BHZ (97, 117 km) DT 14.8 s
I21K.TA.BHZ (294, 140 km) DT 19.2 s
RND.AK.BHZ (172, 143 km) DT 18.8 s
H24K.TA.BHZ (26, 143 km) DT 18.6 s
TRF.AK.BHZ (201, 146 km) DT 20.1 s
KTH.AK.BHZ (214, 150 km) DT 20.7 s
CHUM.AK.BHZ (240, 173 km) DT 21.9 s
CAST.AK.BHZ (226, 197 km) DT 28.0 s
PPD.AK.BHZ (60, 197 km) DT 25.4 s
H21K.TA.BHZ (305, 198 km) DT 25.0 s
–30
–25
–20
–15
–10
–5
0
5
Time (s)

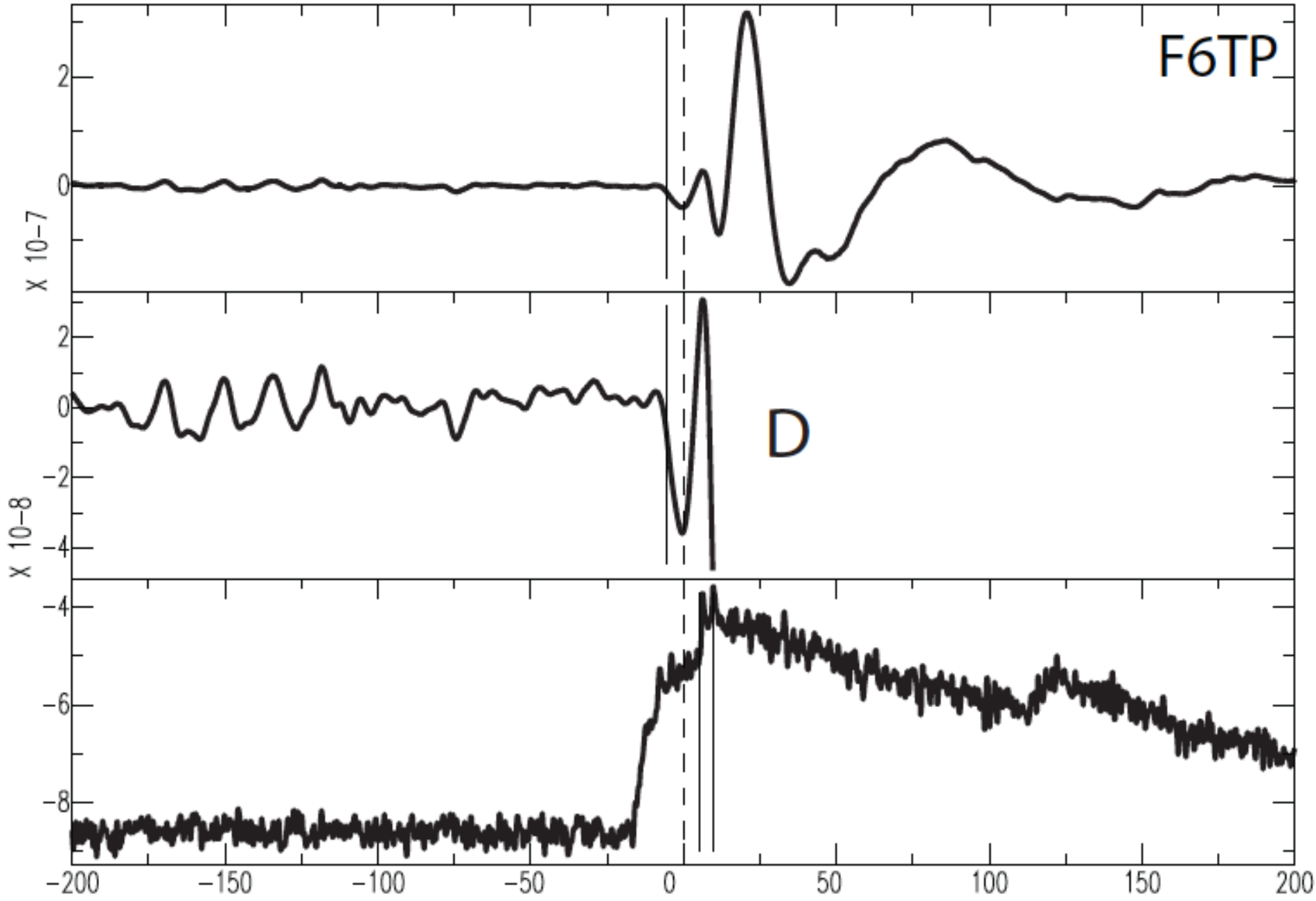


2-8 Hz envelopes of seismograms at the 34 closest stations to the 2016-01-14 earthquake

All stations exhibit the high-frequency foreshock signal.



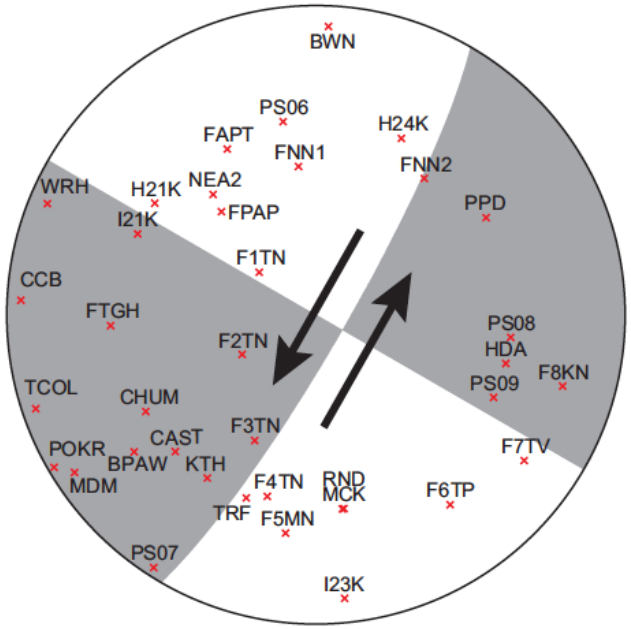

B
2016 VLFE+Earthquake
Up polarity
Down polarity
20 nm/sec
Expanded View Above
bandpass 20-100 s
500 nm/sec
Velocity
500 µm/sec
Envelope
-4
-6
-8
HFF Nucleation
Signal
2-8 Hz envelope
-100
0
100
200
Time (seconds)


F6TP
D
X 10−7
X 10−8
2
0
2
0
−2
−4
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200

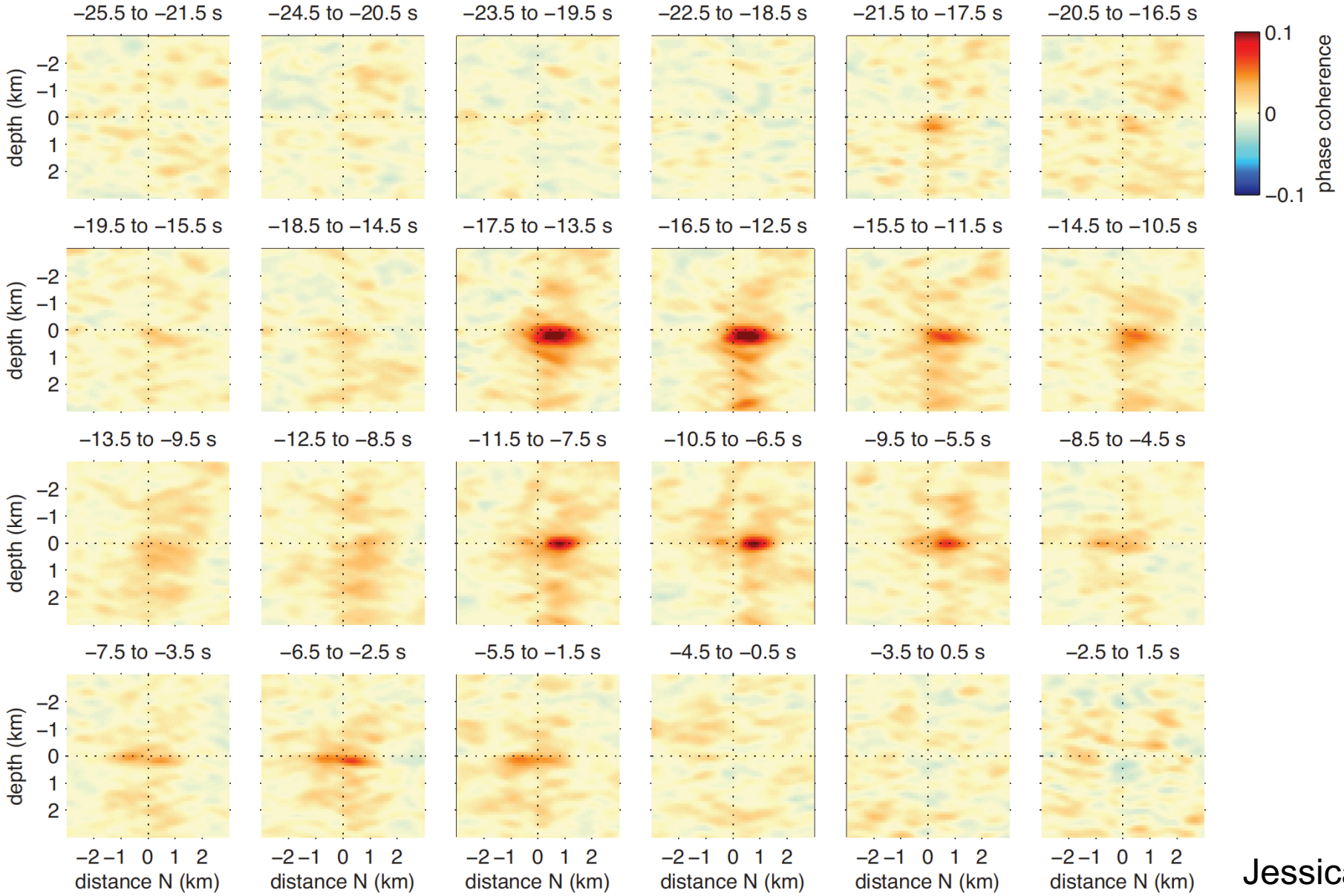
station	distance (km)	azimuth (°)	LFFP	HFP	LFP
F1TN	5.3	127	–	–	(D)
F2TN	6.2	62	–	U	U
FPAP	10.5	138	D	D	D
F3TN	11.0	26	–	U	(U)
FNN1	12.5	173	D	D	D
NEA2	13.2	140	D	D	D
FNN2	15.2	218	U?	D	(U)
FAPT	16.8	152	D	D	D
F4TN	17.4	15	D	–	(D)
FTGH	20.1	87	U	U	U
F5MN	22.9	8	D	D	D
F6TP	25.6	325	D	D	D

Polarity of amplitudes match among three measurements:

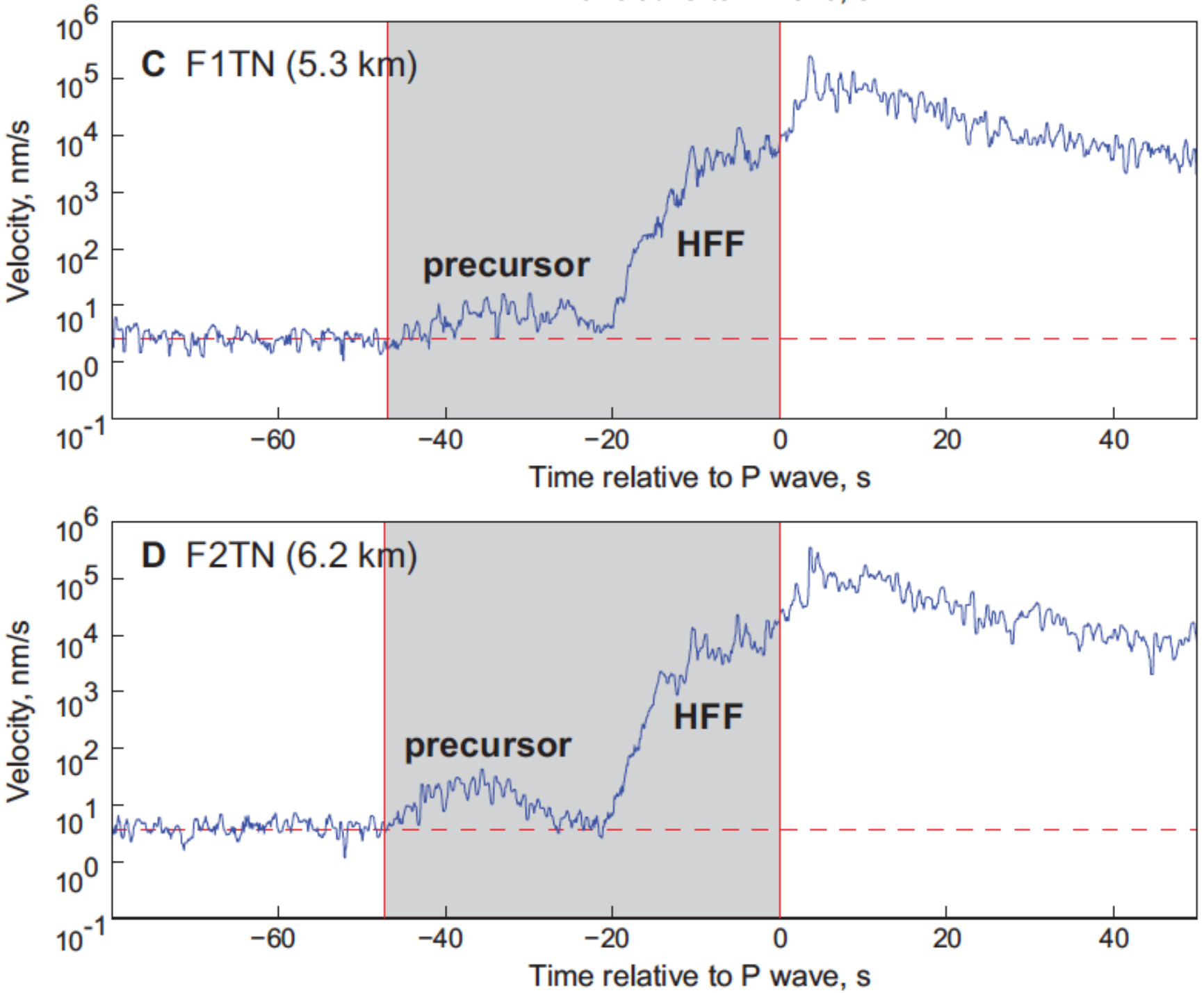
1. **low-frequency polarity from nucleation period**
2. **high-frequency first-motion from earthquake**
3. **how-frequency inferred from moment tensor inversion**

