Workflows of Manual Analysis Helper (MAH)

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Outline

- Manual phase picking
- Repeater detection
- CC clustering
- Source spectrum analysis
- EGF deconvolution

Manual Phase Picking

- Large earthquakes are complete in the public catalogs, while may be missed by matched filter because of poor waveform coherence (e.g. Shelly 2019)
- The S arrivals of a large earthquake can be hard to pick, due to the contamination of P tails
- Thus, it may require manual phase picking to complement the microseismic catalog, and to test the location uncertainty with different combination of phase picks.

Manual Phase Picking

- Input
  - fctlg: catalog file, just rough location would be enough
  - fsta (station_eg.csv): station file
  - data_dir: directory of continuous waveform

- Output
  - fpha_hyp: manually picked and located phase file

Input	Operation	Output	***Notes***
fctlg & fsta	*ctlg2pha.py*	fpha_org	predicted phase arrival
fpha_org	*cut_events.py*	events/[event_name] /[net.sta.chn]	
	SAC *ppk* P/S/N in t0/1/2/3		only use *wh*
events & fpha_org	*head2pha.py*	fpha_man	only phase lines change
fpha_man	*cut_events.py*	events/[event_name] /[net.sta.chn]	may repeat the manual picking process
fpha_man	event location	fpha_hyp	use Hypo-Interface-Py

References

- Douglas, A., Bowers, D., & Young, J. B. (1997). On the onset of P seismograms. *Geophysical Journal International*, *129*(3), 681-690. https://doi.org/10.1111/j.1365-246X.1997.tb04503.x
- Diehl, T., Kissling, E., Bormann, P. (2012): Tutorial for consistent phase picking at local to regional distances. - In: Bormann, P. (Ed.), New Manual of Seismological Observatory Practice 2 (NMSOP-2), Potsdam : Deutsches GeoForschungsZentrum GFZ, 1-21. https://doi.org/10.2312/GFZ.NMSOP-2_IS_11.4
- Lomax, A. (2020). Absolute location of 2019 Ridgecrest seismicity reveals a shallow M w 7.1 hypocenter, migrating and pulsing M w 7.1 foreshocks, and duplex M w 6.4 ruptures. *Bulletin of the Seismological Society of America*, *110*(4), 1845-1858. https://doi.org/10.1785/0120200006

Repeater Detection

- Repeaters indicate aseismic fault slip (Uchida & Burgmann, 2019)
- This helper implement the repeater detection method in Zhou et al. (2022), which utilize both waveform similarity and location:
  - Waveform similarity is measured by CC of long window, covering both P & S waves
  - The location separation is constraint by d(S-P), which is measure by CC of short windows separately for P & S.
  - A strict detection of repeating earthquakes would adopt parameters like (1) average CC>0.9, and (2) dt_sp≤0.01s for at least 3 stations, under a proper frequency band (Uchida, 2019)

Repeater Detection

- Input
  - eg_mess.pha: initial MESS detection
  - fpha_pal (eg_pal_hyp_full.pha): PAL phase file (templates for MESS)
  - eg_mess_cc.ctlg: final relocated MESS catalog
  - fsta (station_eg.csv): station file

- Output
  - eg_rep.clust: repeater sequences
  - eg_rep.pha: all repeaters

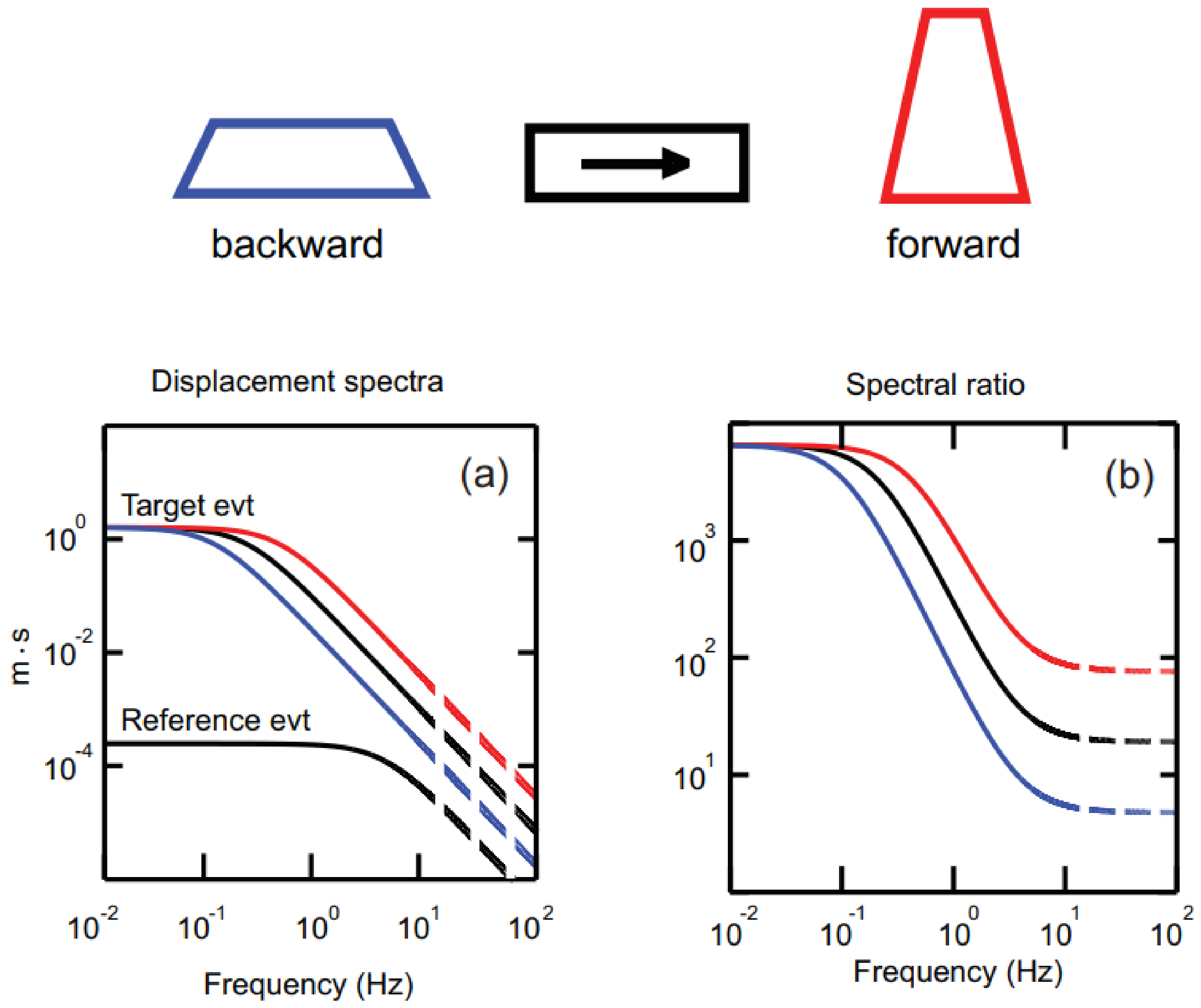
Input	**Operation**	**Output**	***Notes***
fpha_pal & fsta	run MESS	eg_mess.pha eg_mess_cc.ctlg	i.e. run PALM
eg_mess.pha	*run_clustering.py*	eg_rep-org_full.pha	find repeater candidates in MESS detections
eg_rep-org_full.pha	run MESS	eg_mess-rep.pha	detect with high CC threshold, e.g. 0.8
eg_mess-rep.pha	*run_clustering.py*	eg_rep.clust eg_rep.pha	using strict criteria, e.g. cc>0.9, dt_sp≤0.01s

