Possible Fluid Driven Open Crack Events Observed in TCDP Borehole Seismometers

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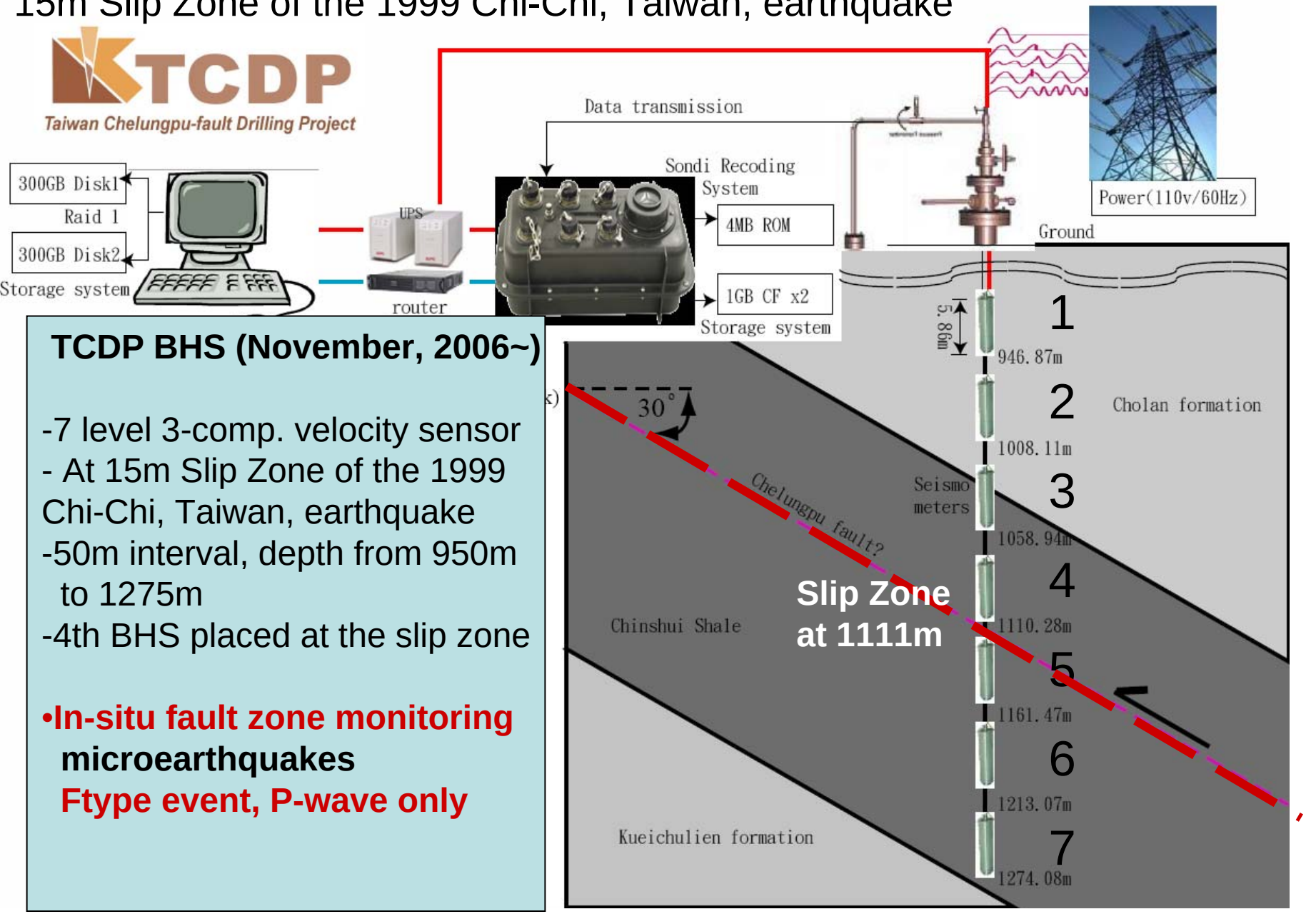
TCDP BHS (June, 2006):
15m Slip Zone of the 1999 Chi-Chi, Taiwan, earthquake