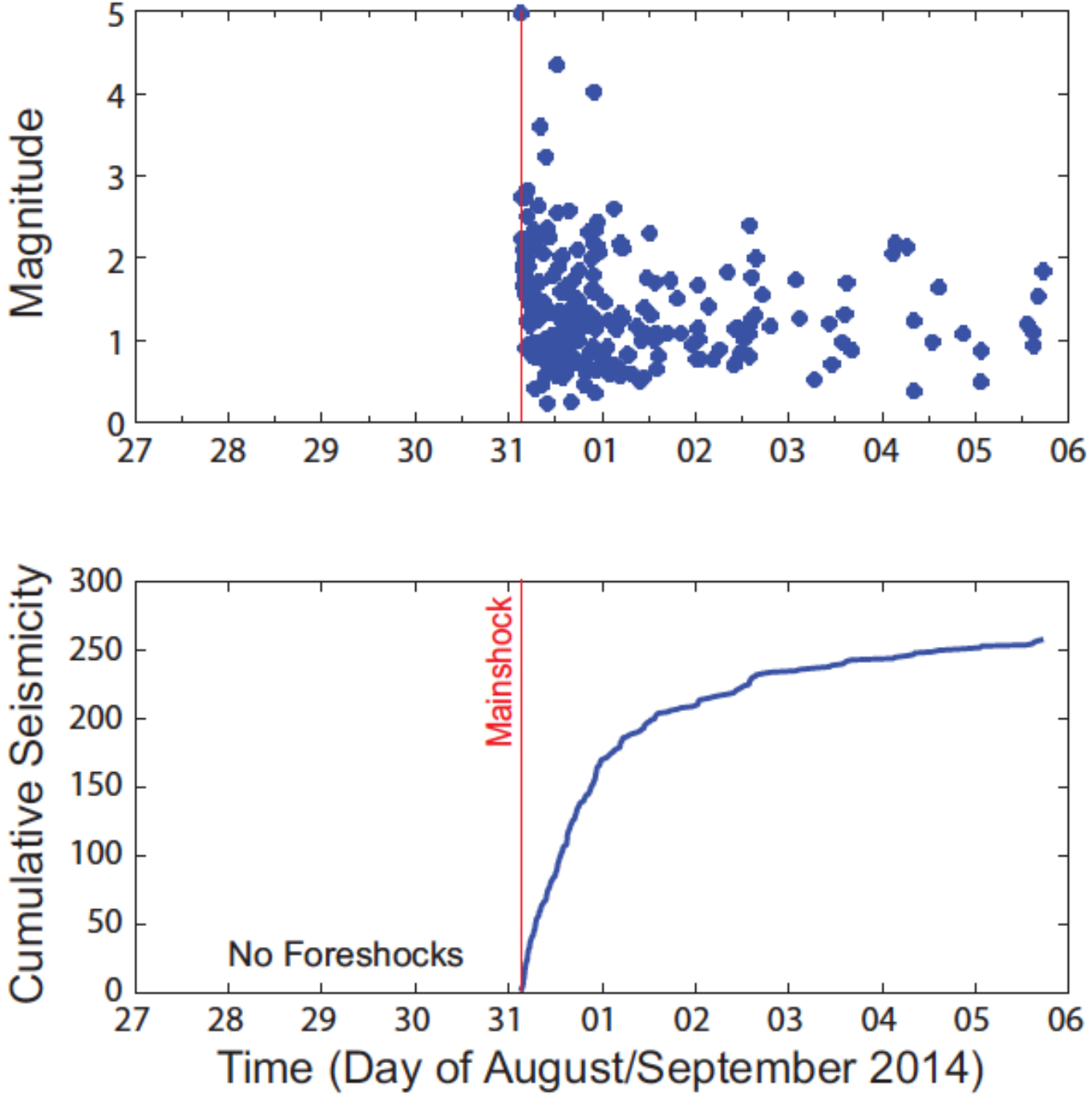


Coherence of foreshock signal with mainshock

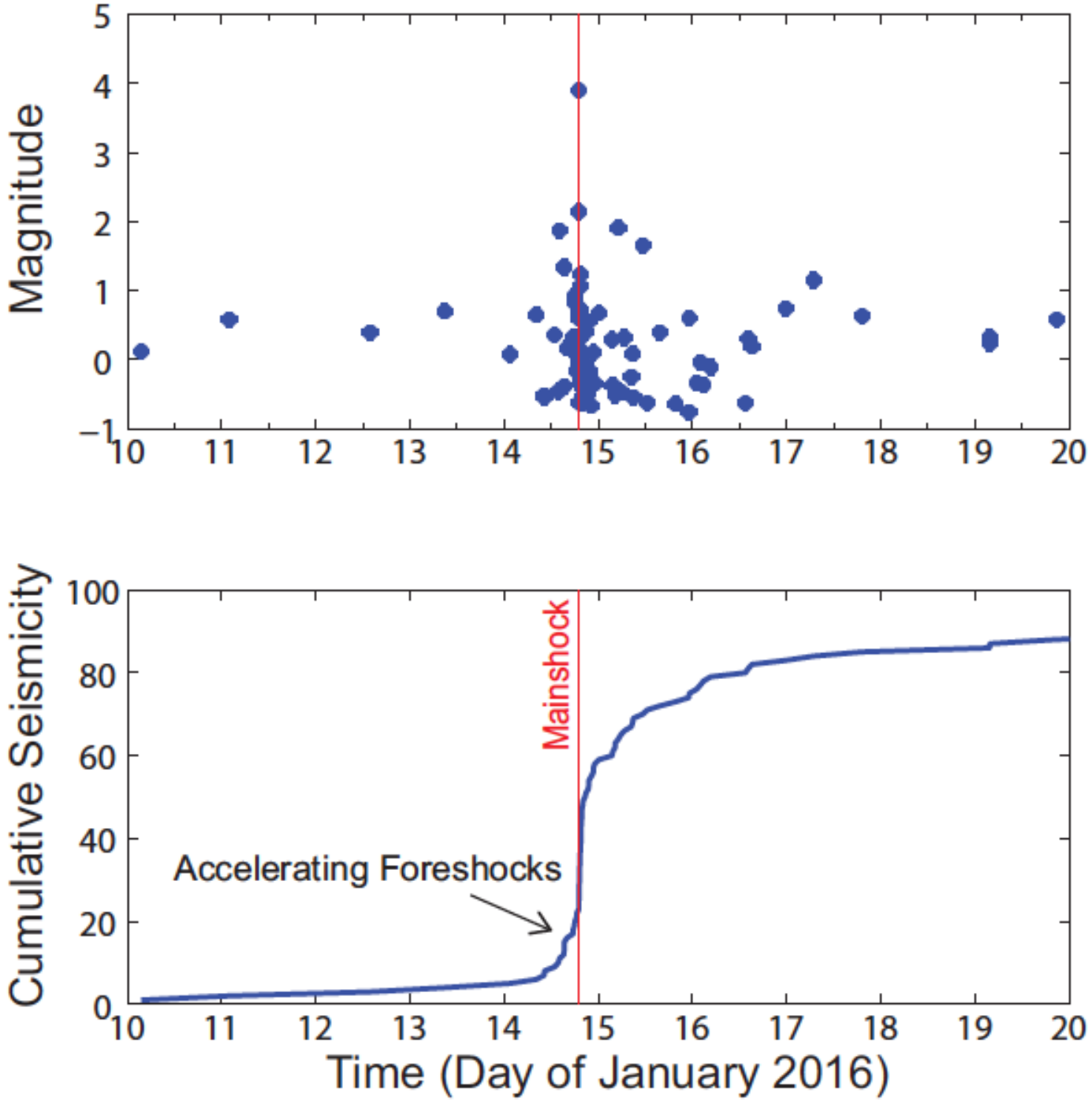


Jessica Hawthorne

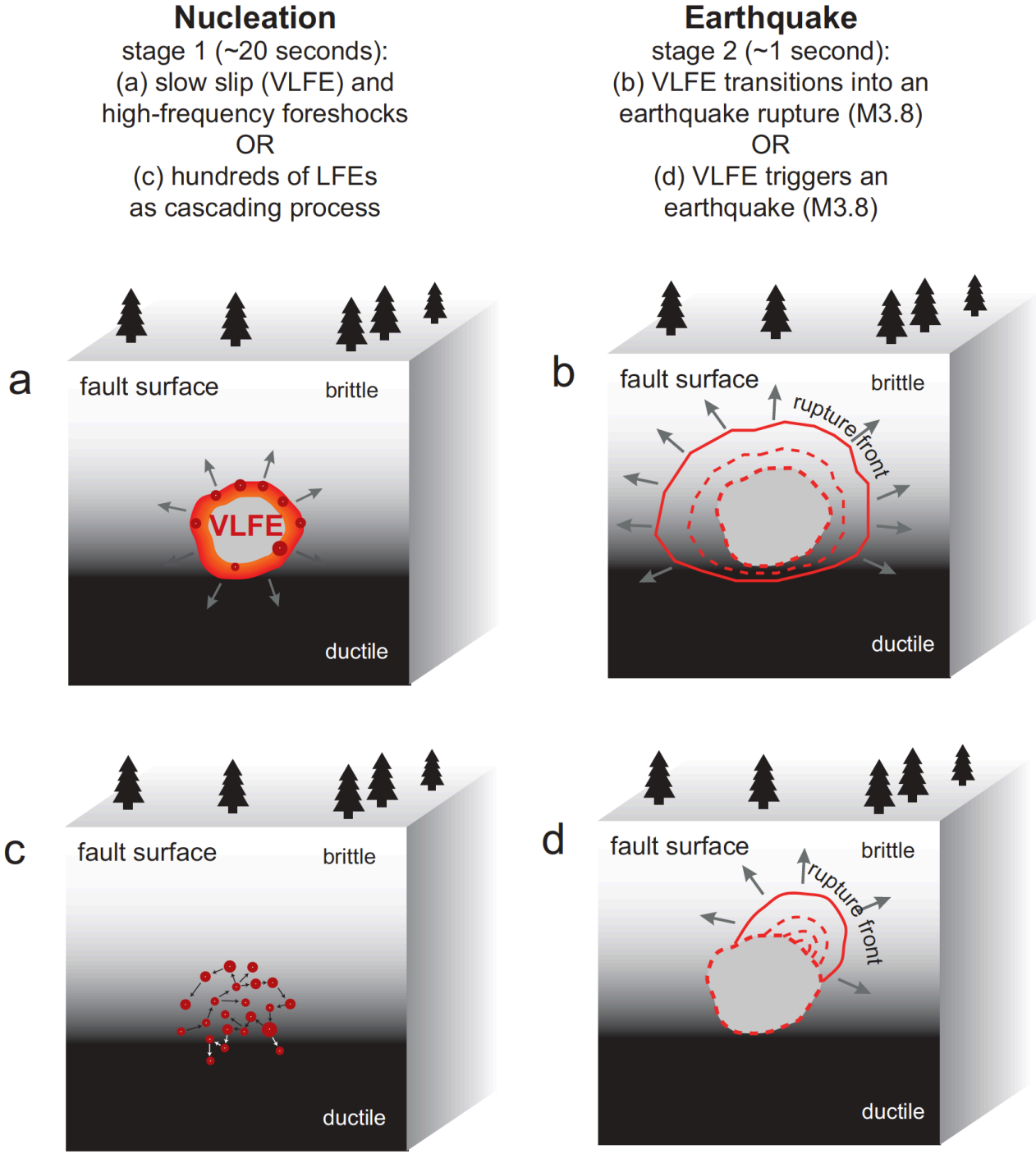

C F1TN (5.3 km)
D F2TN (6.2 km)
precursor
HFF
Velocity, nm/s
Time relative to P wave, s
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
−60
−40
−20
0
20
40