References

- Uchida, N. (2019). Detection of repeating earthquakes and their application in characterizing slow fault slip. *Progress in Earth and Planetary Science*, 6(1), 1-21. https://doi.org/10.1186/s40645-019-0284-z
- **Zhou, Y.**, H. Yue, L. Fang et al. (2021). An Earthquake Detection and Location Architecture for Continuous Seismograms: Phase Picking, Association, Location, and Matched Filter (PALM). *Seismological Research Letters*; 93(1): 413–425. https://doi.org/10.1785/0220210111
- **Zhou, Y.**, H. Yue, S. Zhou et al. (2022). Microseismicity along Xiaojiang Fault Zone (Southeastern Tibetan Plateau) and the Characterization of Interseismic Fault Behavior. *Tectonophysics*; 833: 229364. doi: 10.1016/j.tecto.2022.229364

Source Spectrum

- EGF-based spectral ratio contain information on the source parameters, e.g. stress drop, rupture area etc.
- Rupture directivity can be inferred from azimuthal variation of the corner frequency and high/low frequency component (e.g. Zhou et al 2022)



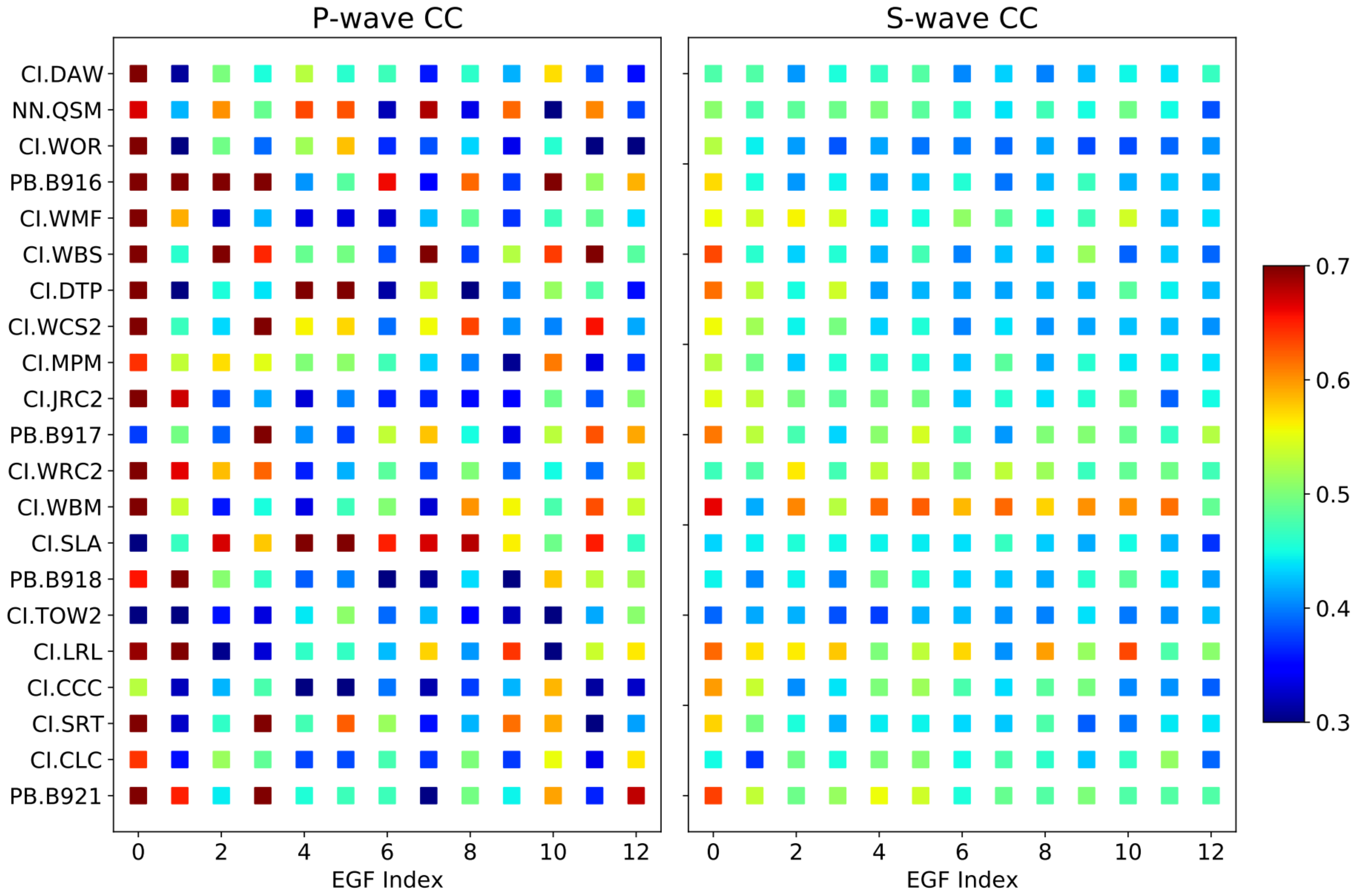
Calderoni et al., GJI 2015

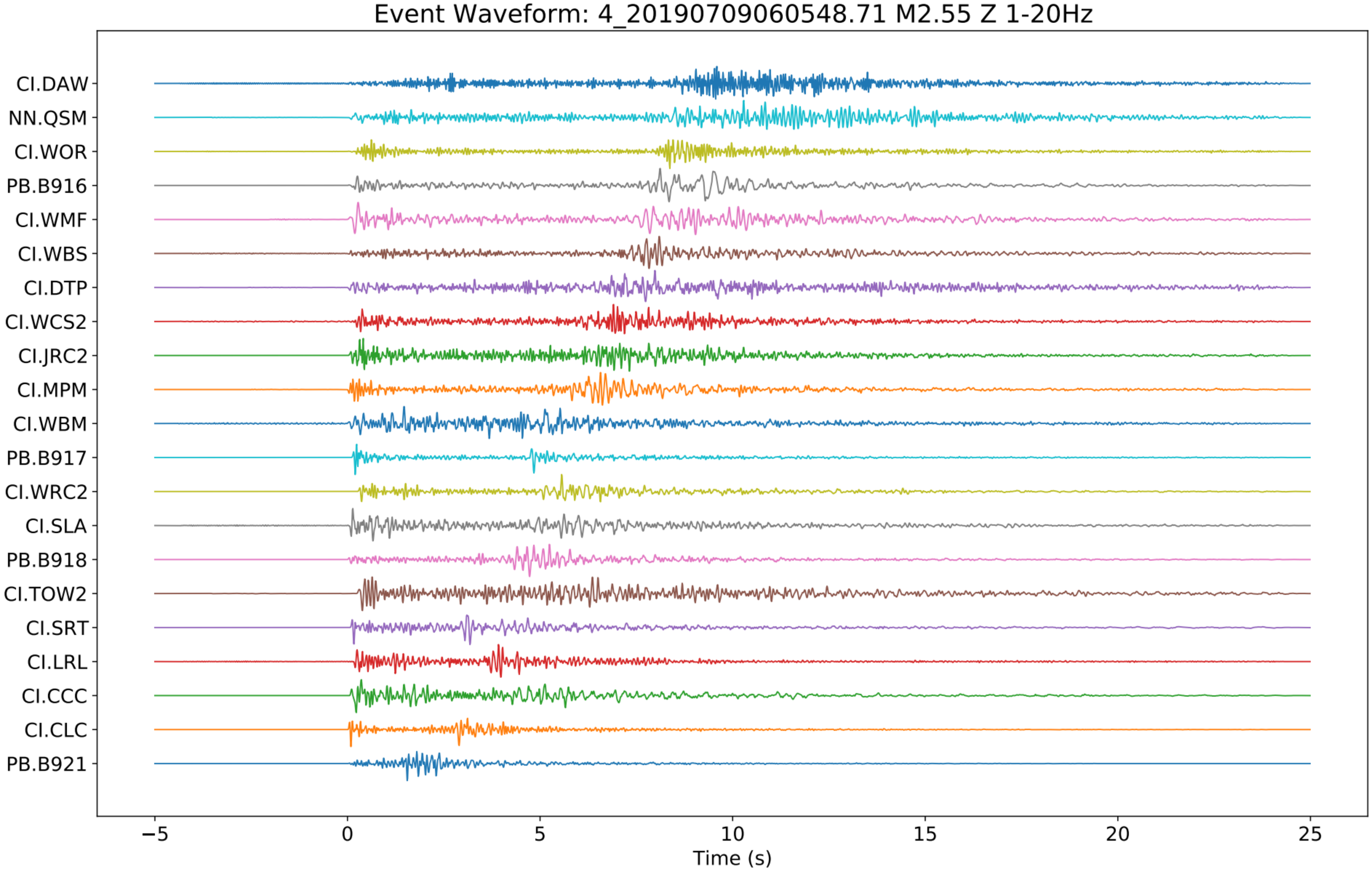
Source Spectrum

- Inputs
  - fpha_tar: phases for the target events
  - fctlg_all: catalog that contain all available events