TCDP
Taiwan Chelungpu-fault Drilling Project



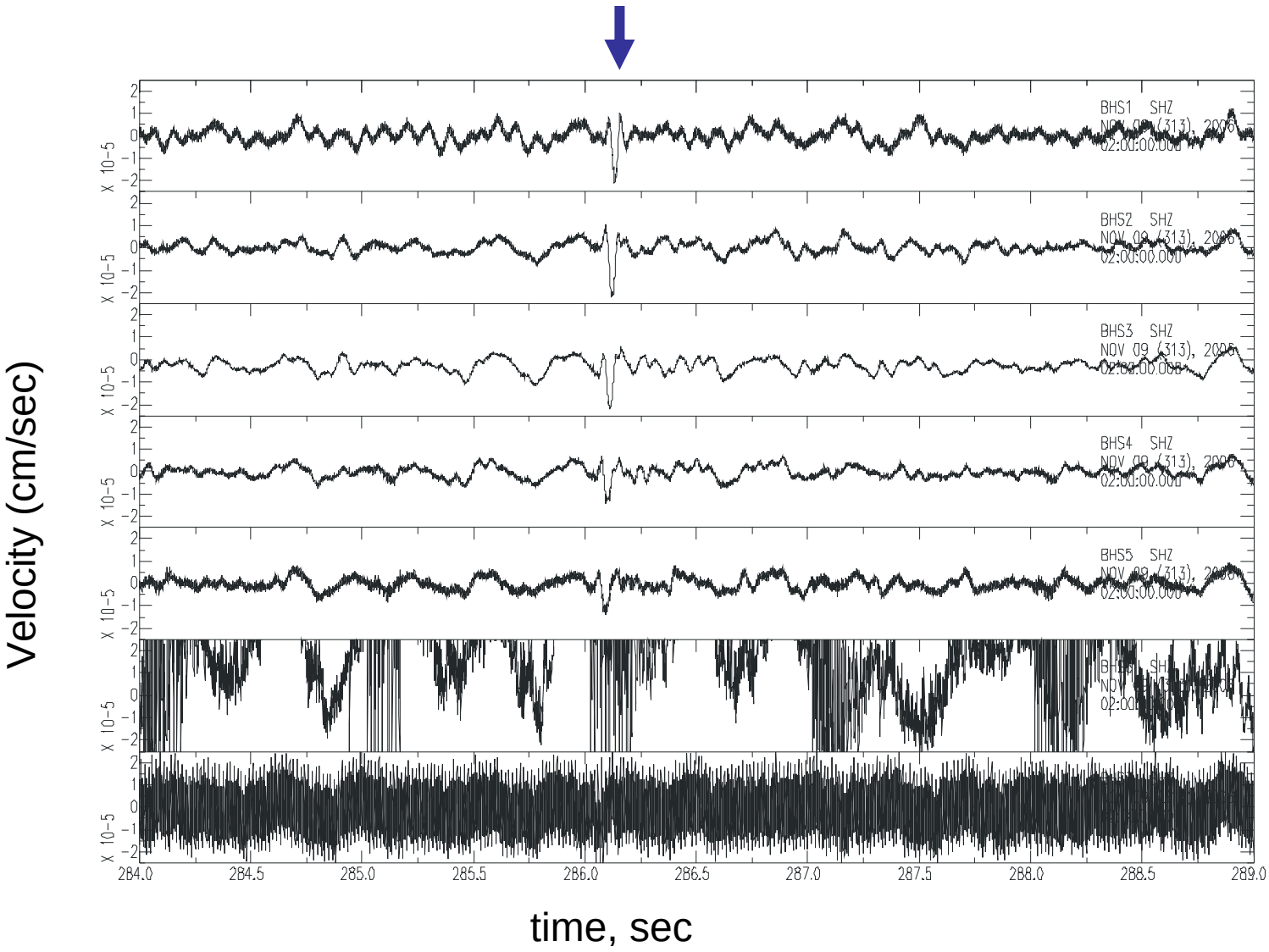
TCDP BHS (November, 2006~)

-7 level 3-comp. velocity sensor
- At 15m Slip Zone of the 1999 Chi-Chi, Taiwan, earthquake
-50m interval, depth from 950m to 1275m
-4th BHS placed at the slip zone