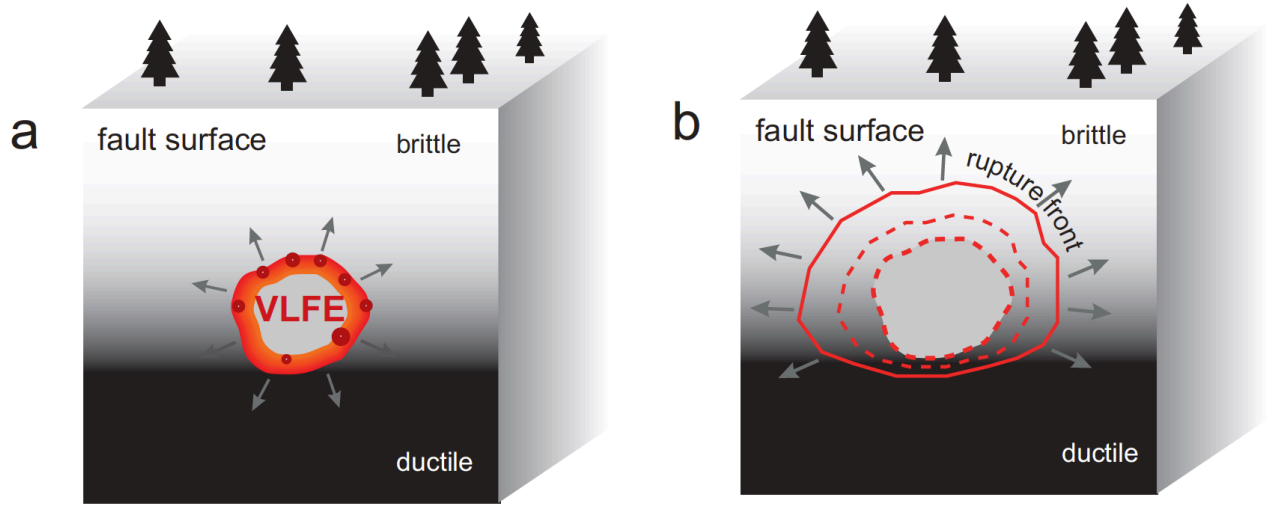


Steve Holtkamp

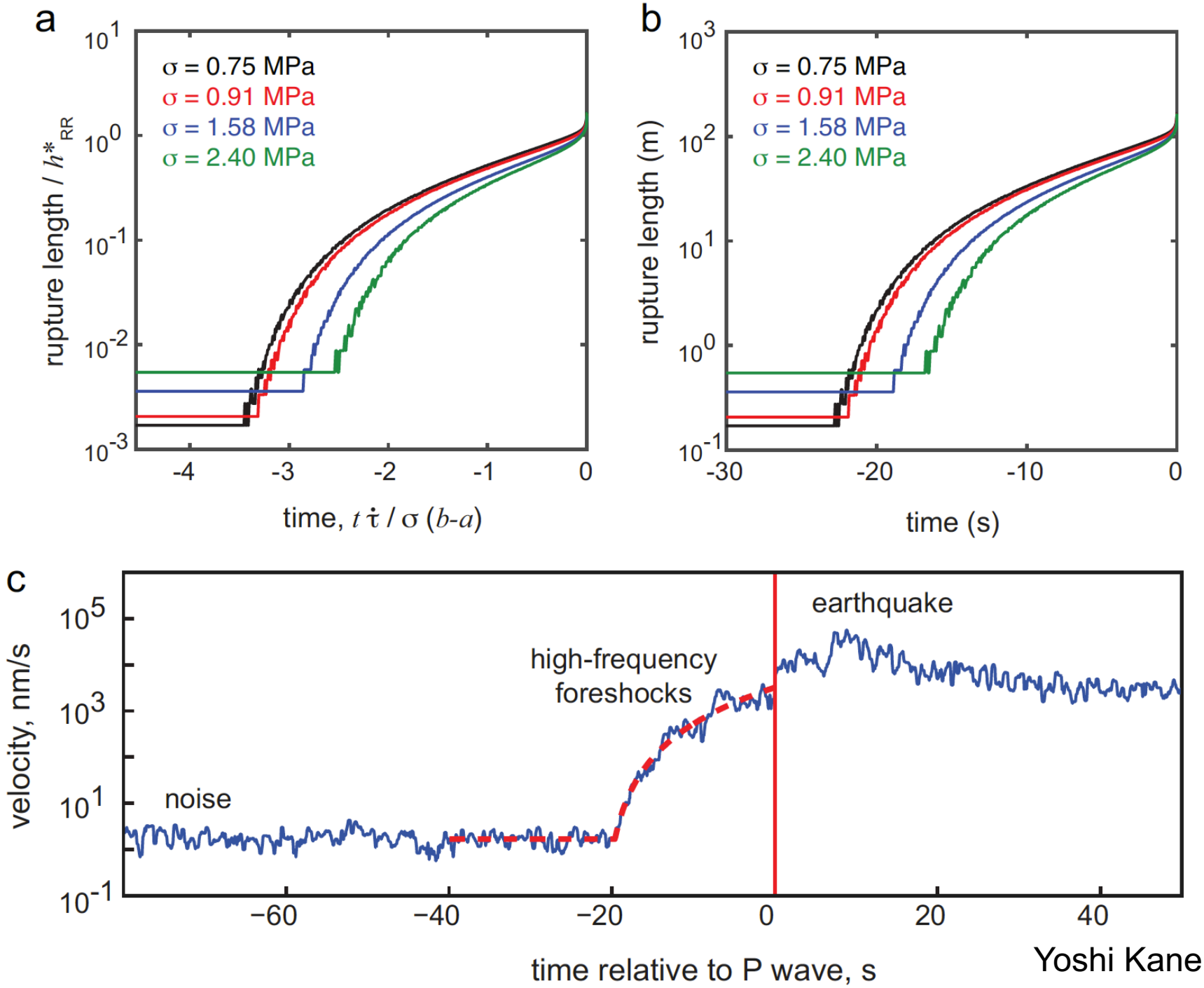


Steve Holtkamp


Nucleation
stage 1 (~20 seconds):
(a) slow slip (VLFE) and
high-frequency foreshocks
OR
(c) hundreds of LFEs
as cascading process
Earthquake
stage 2 (~1 second):
(b) VLFE transitions into an
earthquake rupture (M3.8)
OR
(d) VLFE triggers an
earthquake (M3.8)
a
fault surface
brittle
VLFE
ductile
b
fault surface
brittle
rupture front
ductile
c
fault surface
brittle
ductile
d
fault surface
brittle
rupture front
ductile



observation	stage in Fig. 4	2012 VLFE + EQ	2013 VLFE	2015 VLFE precursor	2015 VLFE	2016 VLFE + EQ
aseismic slow-slip initiation	0	Y-I	Y-I	Y-I	Y-I	Y-I
high-frequency signal (Fig. 1b)	1	Y	Y	Y	Y	Y
low-frequency signal (VLFE)	1	Y-I	Y	Y-I	Y	Y
earthquake	2	Y	N	N	N	Y


a
σ = 0.75 MPa
σ = 0.91 MPa
σ = 1.58 MPa
σ = 2.40 MPa
rupture length / h^*_{RR}
time, $t\,\dot{\tau}$ / σ (b-a)
b
σ = 0.75 MPa
σ = 0.91 MPa
σ = 1.58 MPa
σ = 2.40 MPa
rupture length (m)
time (s)
c
velocity, nm/s
noise
high-frequency
foreshocks
earthquake
time relative to P wave, s
Yoshi Kaneko

Summary

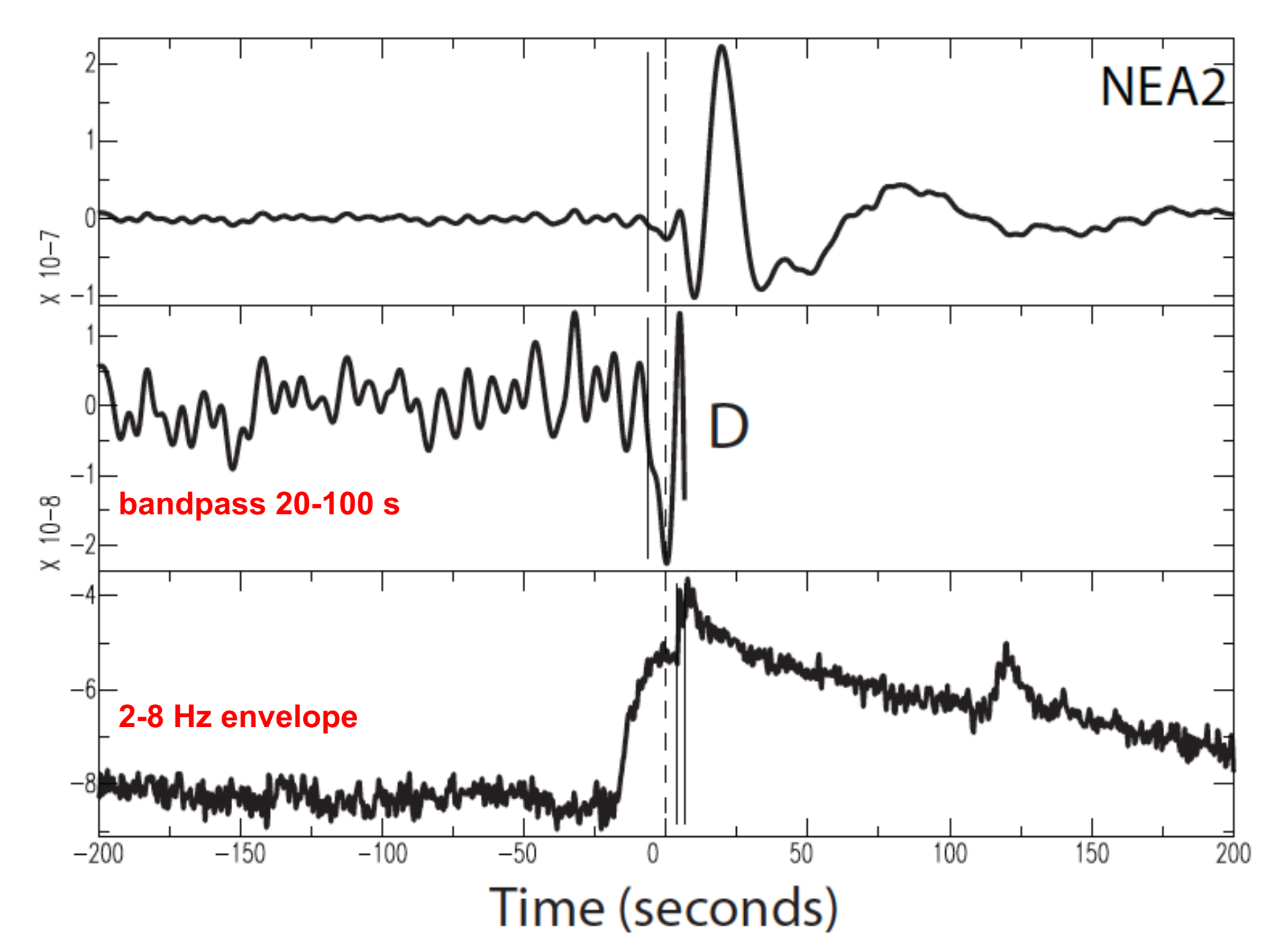
1. We present evidence for nucleation prior to a M 3.8 earthquake.
2. The **Minto Flats fault zone** of central Alaska produces a variety of events in the lower crust:
   - normal earthquakes
   - very-low-frequency earthquakes (HF and LF waves)
   - very-low-frequency earthquakes transitioning into earthquakes (2012 and 2016)
3. We will apply numerical models of fault slip to explain the observations and to better understand the conditions at the base of the seismogenic zone (Yoshi Kaneko).

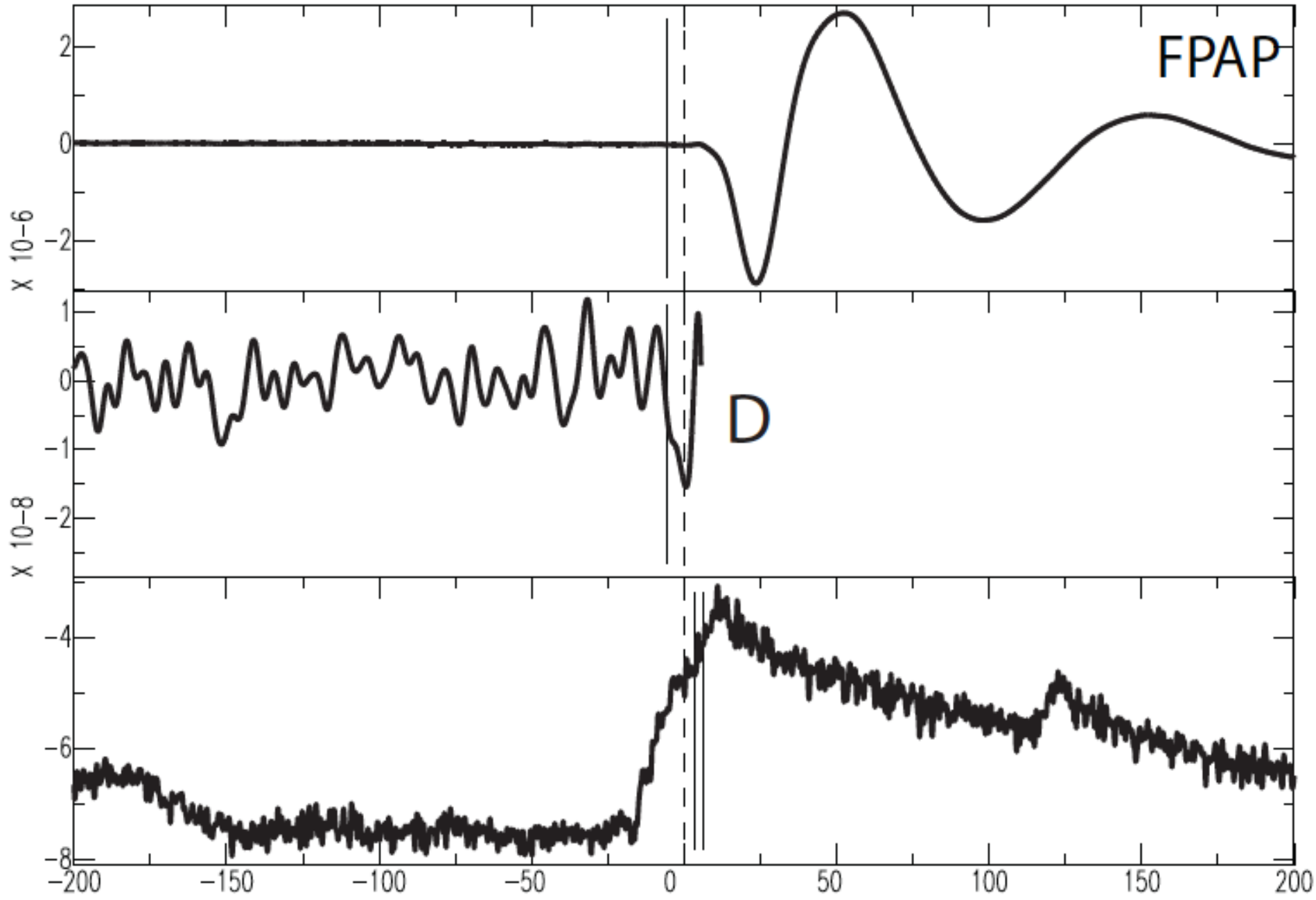
Please check out several posters on the Minto Flats fault zone:

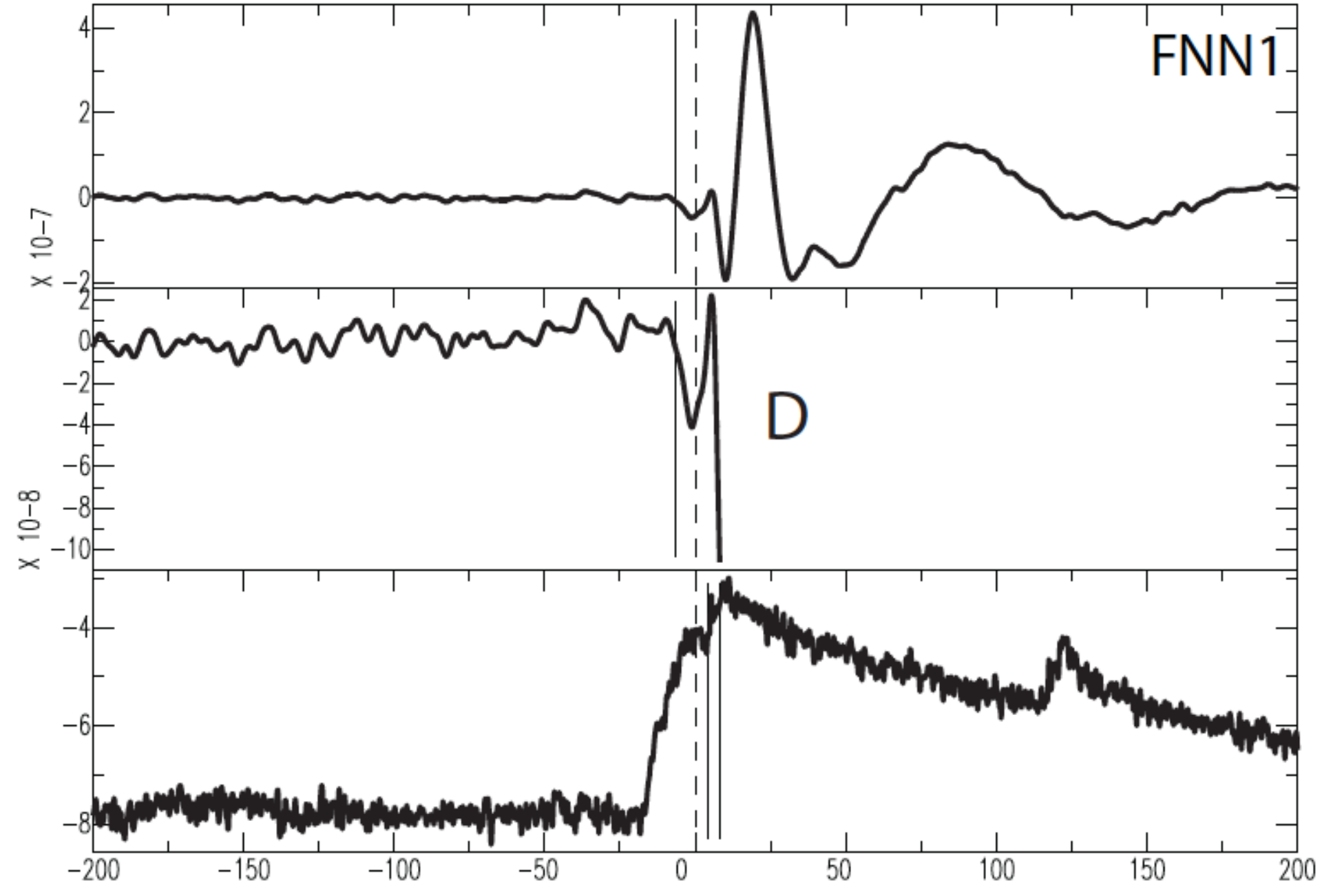
Vipul Silwal, Kyle Smith, Nealey Sims, Stephen Holtkamp