  - fsta (station_eg.csv): station file

- Outputs
  - spectrum of target & EGFs
  - comparison of spectral ratio on different stations
  - stacked spectral ratio and estimated source parameters

Input	**Operation**	**Output**	***Notes***
fctlg_all & fsta	*select_egf_loc.py*	fpha_egf_org	select EGF by time, location, & magnitude
fpha_tar & fpha_egf_org	*cut_events.py*	input/events_tar input/events_egf	cut raw data
fpha_egf_org & input/events_egf	*pick_events.py*	fpha_egf_org	refine original pick with STA/LTA
fpha_egf_org	*calc_egf-cc.py & plot_egf-cc.py*	eg_tar-egf.cc & eg_tar-egf-cc.pdf	
eg_tar-egf.cc	select_egf_cc.py	fpha_egf	select with CC (not strict criteria as well)
fpha_egf	*plot_waveform-events.py*	evid_name.pdf	inspect selected events

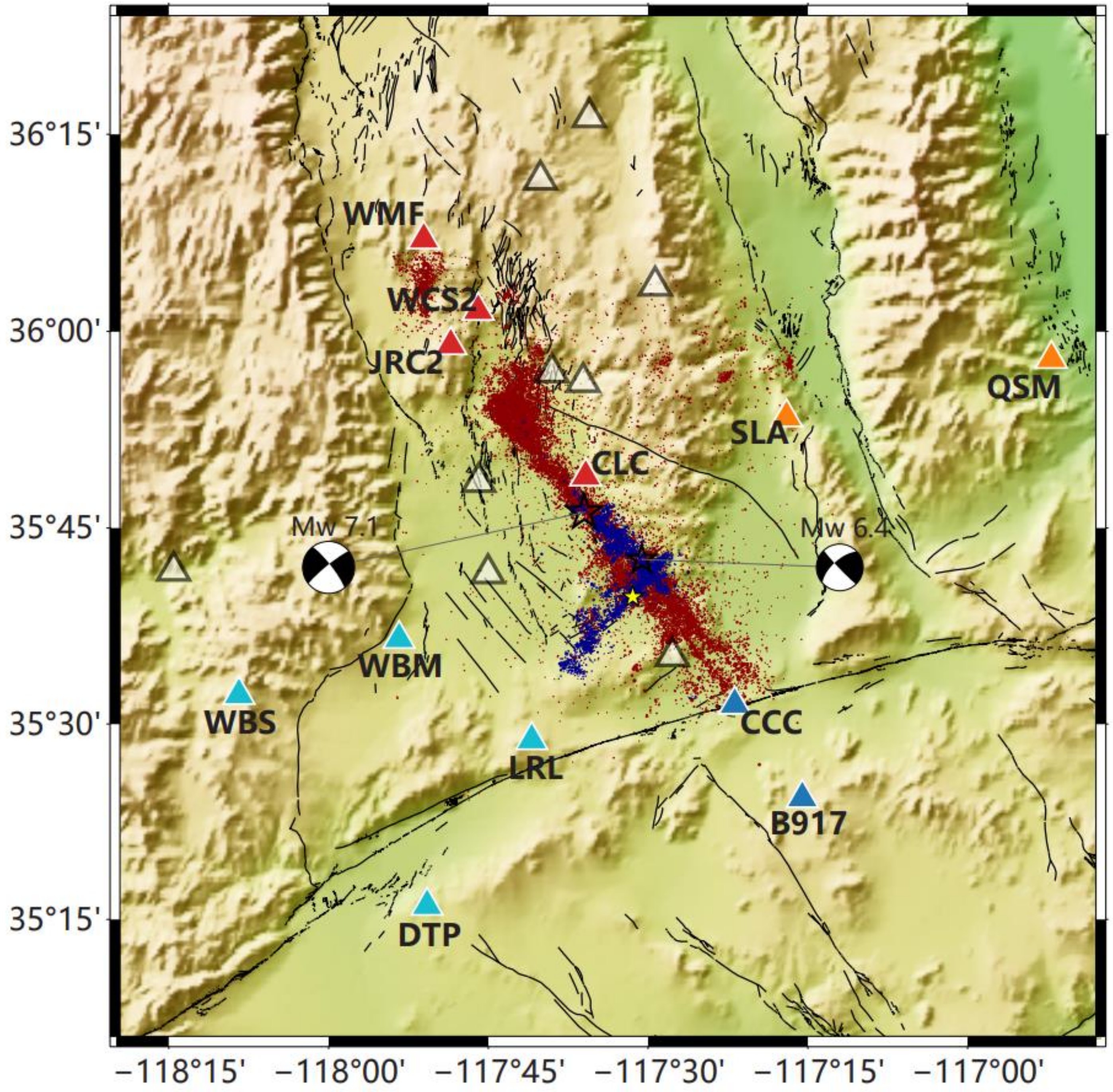

P-wave CC
S-wave CC
CI.DAW
NN.QSM
CI.WOR
PB.B916
CI.WMF
CI.WBS
CI.DTP
CI.WCS2
CI.MPM
CI.JRC2
PB.B917
CI.WRC2
CI.WBM
CI.SLA
PB.B918
CI.TOW2
CI.LRL
CI.CCC
CI.SRT
CI.CLC
PB.B921
0
2
4
6
8
10
12
EGF Index
0.7
0.6
0.5
0.4
0.3



Event Waveform: 4_20190709060548.71 M2.55 Z 1-20Hz
CI.DAW
NN.QSM
CI.WOR
PB.B916
CI.WMF
CI.WBS
CI.DTP
CI.WCS2
CI.JRC2
CI.MPM
CI.WBM
PB.B917
CI.WRC2
CI.SLA
PB.B918
CI.TOW2
CI.SRT
CI.LRL
CI.CCC
CI.CLC
PB.B921
−5
0
5
10
15
20
25
Time (s)