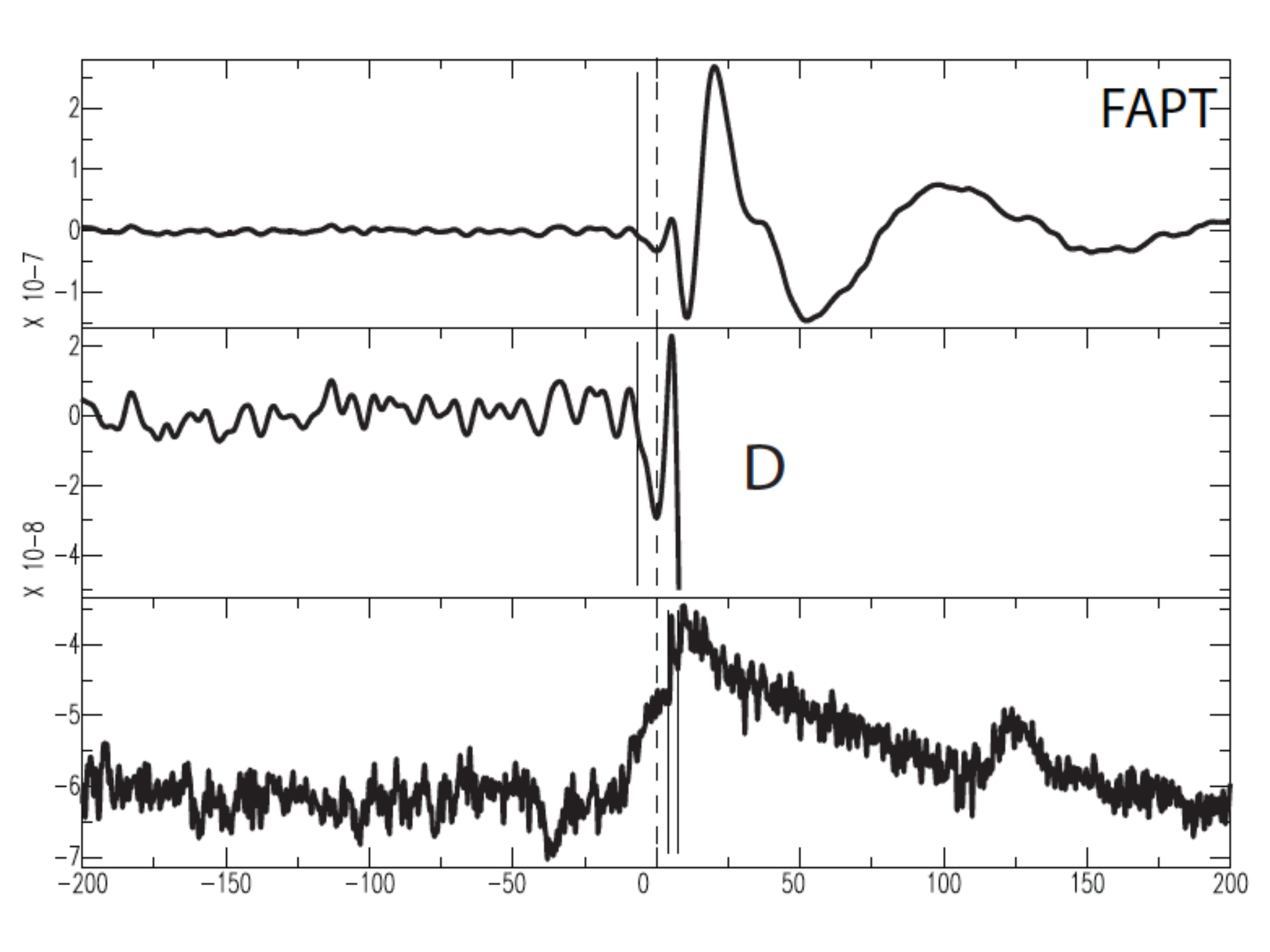
THANK YOU! ctape@alaska.edu

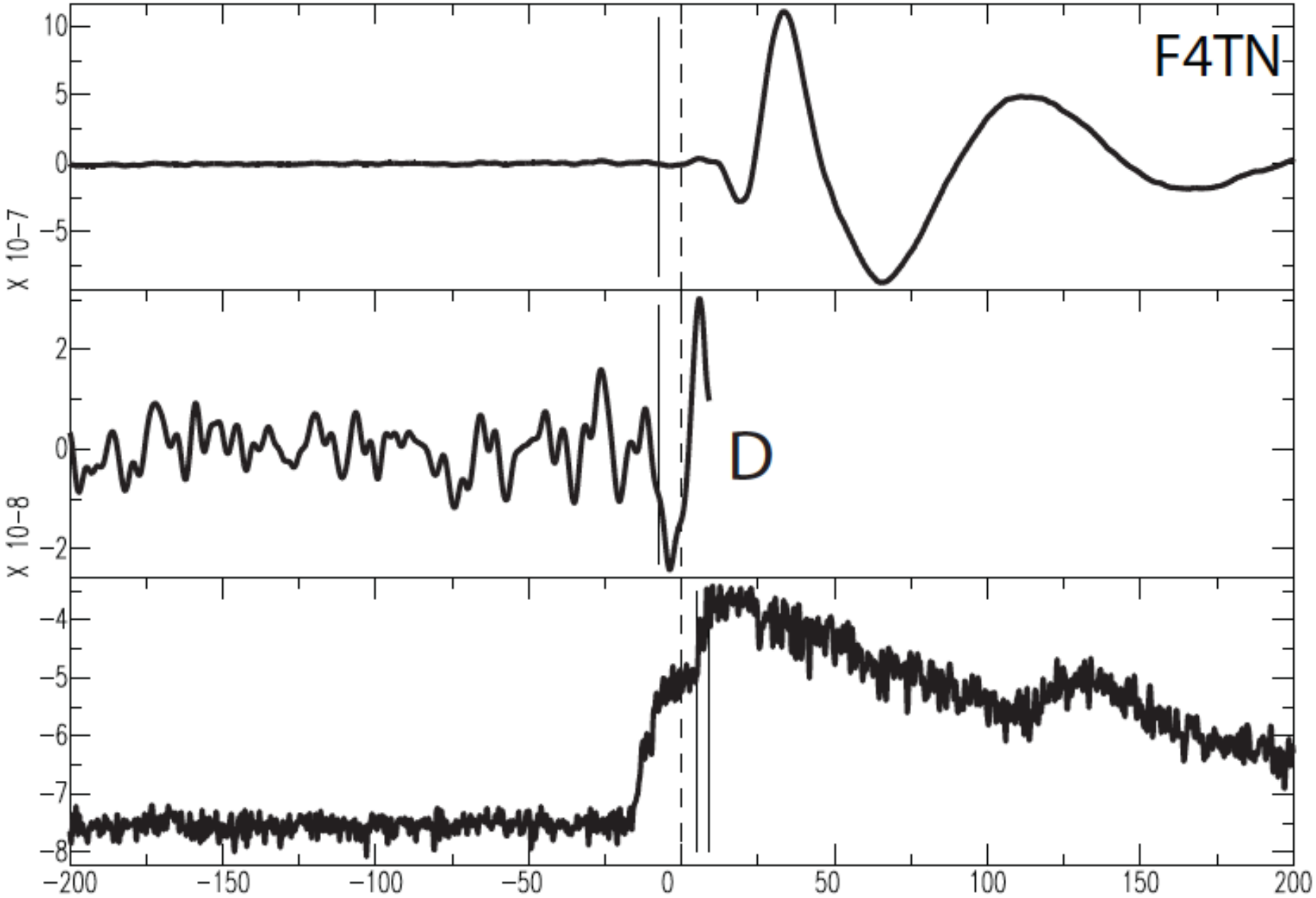
EXTRA SLIDES

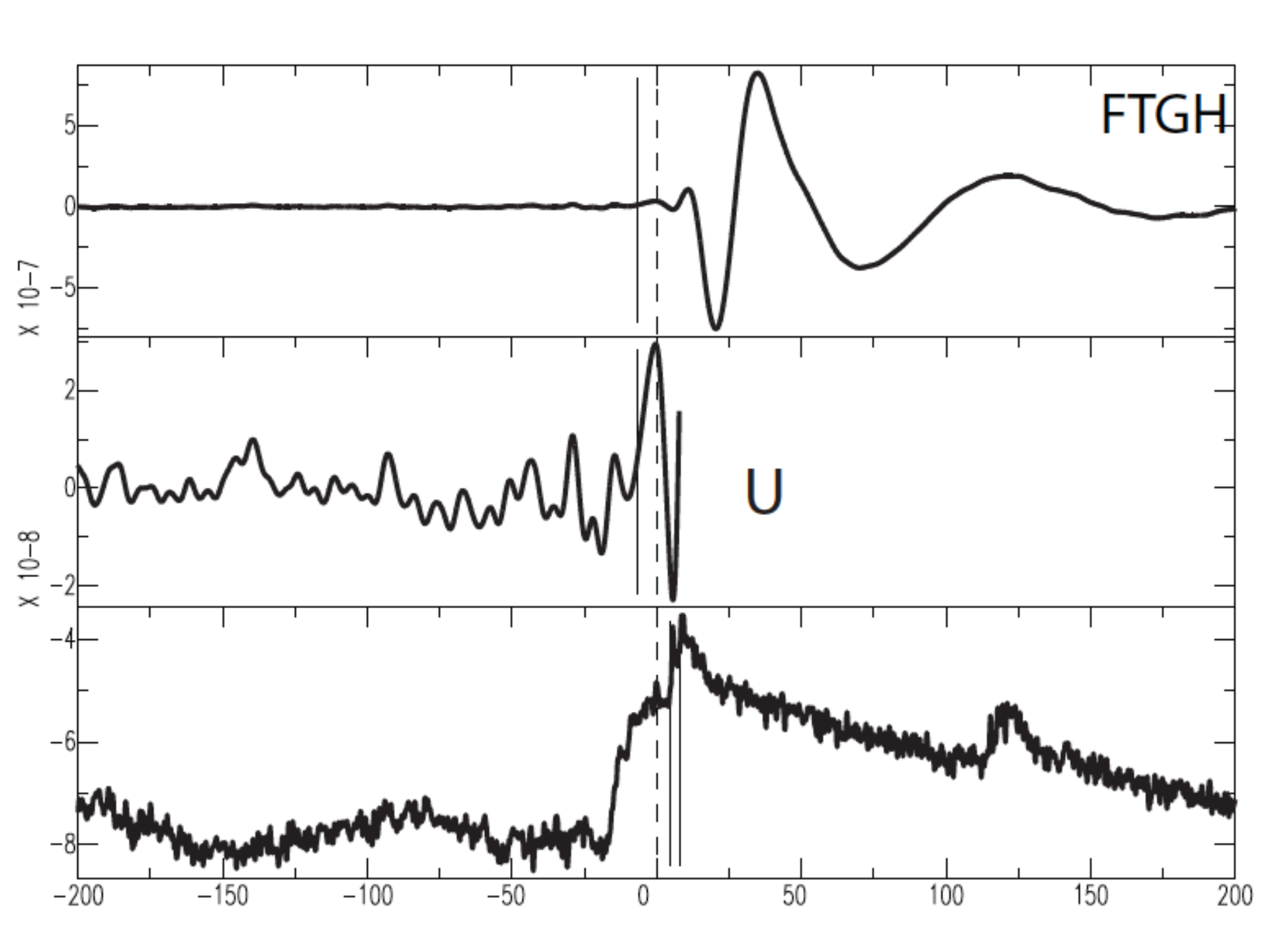

NEA2
X 10−7
D
X 10−8
bandpass 20-100 s
2-8 Hz envelope
2
1
0
−1
1
0
−1
−2
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200
Time (seconds)

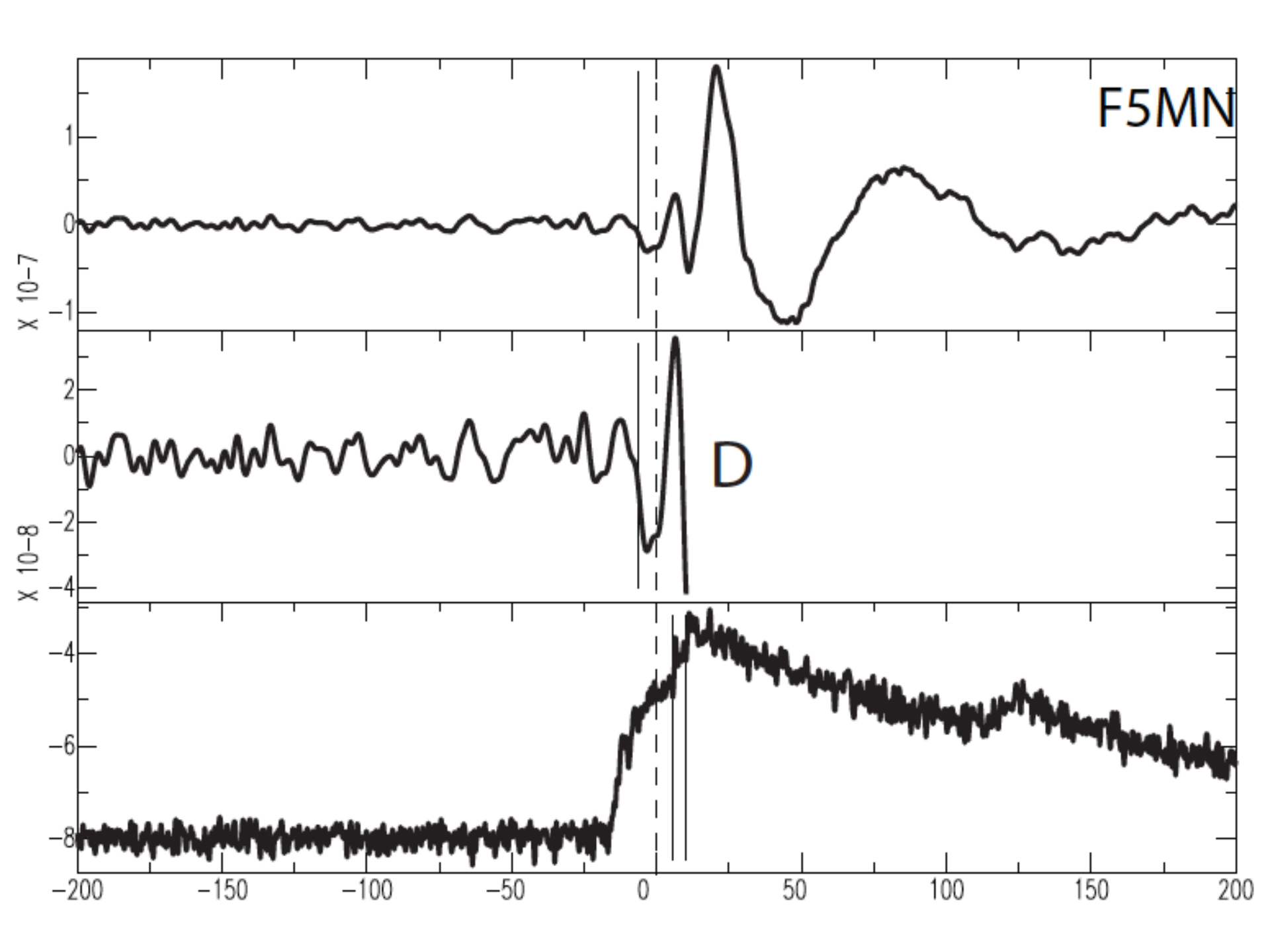

FPAP
D
X 10−6
X 10−8
2
0
−2
1
0
−1
−2
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200

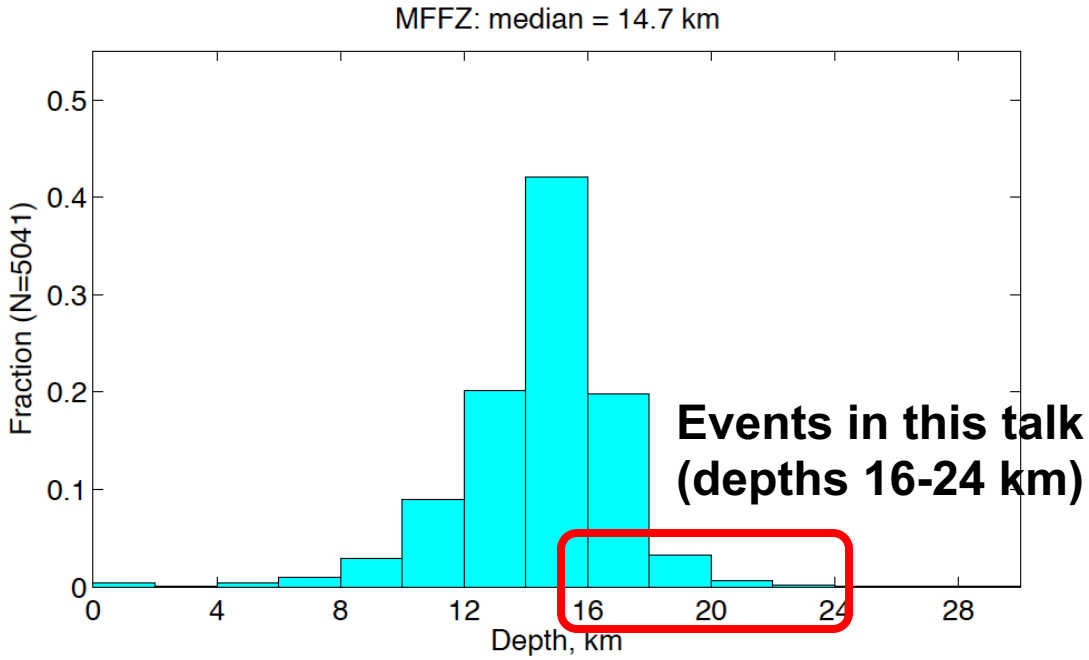

FNN1
D
X 10−7
X 10−8
4
2
0
−2
2
0
−2
−4
−6
−8
−10
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200

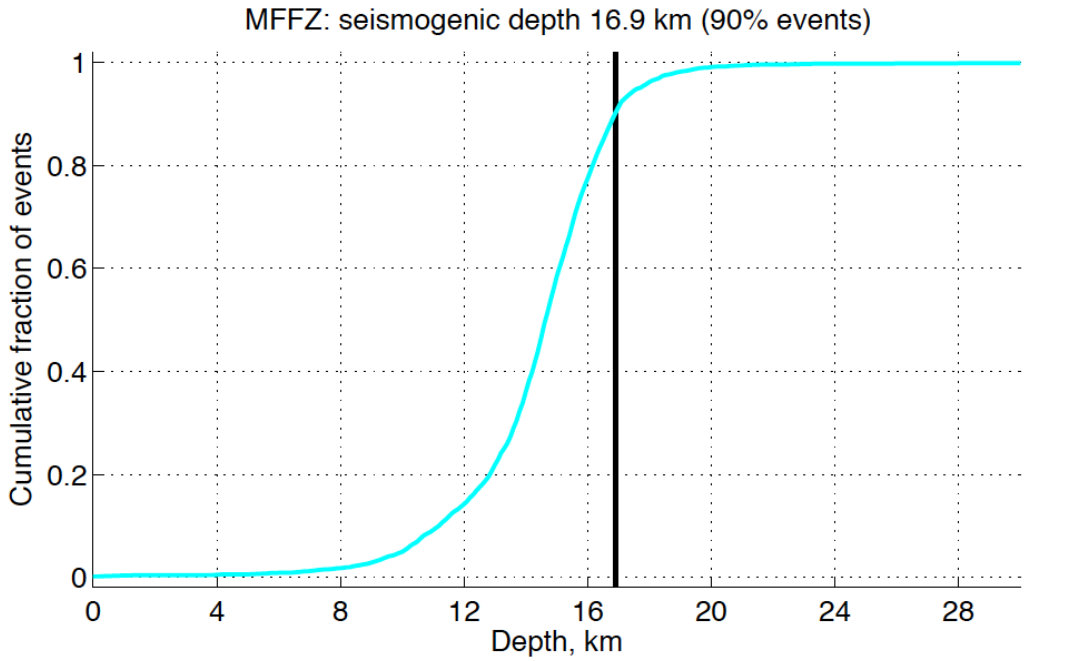

FAPT
D
X 10−7
X 10−8
2
1
0
−1
2
0
−2
−4
−4
−5
−6
−7
−200
−150
−100
−50
0
50
100
150
200


F4TN
D
X 10−7
X 10−8
10
5
0
−5
2
0
−2
−4
−5
−6
−7
−8
−200
−150
−100
−50
0
50
100
150
200

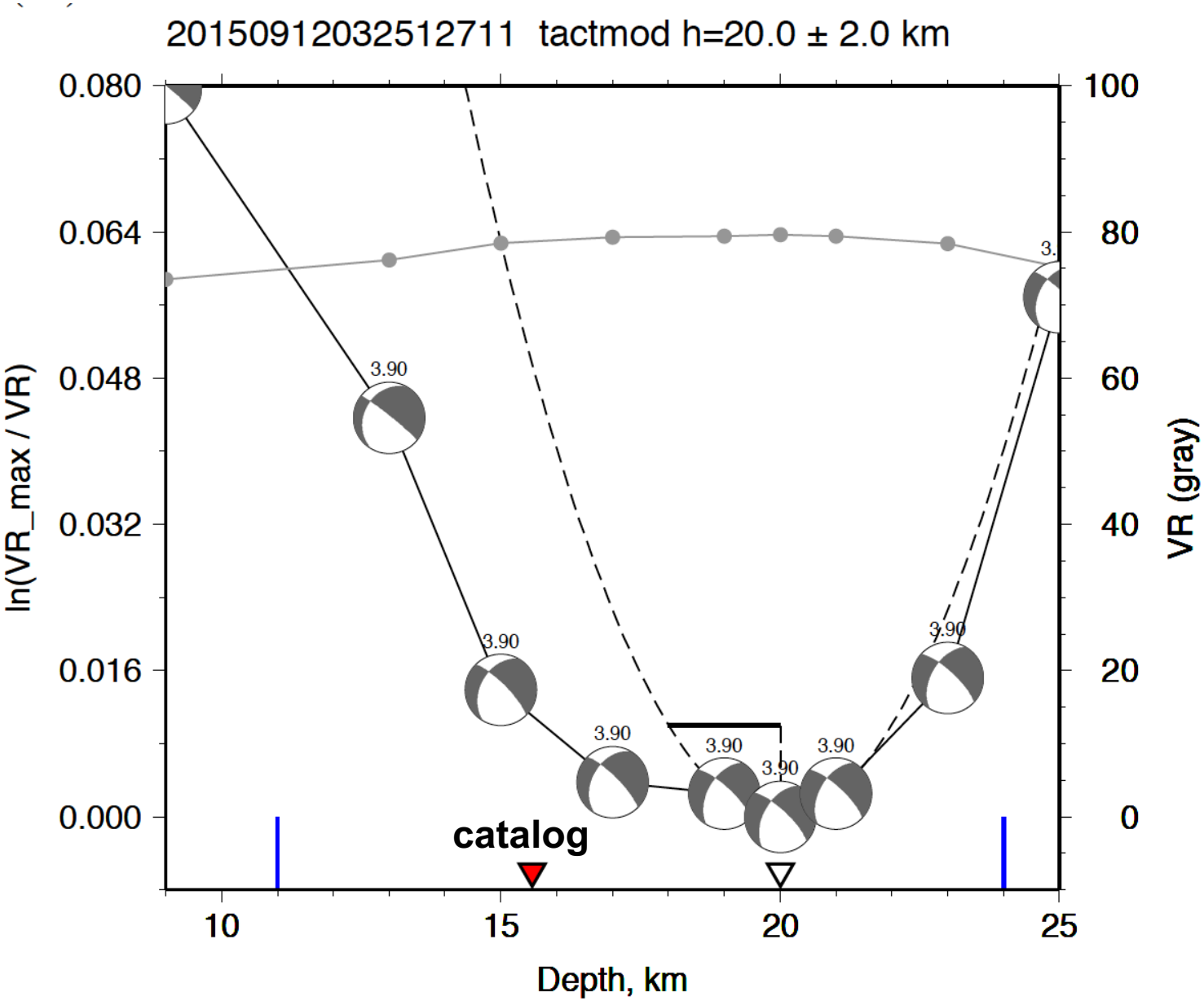

FTGH
U
X 10−7
X 10−8
5
0
−5
2
0
−2
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200


F5MN
D
X 10−7
X 10−8
1
0
−1
2
0
−2
−4
−4
−6
−8
−200
−150
−100
−50
0
50
100
150
200

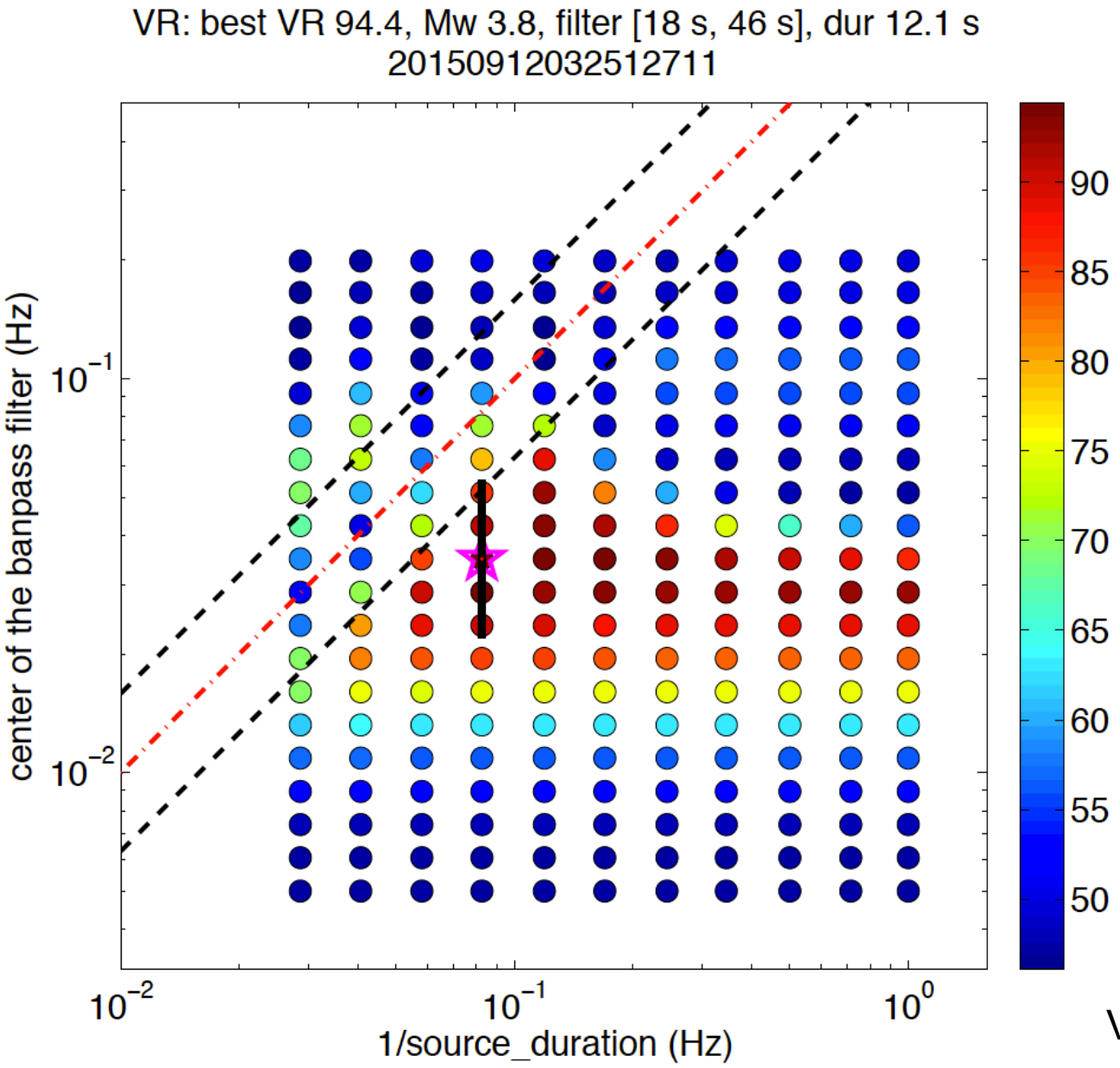

MFFZ: median = 14.7 km
Fraction (N=5041)
0.5
0.4
0.3
0.2
0.1
0
0
4
8
12
16
20
24
28
Depth, km
Events in this talk
(depths 16-24 km)