Spectral Ratio Calculation and Analysis

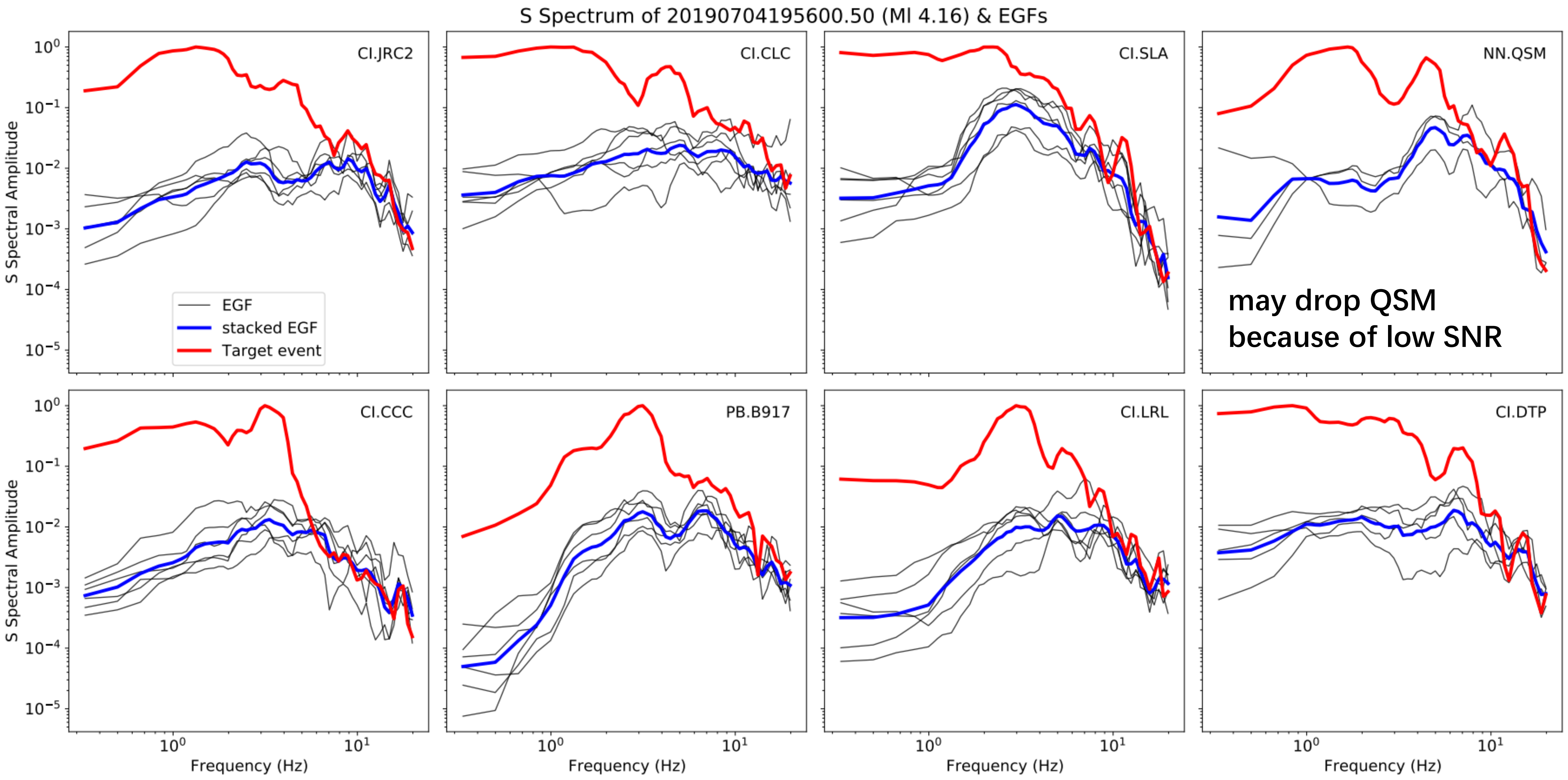
Input	**Operation**	**Output**	***Notes***
fpha_egf & fpha_tar	*plot_spec-s.py*	eg_spec-s_name.pdf	check the consistency between spectrum of EGFs
fpha_egf & fpha_tar	*plot_spec-ratio-compare.py*	eg_spec-ratio-compare_name.pdf	resolve rupture directivity first to determine the fault plane
fpha_egf & fpha_tar	*plot_spec-ratio-stack.py*	eg_spec-ratio-stack_name.pdf	use fault-normal stations to estimate source parameters



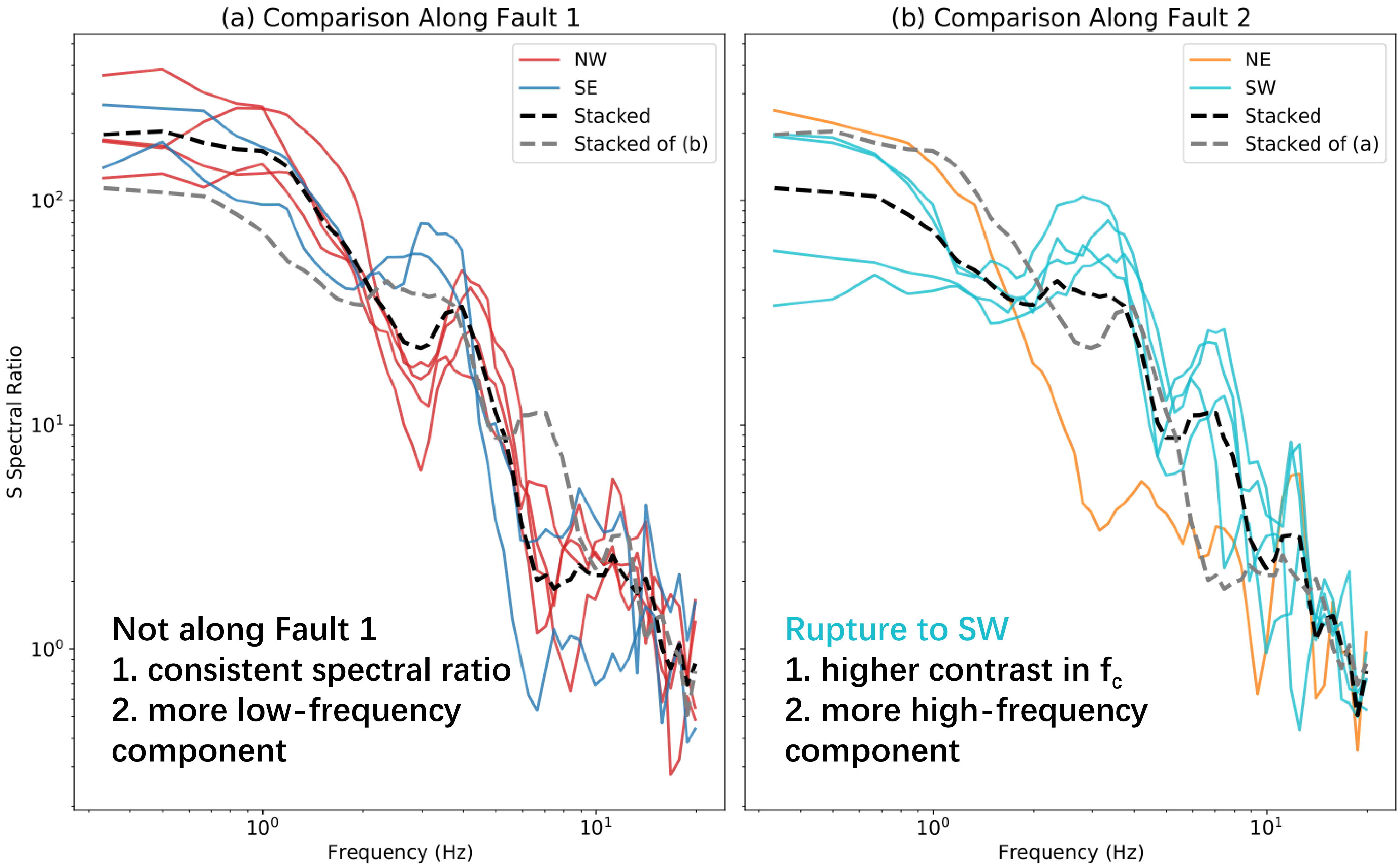
Aftershocks show two fault trends, thus two possible rupture directivity exists