MFFZ: seismogenic depth 16.9 km (90% events)
Cumulative fraction of events
1
0.8
0.6
0.4
0.2
0
0
4
8
12
16
20
24
28
Depth, km

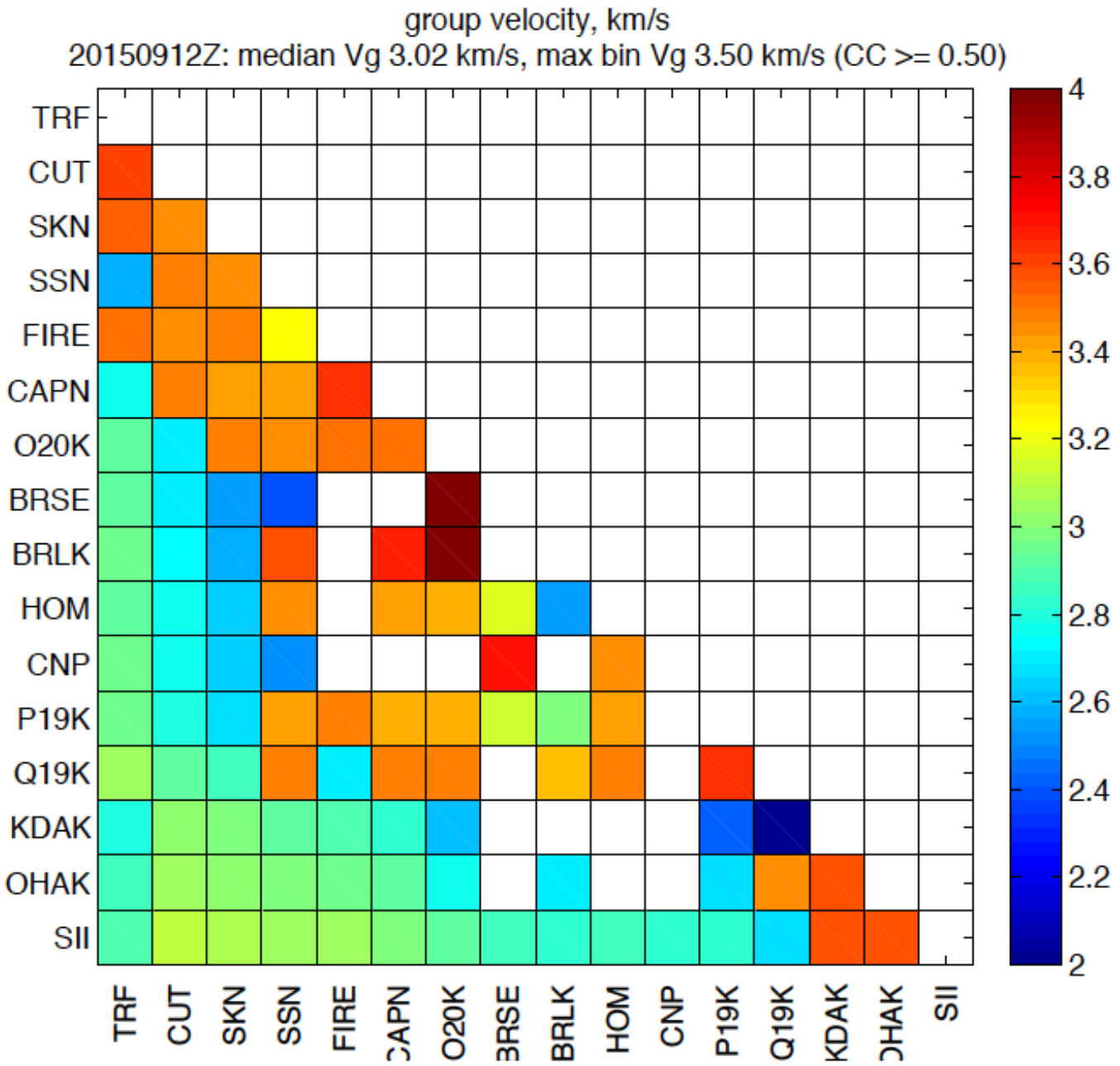
Depth estimation from moment tensor inversion

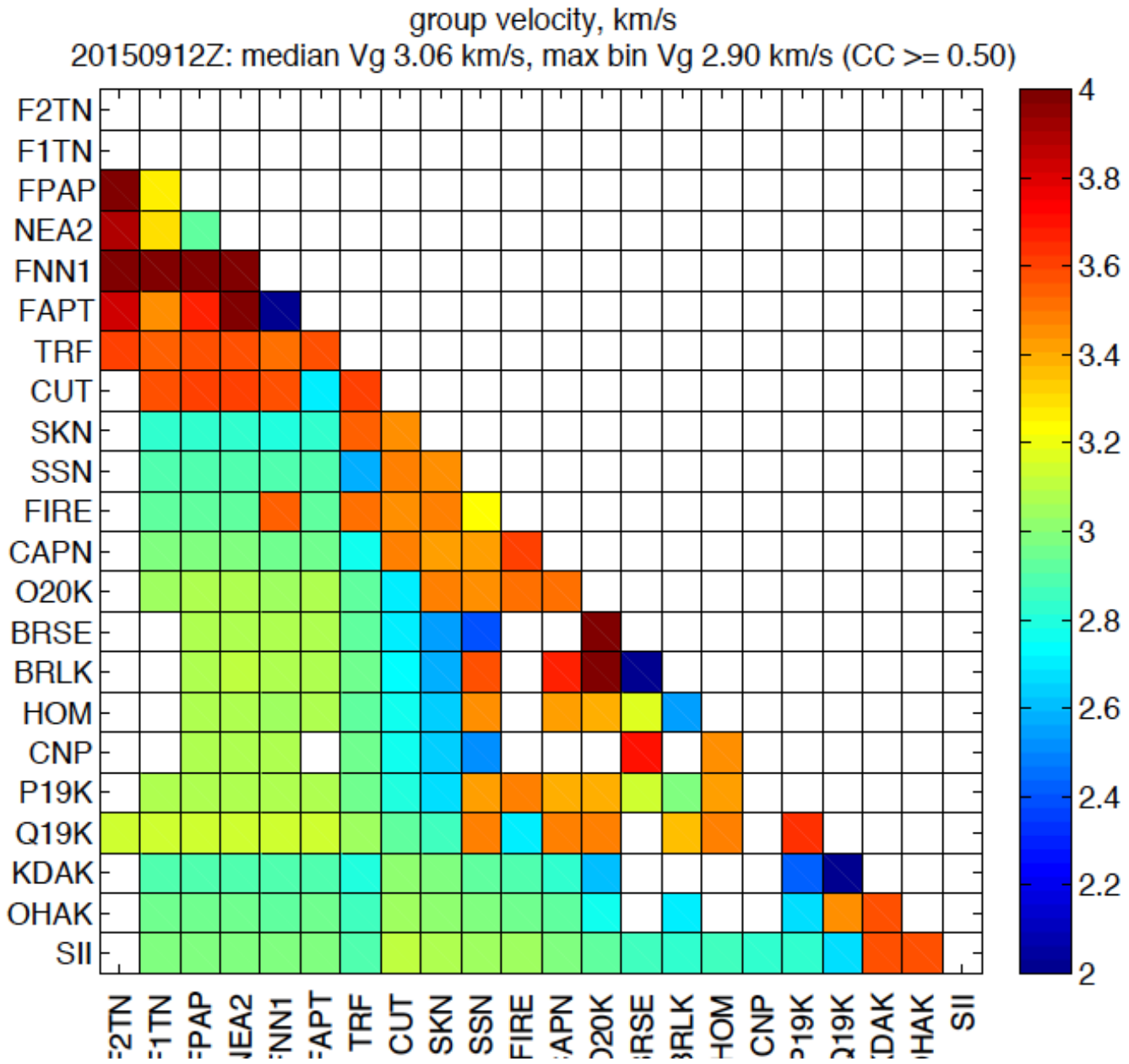


Estimating source duration

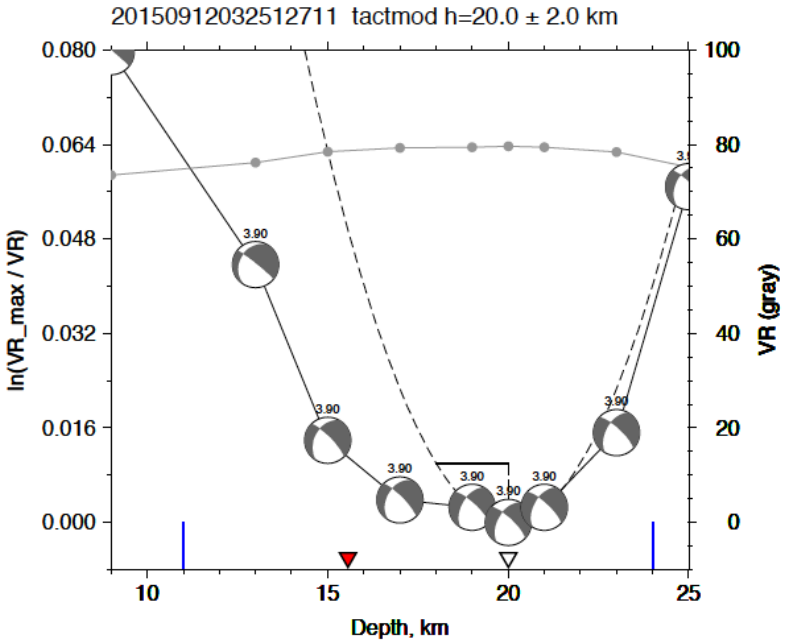


Vipul Silwal

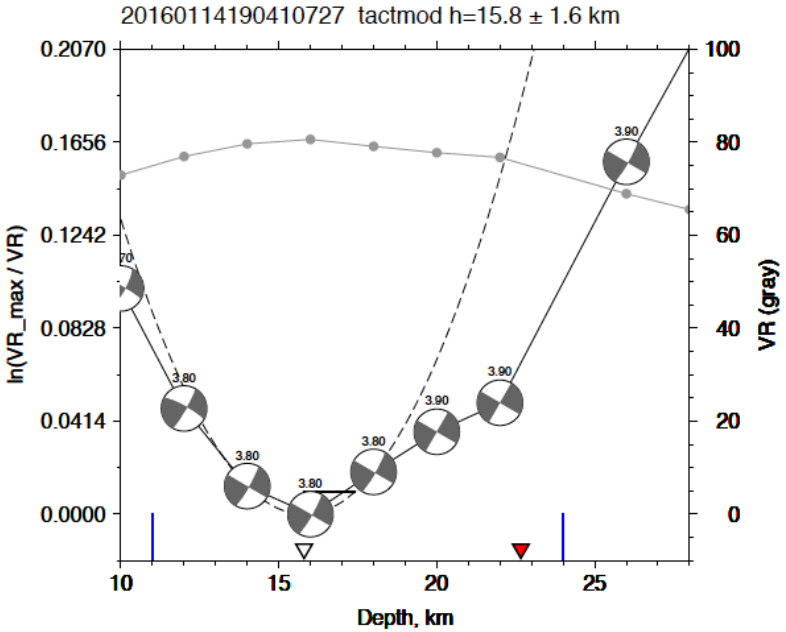

group velocity, km/s
20150912Z: median Vg 3.02 km/s, max bin Vg 3.50 km/s (CC >= 0.50)
TRF
CUT
SKN
SSN
FIRE
CAPN
O20K
BRSE
BRLK
HOM
CNP
P19K
Q19K
KDAK
OHAK
SII
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2


group velocity, km/s
20150912Z: median Vg 3.06 km/s, max bin Vg 2.90 km/s (CC >= 0.50)
F2TN
F1TN
FPAP
NEA2
FNN1
FAPT
TRF
CUT
SKN
SSN
FIRE
CAPN
O20K
BRSE
BRLK
HOM
CNP
P19K
Q19K
KDAK
OHAK
SII
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2

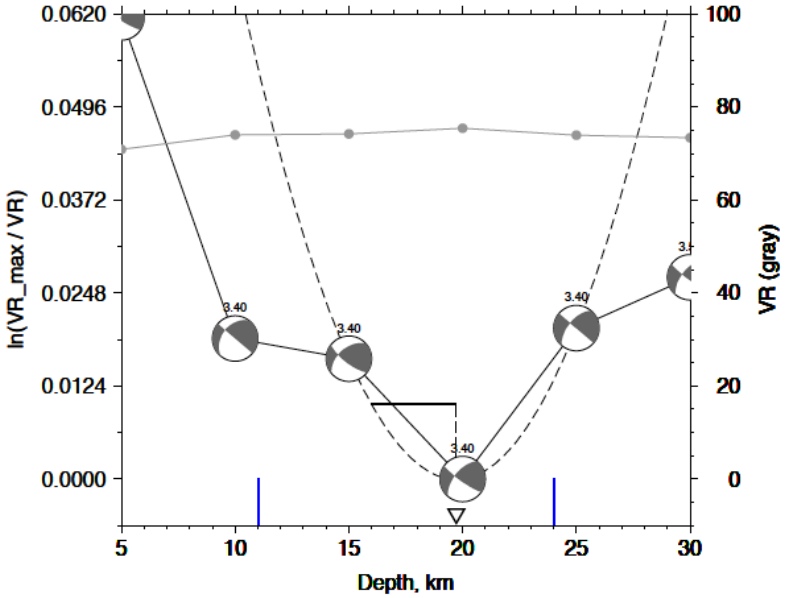
(A)


20150912032512711 tactmod h=20.0 ± 2.0 km
ln(VR_max / VR)
VR (gray)
Depth, km
0.080
0.064
0.048
0.032
0.016
0.000
100
80
60
40
20
0
10
15
20
25
3.90

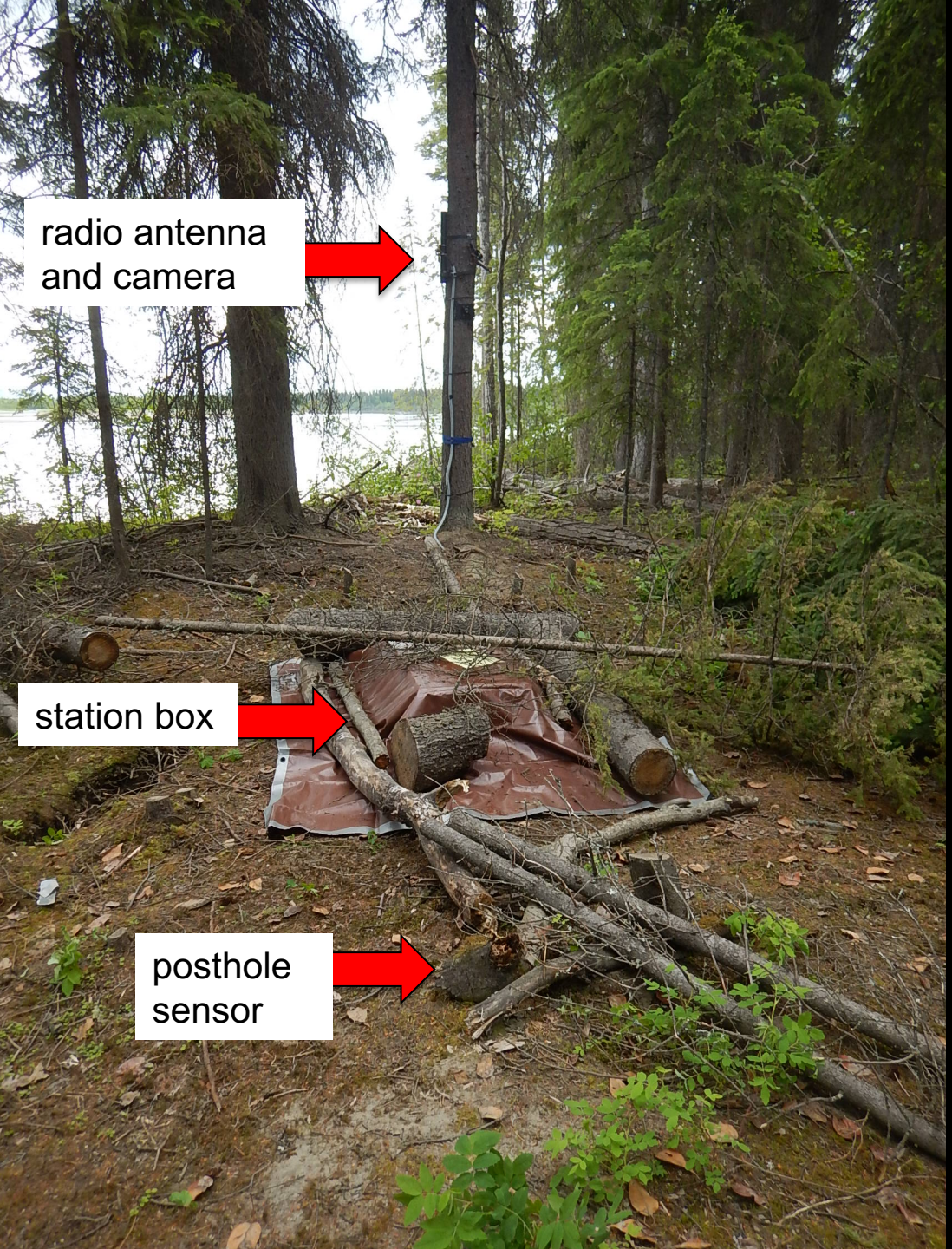
(B)


20160114190410727 tactmod h=15.8 ± 1.6 km
ln(VR_max / VR)
VR (gray)
Depth, km
0.2070
0.1656
0.1242
0.0828
0.0414
0.0000
100
80
60
40
20
0
10
15
20
25
3.90
3.80

(C)


20130312073950214 tactmod h=19.7 ± 3.7 km
ln(VR_max / VR)
VR (gray)
Depth, km
0.0620
0.0496
0.0372
0.0248
0.0124
0.0000
100
80
60
40
20
0
5
10
15
20
25
30
3.40

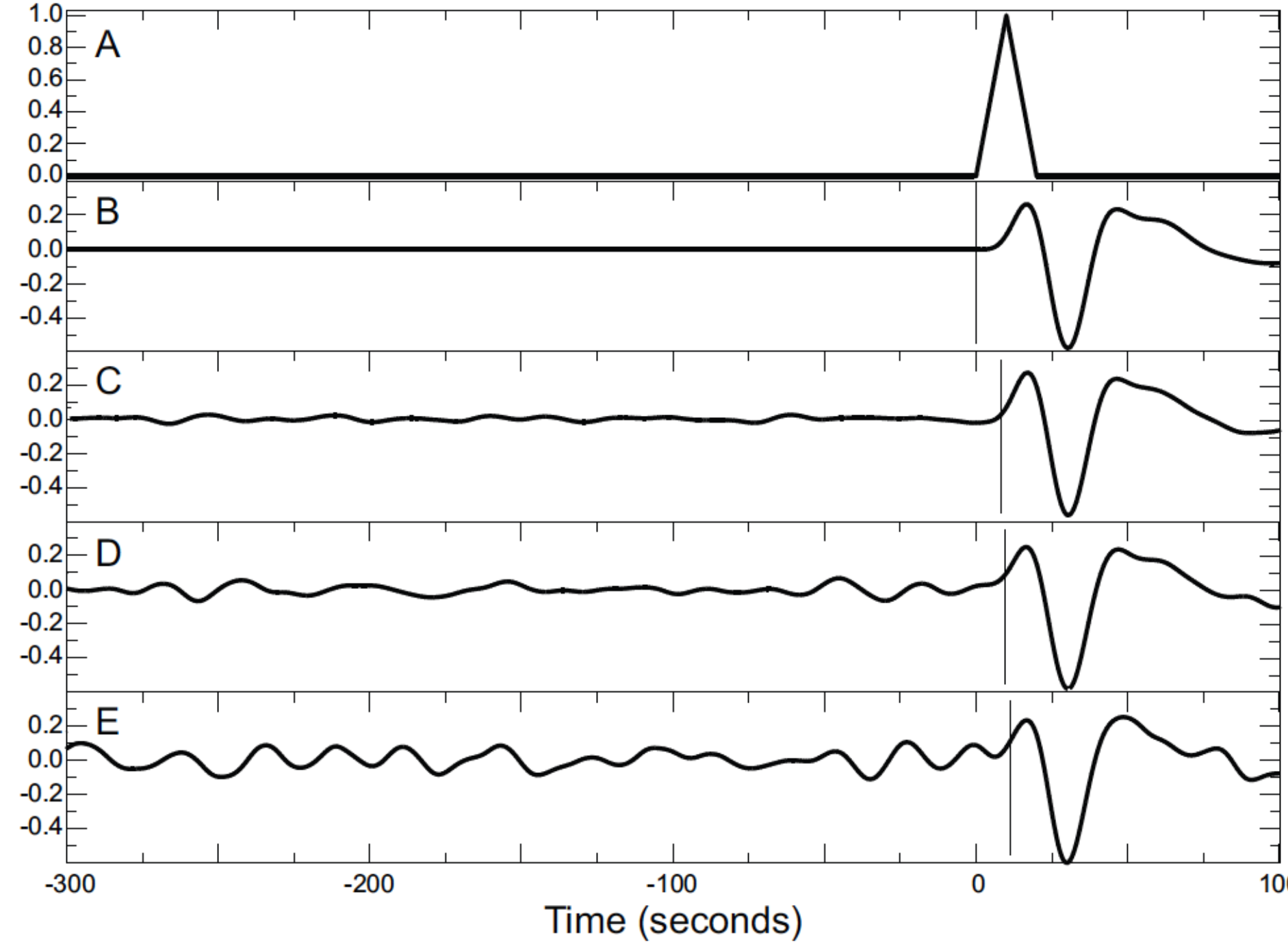
FLATS station F3TN

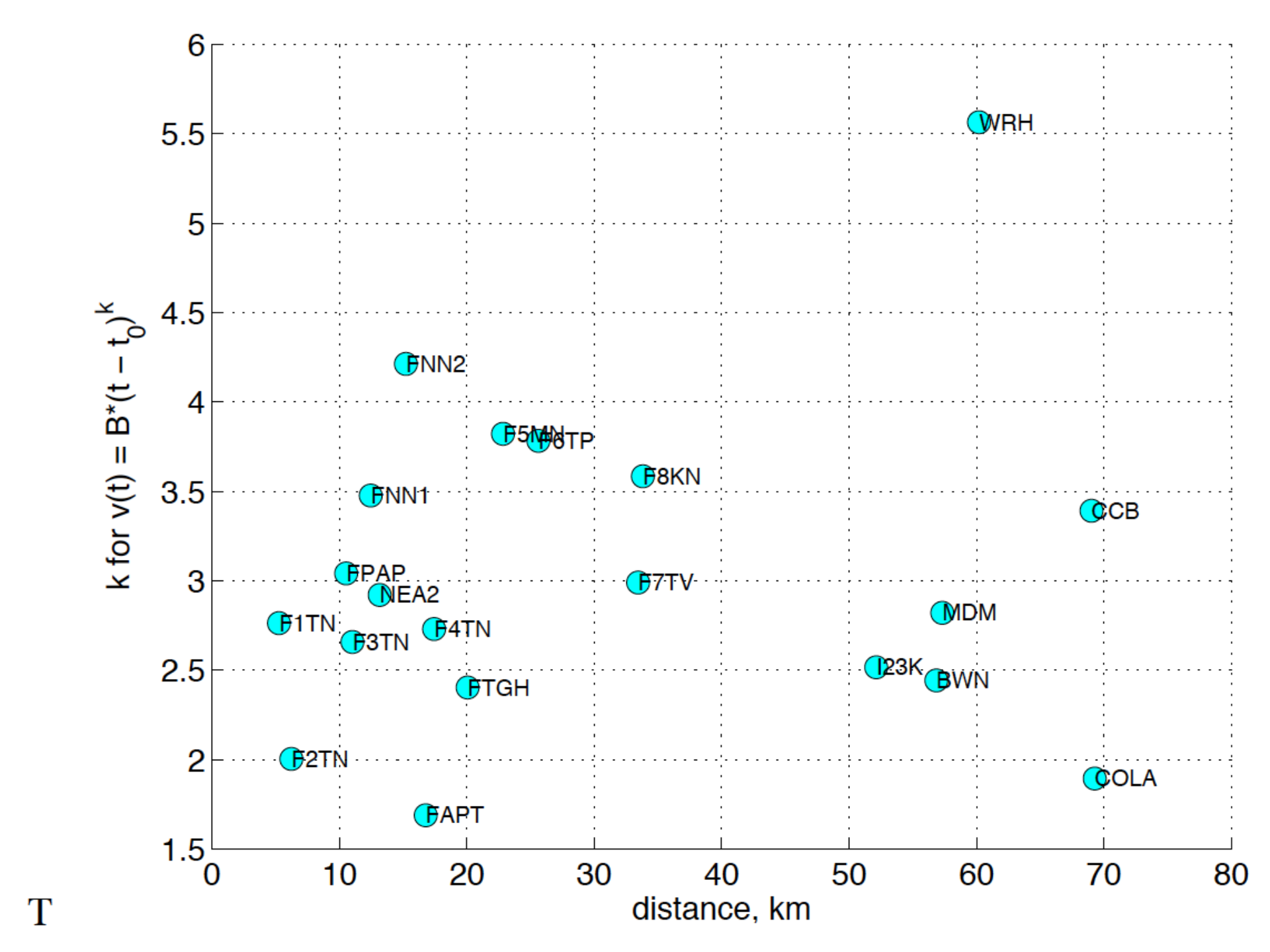


½ bear deterrent experiment

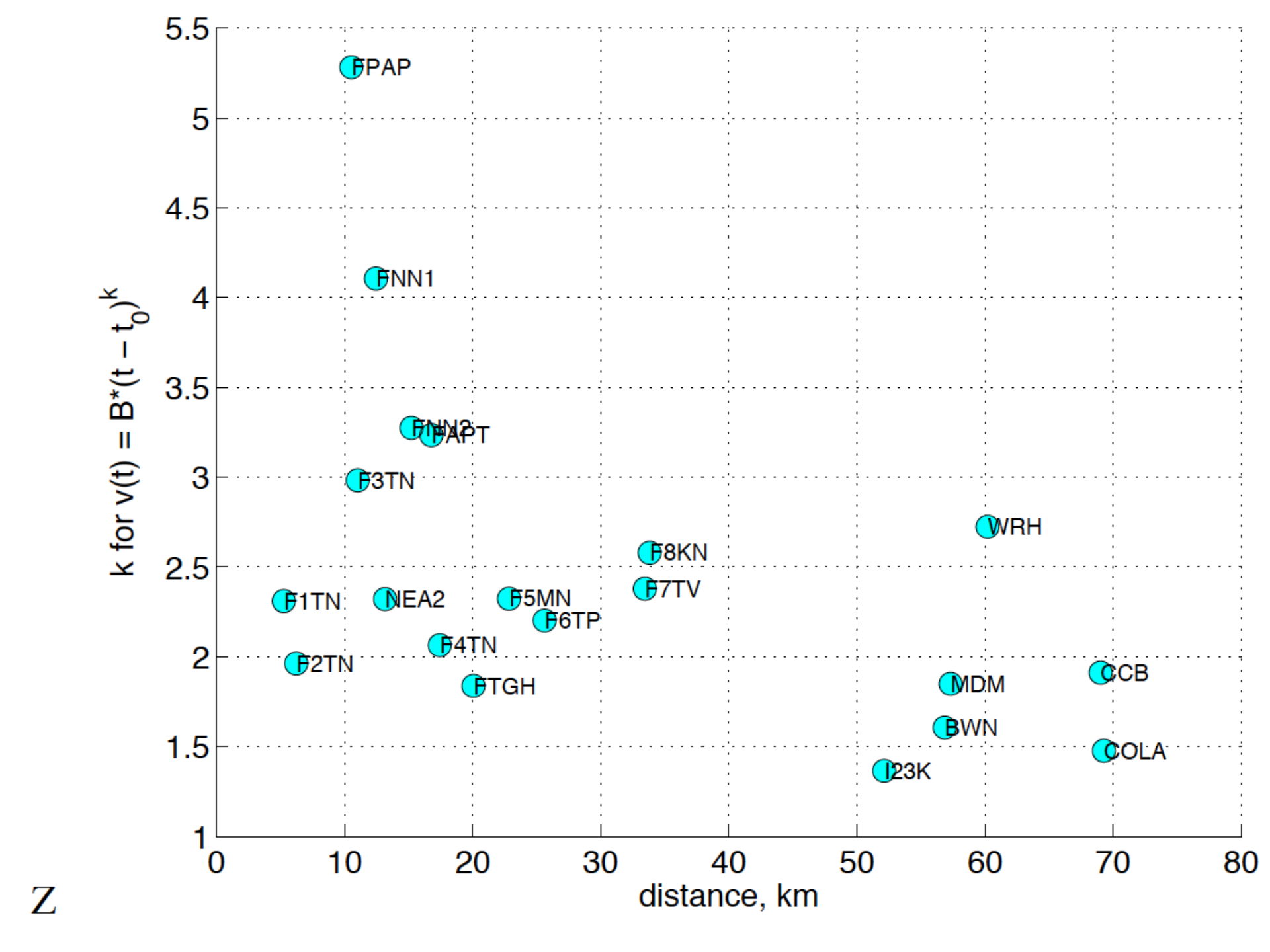
¼ experiment with cheap hunting cameras in Alaska winter