⇩

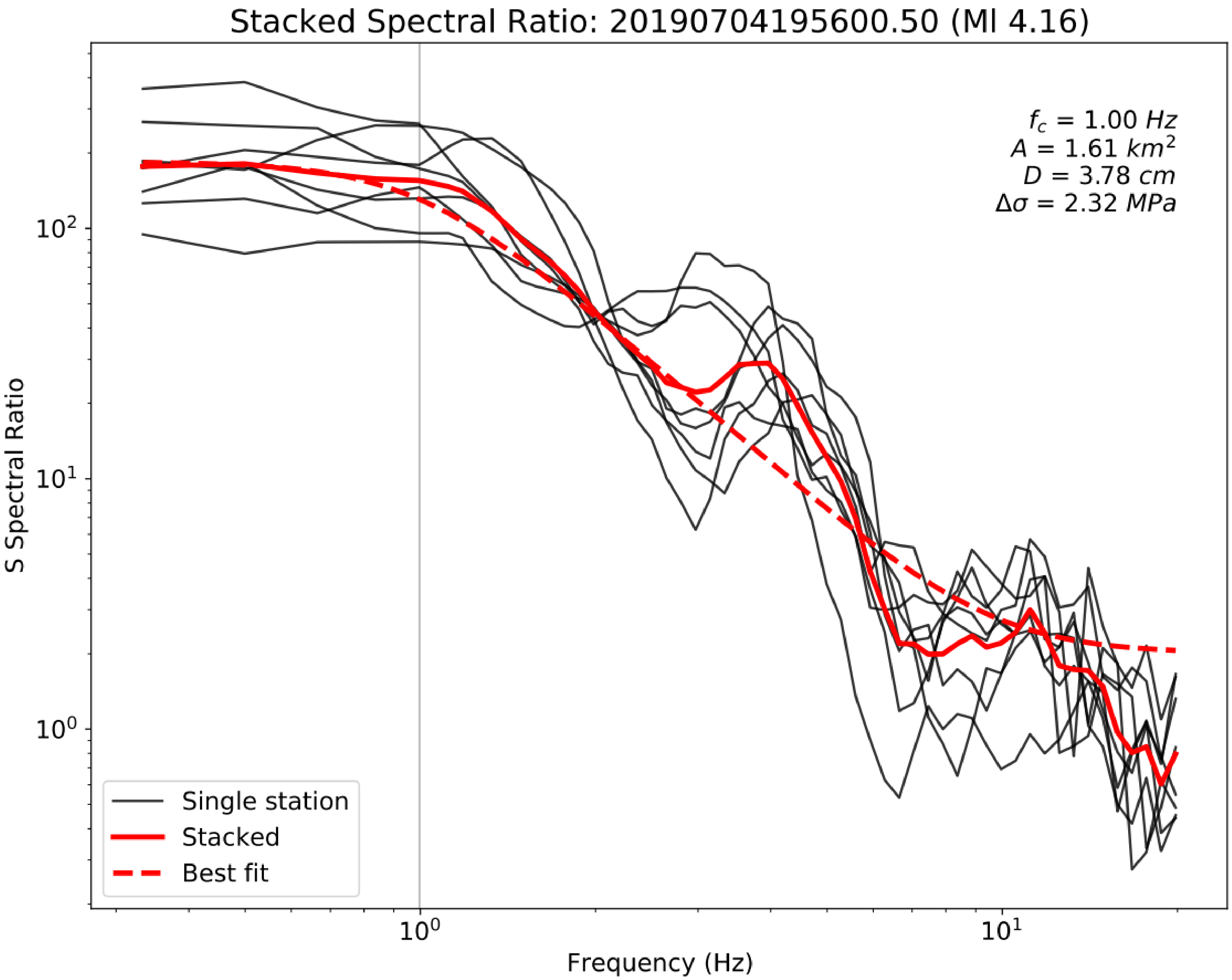
Compare spectral ratio on two sets of stations: along Fault_1 (NE) & along Fault_2 (NW) → the direction with more significant contrast indicate the ruptured fault



S Spectrum of 20190704195600.50 (Ml 4.16) & EGFs
CI.JRC2
CI.CLC
CI.SLA
NN.QSM
CI.CCC
PB.B917
CI.LRL
CI.DTP
EGF
stacked EGF
Target event
S Spectral Amplitude
Frequency (Hz)
may drop QSM
because of low SNR



(a) Comparison Along Fault 1
(b) Comparison Along Fault 2
NW
SE
Stacked
Stacked of (b)
NE
SW
Stacked
Stacked of (a)
S Spectral Ratio
10^2
10^1
10^0
10^0
10^1
Frequency (Hz)
Not along Fault 1
1. consistent spectral ratio
2. more low-frequency component
Rupture to SW
1. higher contrast in f_c
2. more high-frequency component



Stacked Spectral Ratio: 20190704195600.50 (Ml 4.16)
f_c = 1.00 Hz
A = 1.61 km^2
D = 3.78 cm
$\Delta\sigma$ = 2.32 MPa
S Spectral Ratio
10^2
10^1
10^0
Frequency (Hz)
Single station
Stacked
Best fit