¼ outreach opportunity

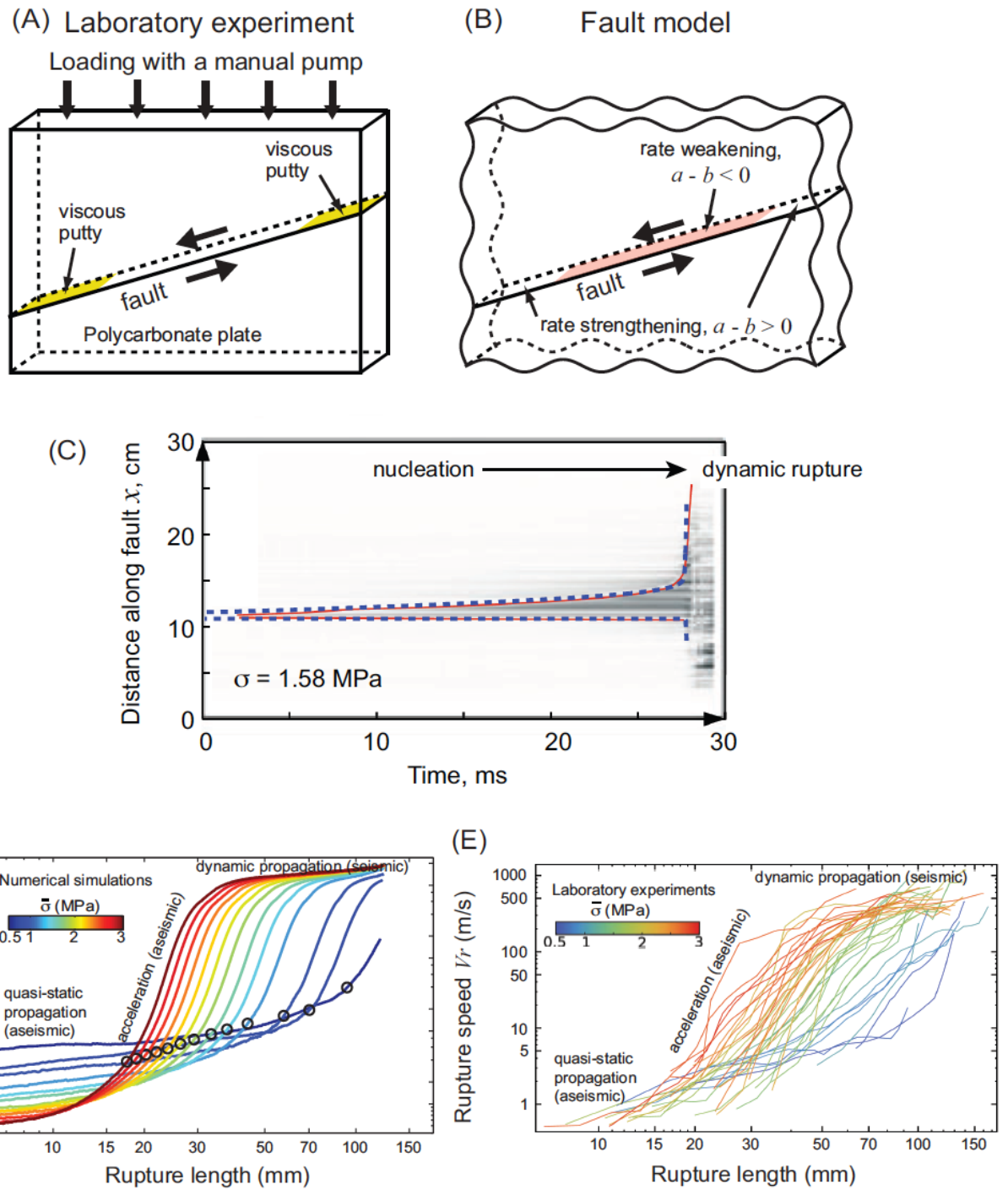

A
B
C
D
E
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-300
-200
-100
0
100
Time (seconds)

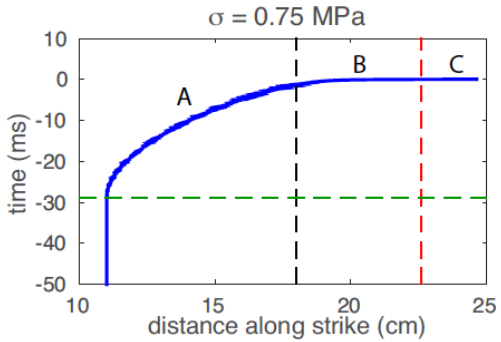

k for v(t) = B*(t – t0)^k
distance, km
WRH
FNN2
F5MN
F6TP
F8KN
FNN1
CCB
FPAP
NEA2
F7TV
MDM
F1TN
F4TN
F3TN
I23K
BWN
FTGH
F2TN
COLA
FAPT

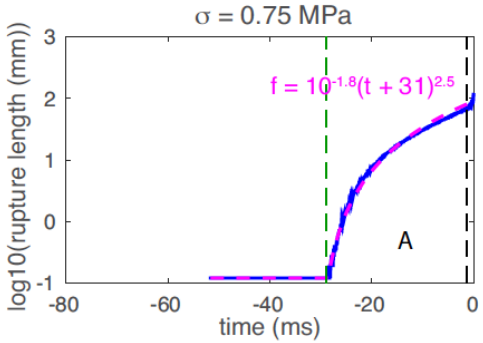
T

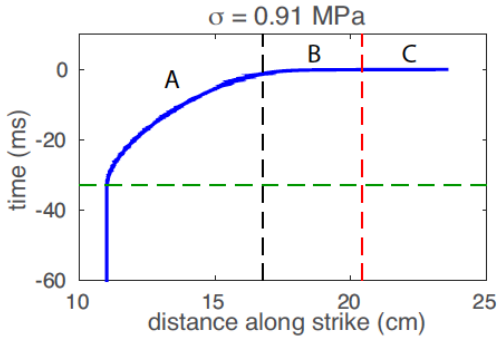

k for v(t) = B*(t – t0)^k
distance, km
FPAP
FNN1
FNN2
FAPT
F3TN
WRH
F8KN
F7TV
F1TN
NEA2
F5MN
F6TP
F4TN
F2TN
FTGH
MDM
CCB
BWN
COLA
I23K
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60
70
80

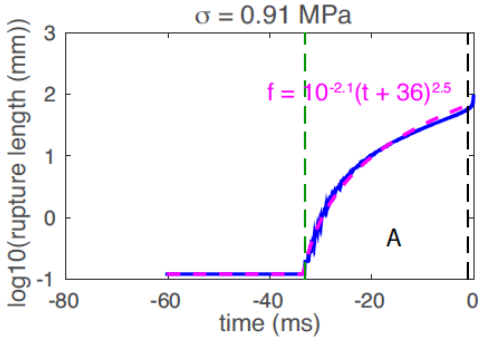
Z

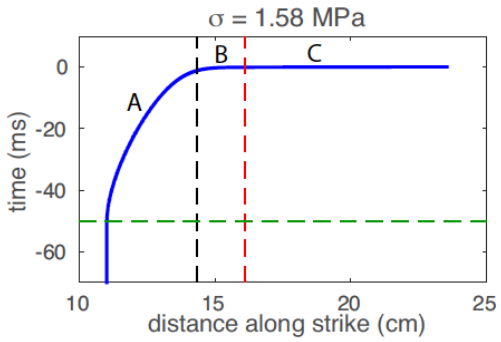

(A) Laboratory experiment
Loading with a manual pump
viscous putty
viscous putty
fault
Polycarbonate plate
(B) Fault model
rate weakening, $a - b < 0$
fault
rate strengthening, $a - b > 0$
(C)
nucleation
dynamic rupture
Distance along fault x, cm
σ = 1.58 MPa
Time, ms
(D)
Numerical simulations
$\bar{\sigma}$ (MPa)
0.5 1 2 3
dynamic propagation (seismic)
acceleration (aseismic)
quasi-static propagation (aseismic)
Rupture speed Vr (m/s)
Rupture length (mm)
(E)
Laboratory experiments
$\bar{\sigma}$ (MPa)
0.5 1 2 3
dynamic propagation (seismic)
acceleration (aseismic)
quasi-static propagation (aseismic)
Rupture speed Vr (m/s)
Rupture length (mm)

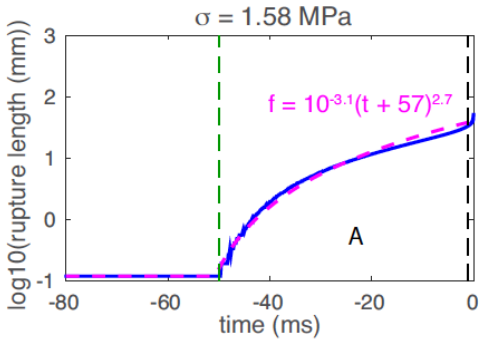

σ = 0.75 MPa
A
B
C
time (ms)
distance along strike (cm)

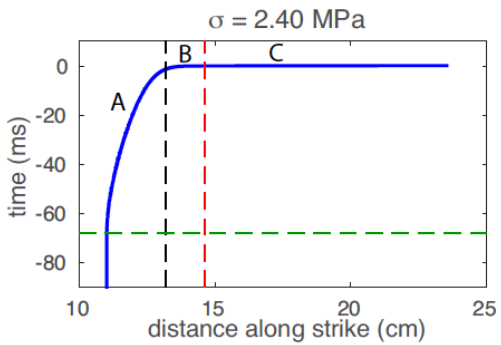

σ = 0.75 MPa
f = 10^-1.8(t + 31)^2.5
A
log10(rupture length (mm))
time (ms)

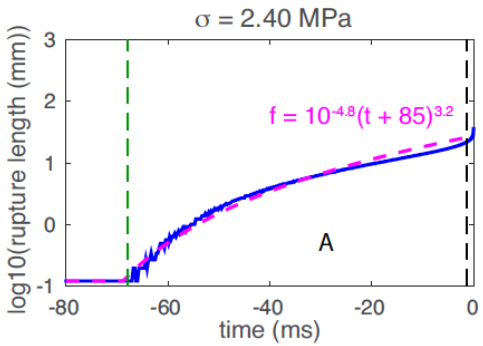

σ = 0.91 MPa
A
B
C
time (ms)
distance along strike (cm)


σ = 0.91 MPa
f = 10^-2.1(t + 36)^2.5
A
log10(rupture length (mm))
time (ms)


σ = 1.58 MPa
A
B
C
time (ms)
distance along strike (cm)


σ = 1.58 MPa
f = 10^-3.1(t + 57)^2.7
A
log10(rupture length (mm))
time (ms)


σ = 2.40 MPa
A
B
C
time (ms)
distance along strike (cm)


σ = 2.40 MPa
f = 10^-4.8(t + 85)^3.2
A
log10(rupture length (mm))
time (ms)

FNN2 servicing: 2016-07-26

FNN2: 6 days later

(photo 2016-08-20)

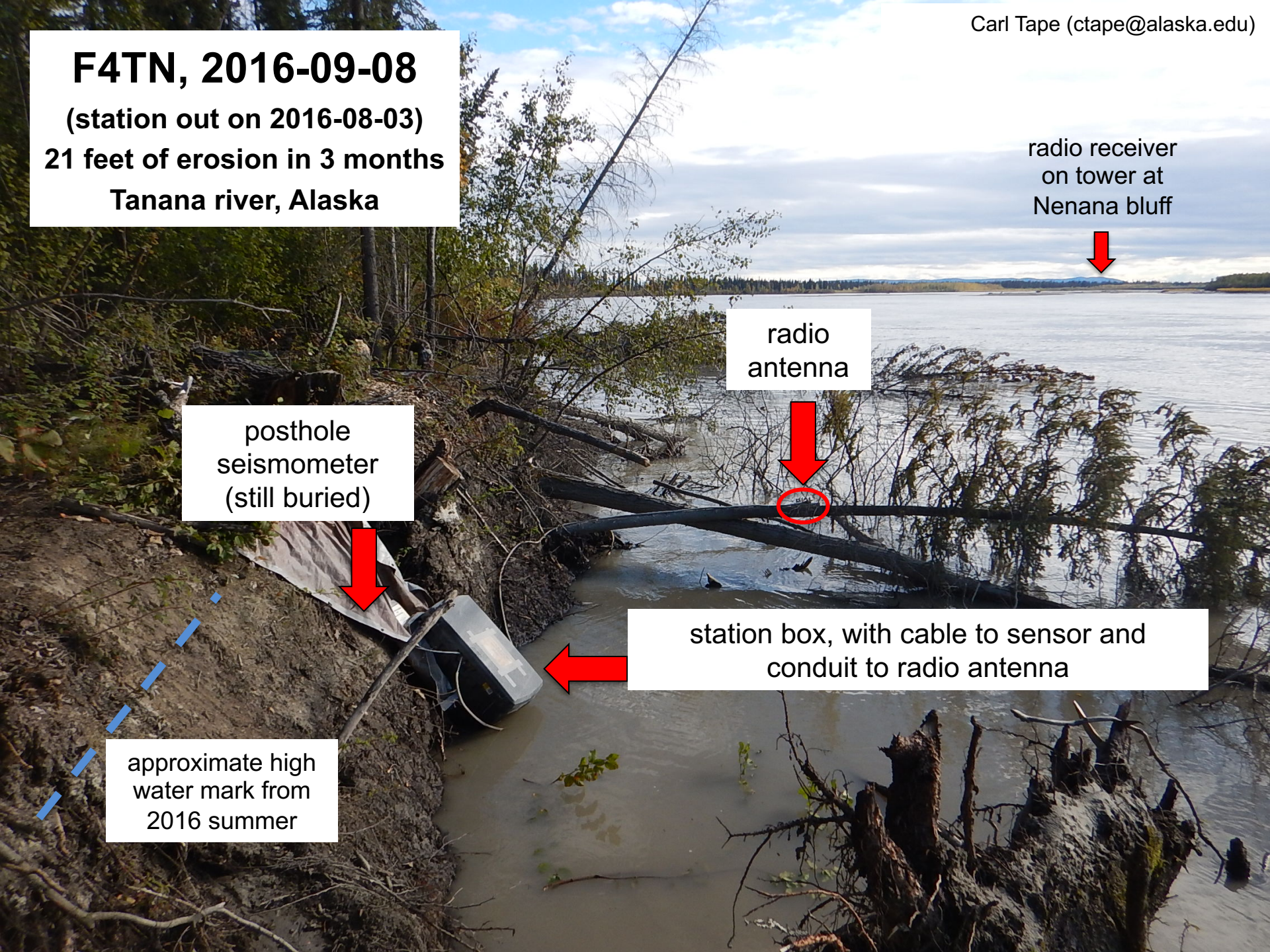
Carl Tape (ctape@alaska.edu)

F4TN, 2016-09-08

(station out on 2016-08-03)

21 feet of erosion in 3 months

Tanana river, Alaska




FLATS station F3TN
(survival of the fittest!)
vandals
MOULTRIE
25°C
F3TNMOV
14 MAY 2016 11:02 am