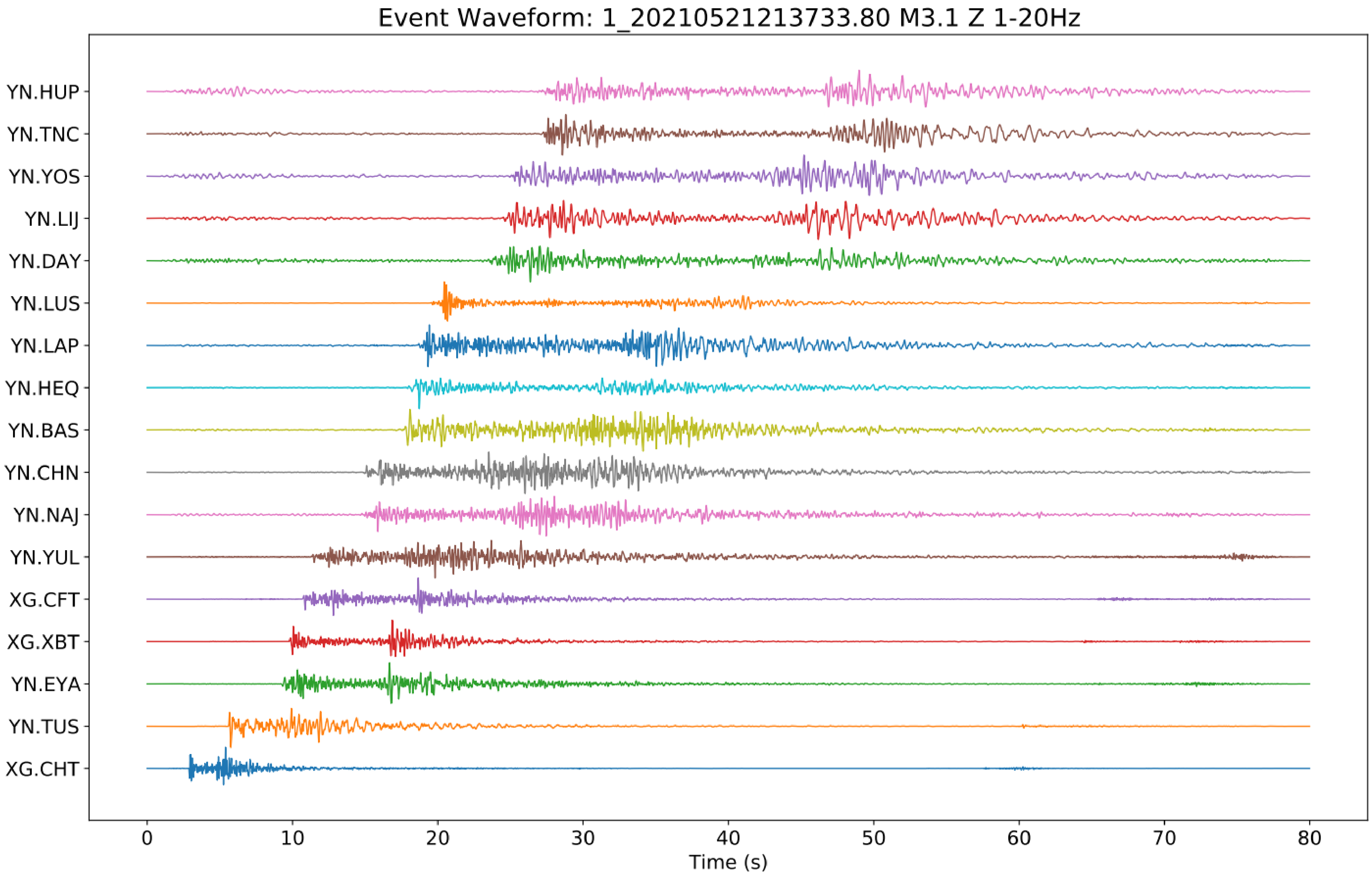
2. PLD for Source Time Function

- Input
  - fctlg_tar: catalog that contains target events
  - fctlg_all: catalog that contains all available events
  - fsta: station file
  - data_dir: directory of continuous data
- Output
  - pld_stf_pha.npy

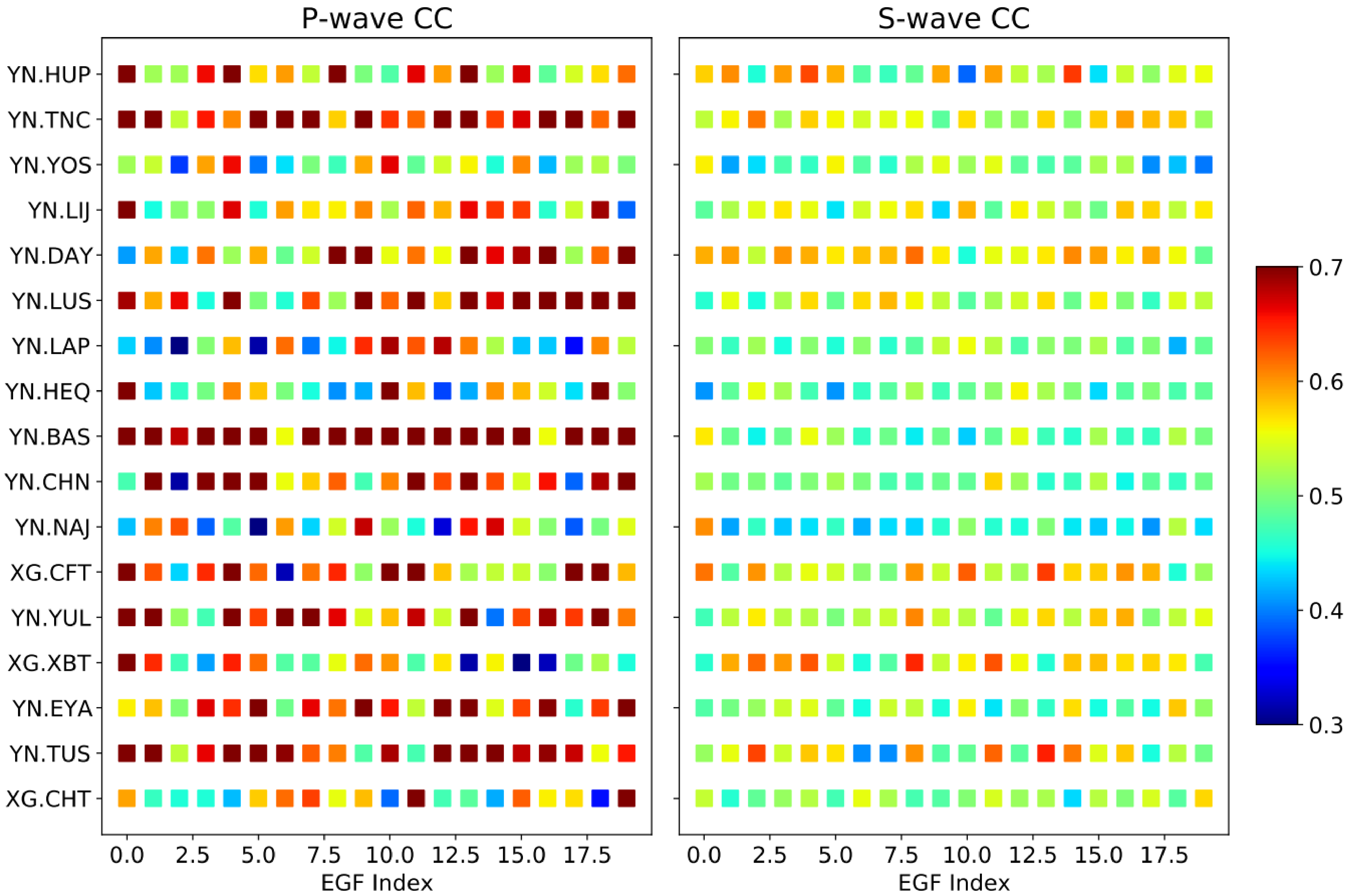
2.1 Prepare Target & EGF Event Data

Input	Operation	Command	Output	*Notes*
fctlg_tar & fsta	select EGF & make phase file	*ctlg2pha.py*	fpha_tar_org	predicted phase arrival, need manual repick
fpha_tar_org	cut Target events	*cut_events-small.py*	input/events_tar	cut raw data
	SAC *ppk*	*head2pha.py*	fpha_tar	mark P/S/N in t0/1/2, only use *wh*
fpha_tar	cut Target events	*cut_events-small.py*	input/events_tar	optional
fpha_tar	event location		fpha_tar_hyp	optional

Input	Operation	Command	Output	*Notes*
fctlg_all & fsta	make phase file	*ctlg2pha.py*	fpha_all_org	predicted phase arrival, not accurate
fpha_all_org	cut events (filtered)	*cut_events-big.py*	bigdata/events	low freq_band, e.g. [0.5,5]
events_tar & events_all	CC selection	*calc_egf-cc.py*	fcc_tar-egf	no filter here
		select_egf.py	fpha_egf_org	should remain <20 EGF candidates
fpha_egf_org	inspect event waveform	*plot_waveform-events.py*	evid_name.pdf	check overall SNR of each candidate EGF
	inspect CC	*plot_egf-cc.py*	egf_cc.pdf	check overall CC of each candidate EGF
fpha_egf_org	cut events (raw data)	*cut_events-small.py*	input/events_egf	no filter here
	SAC *ppk*	*head2pha.py*	fpha_egf	optional



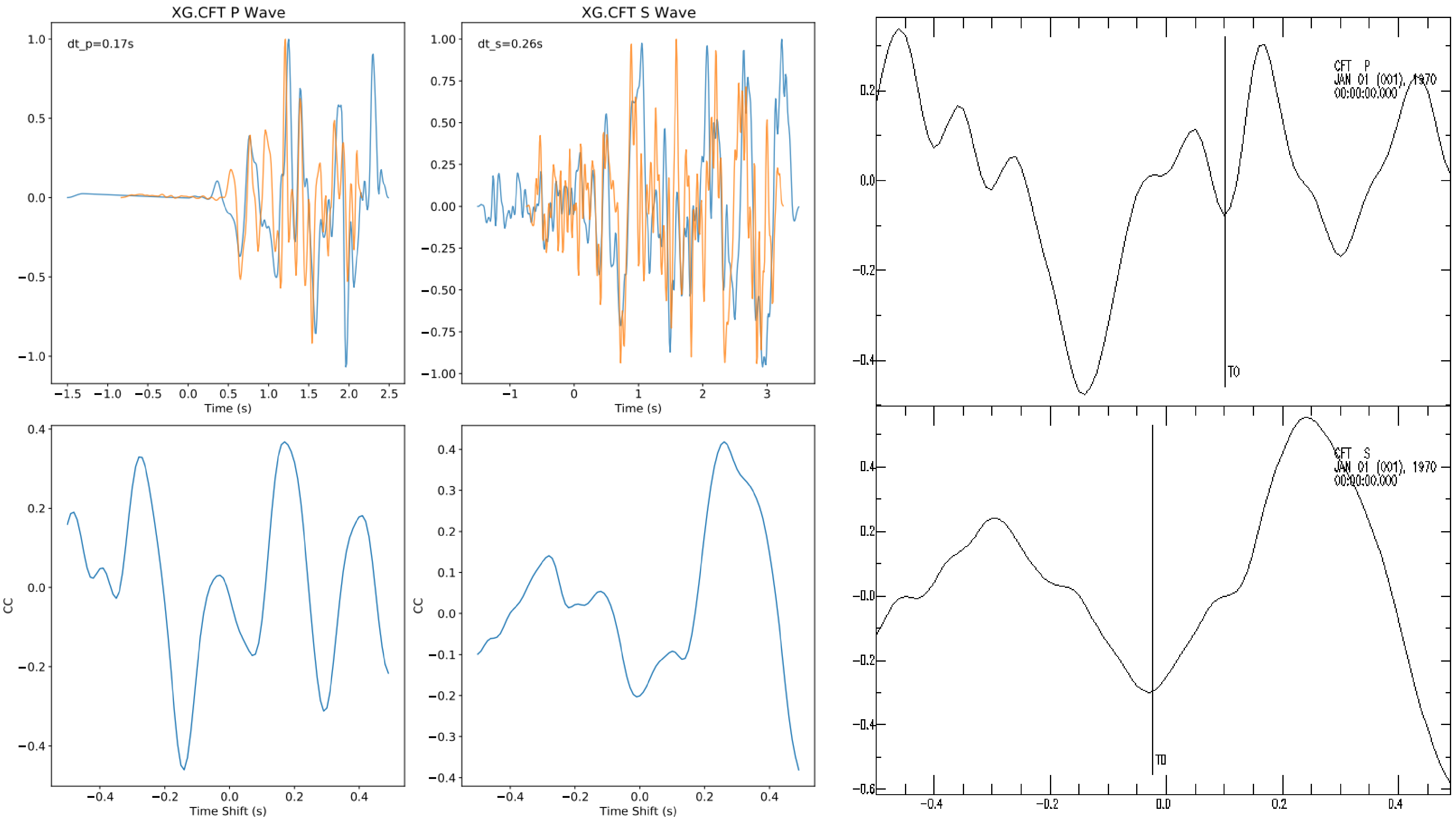
Event Waveform: 1_20210521213733.80 M3.1 Z 1-20Hz
YN.HUP
YN.TNC
YN.YOS
YN.LIJ
YN.DAY
YN.LUS
YN.LAP
YN.HEQ
YN.BAS
YN.CHN
YN.NAJ
YN.YUL
XG.CFT
XG.XBT
YN.EYA
YN.TUS
XG.CHT
0
10
20
30
40
50
60
70
80
Time (s)

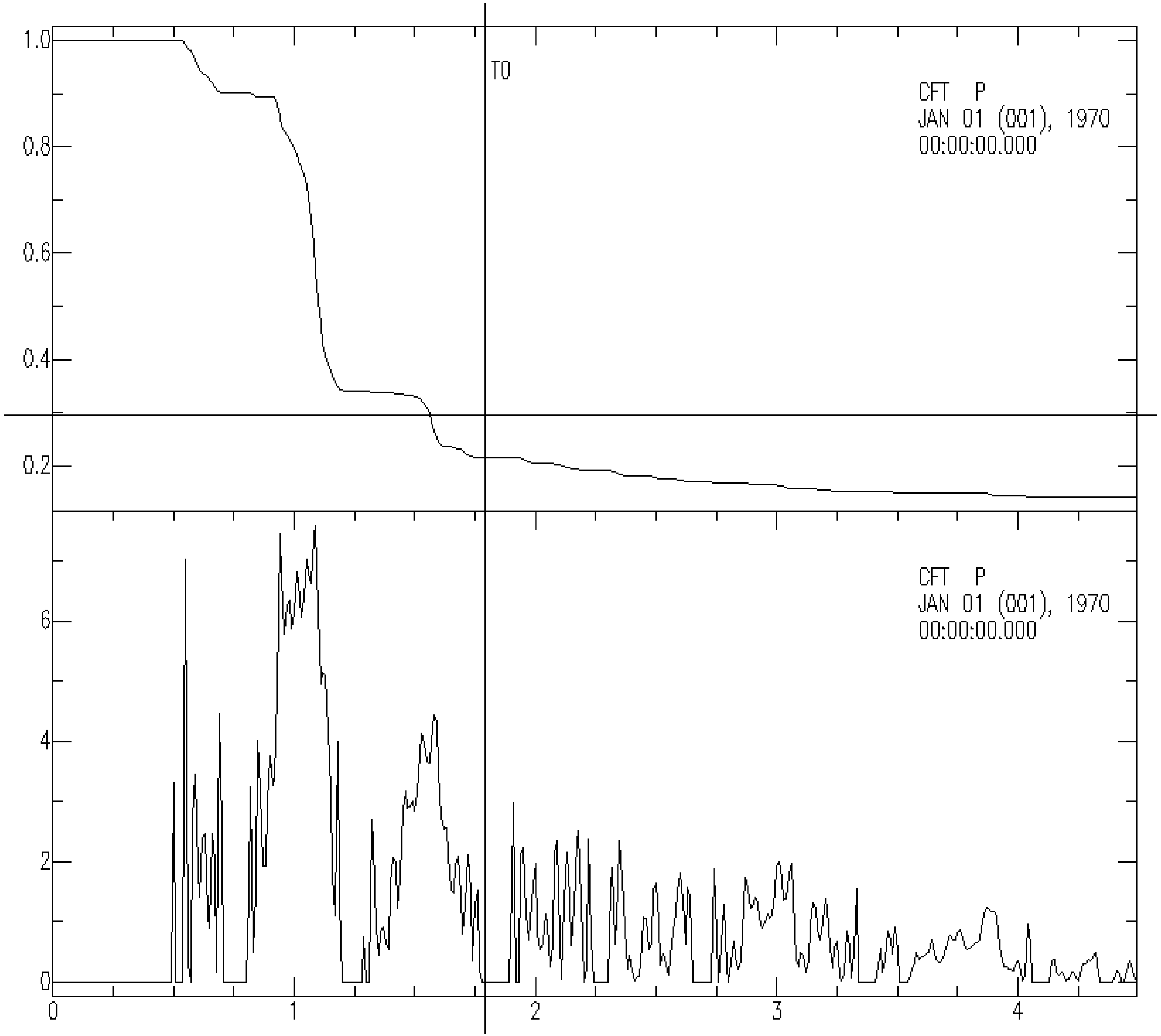


P-wave CC
S-wave CC
YN.HUP
YN.TNC
YN.YOS
YN.LIJ
YN.DAY
YN.LUS
YN.LAP
YN.HEQ
YN.BAS
YN.CHN
YN.NAJ
XG.CFT
YN.YUL
XG.XBT
YN.EYA
YN.TUS
XG.CHT
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
EGF Index
0.7
0.6
0.5
0.4
0.3

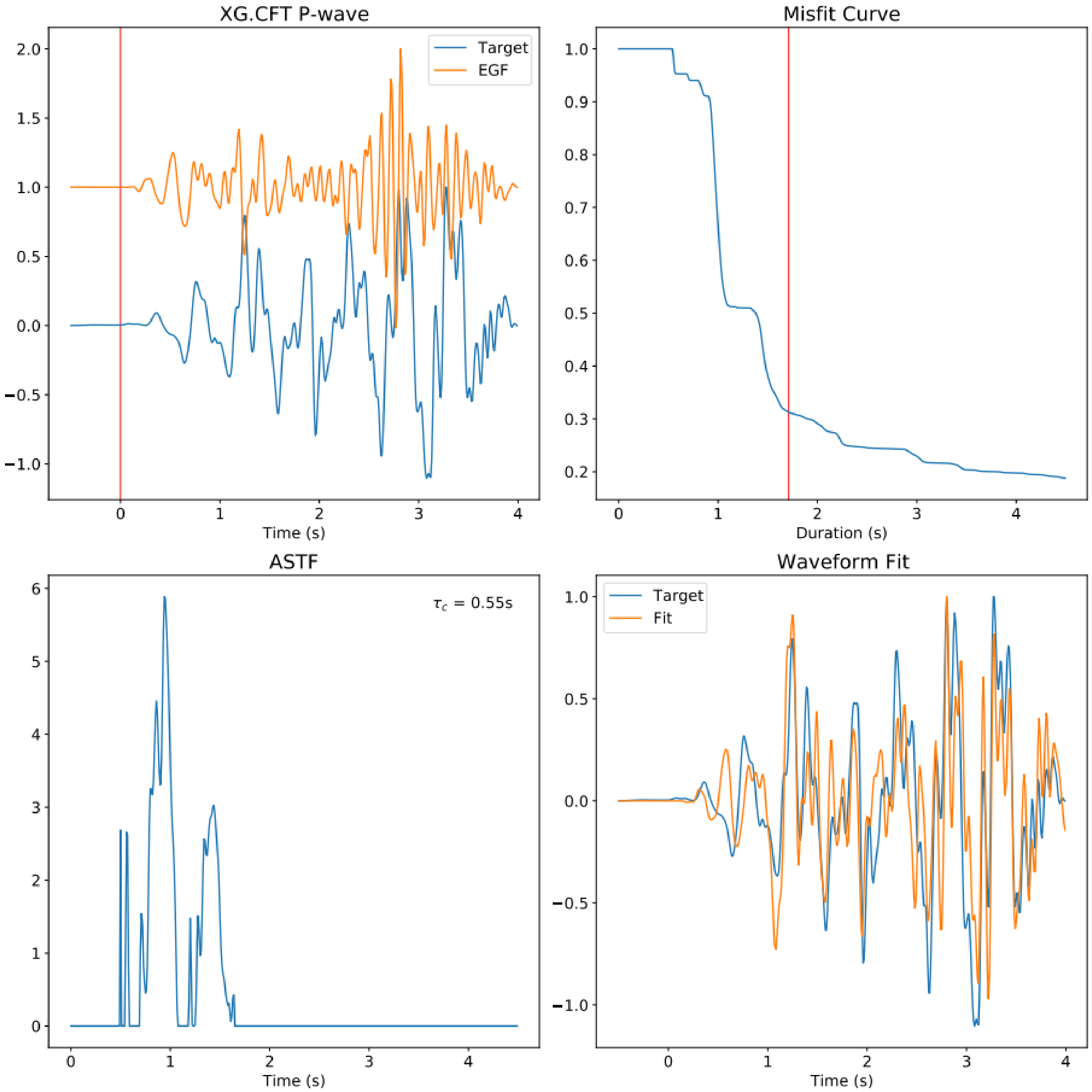
2.2 Perform PLD (for the best EGF)

Input	**Operation**	**Command**	**Output**	***Notes***
events_tar & events_egf	CC alignment	*pick_cc.py*	tar/egf/ cc_sta_egf.pdf & sta/cc_pha.sac	
	manual pick CC to align tar & egf	SAC *ppk*	*t0* marks to calc *t1* marks not to calc	pick the first backward amin near global amax
cc_pha.sac	calc PLD misfit	*calc_pld-misfit.py*	tar/egf/sta pld_err_pha.sac & pld_stf_pha.sac	use SAC to pick the end time on misfit curve
	plot final PLD result	*plot_pld.py*	tar/egf/ pld_sta_pha.pdf & sta/pld_stf_pha.npy	


XG.CFT P Wave
dt_p=0.17s
Time (s)
XG.CFT S Wave
dt_s=0.26s
Time (s)
CC
Time Shift (s)
CC
Time Shift (s)
CFT P
JAN 01 (001), 1970
00:00:00.000
T0
CFT S
JAN 01 (001), 1970
00:00:00.000
T0



1.0
0.8
0.6
0.4
0.2
T0
CFT P
JAN 01 (001), 1970
00:00:00.000
6
4
2
0
CFT P
JAN 01 (001), 1970
00:00:00.000
0
1
2
3
4



XG.CFT P-wave
Target
EGF
Time (s)
Misfit Curve
Duration (s)
ASTF
τ_c = 0.55s
Time (s)
Waveform Fit
Target
Fit
Time (s)