•In-situ fault zone monitoring microearthquakes
Ftype event, P-wave only

F type Event: P-wave only

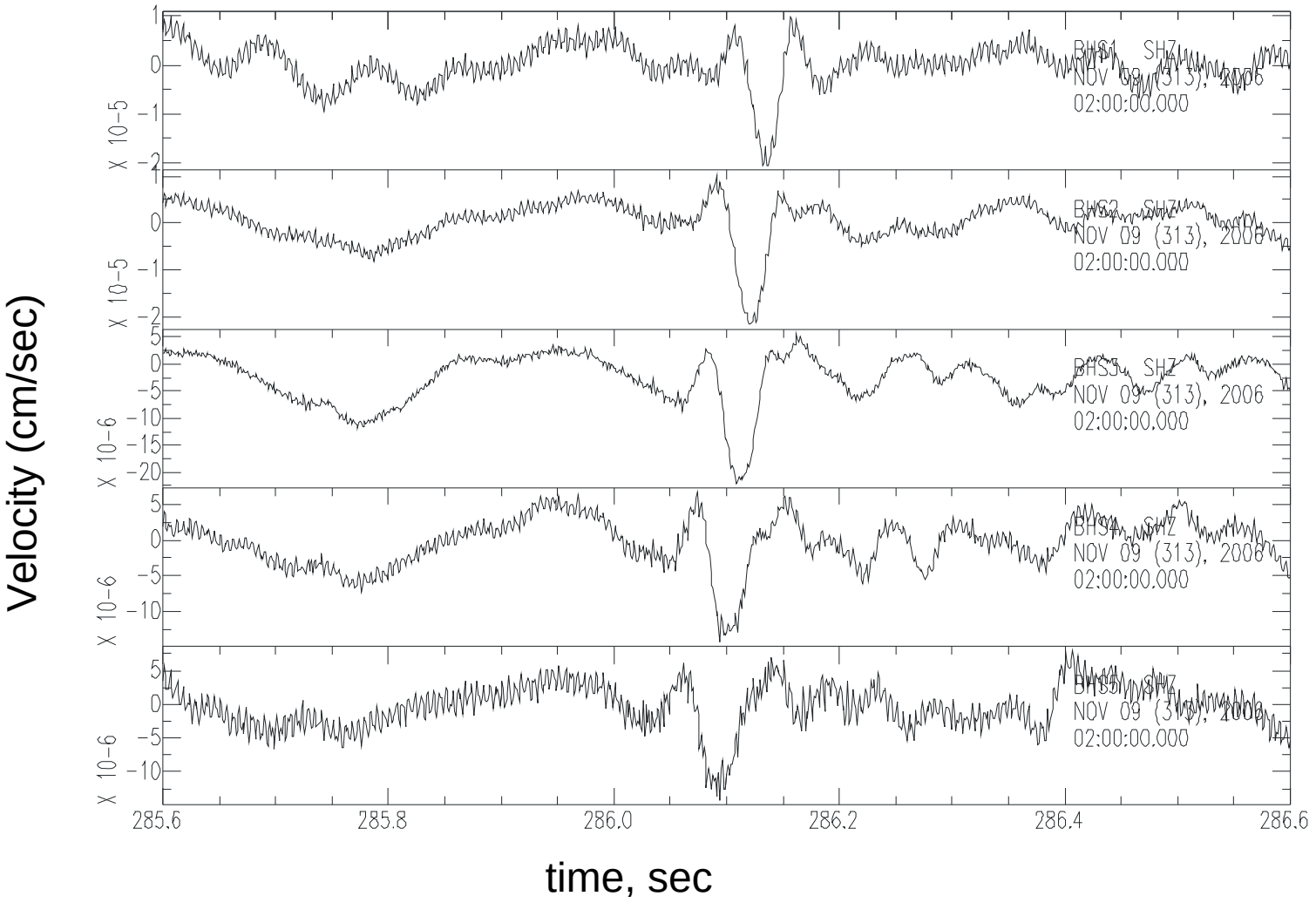
2006/11/09 02:00 Z-Comp (5 sec records)



F type events:

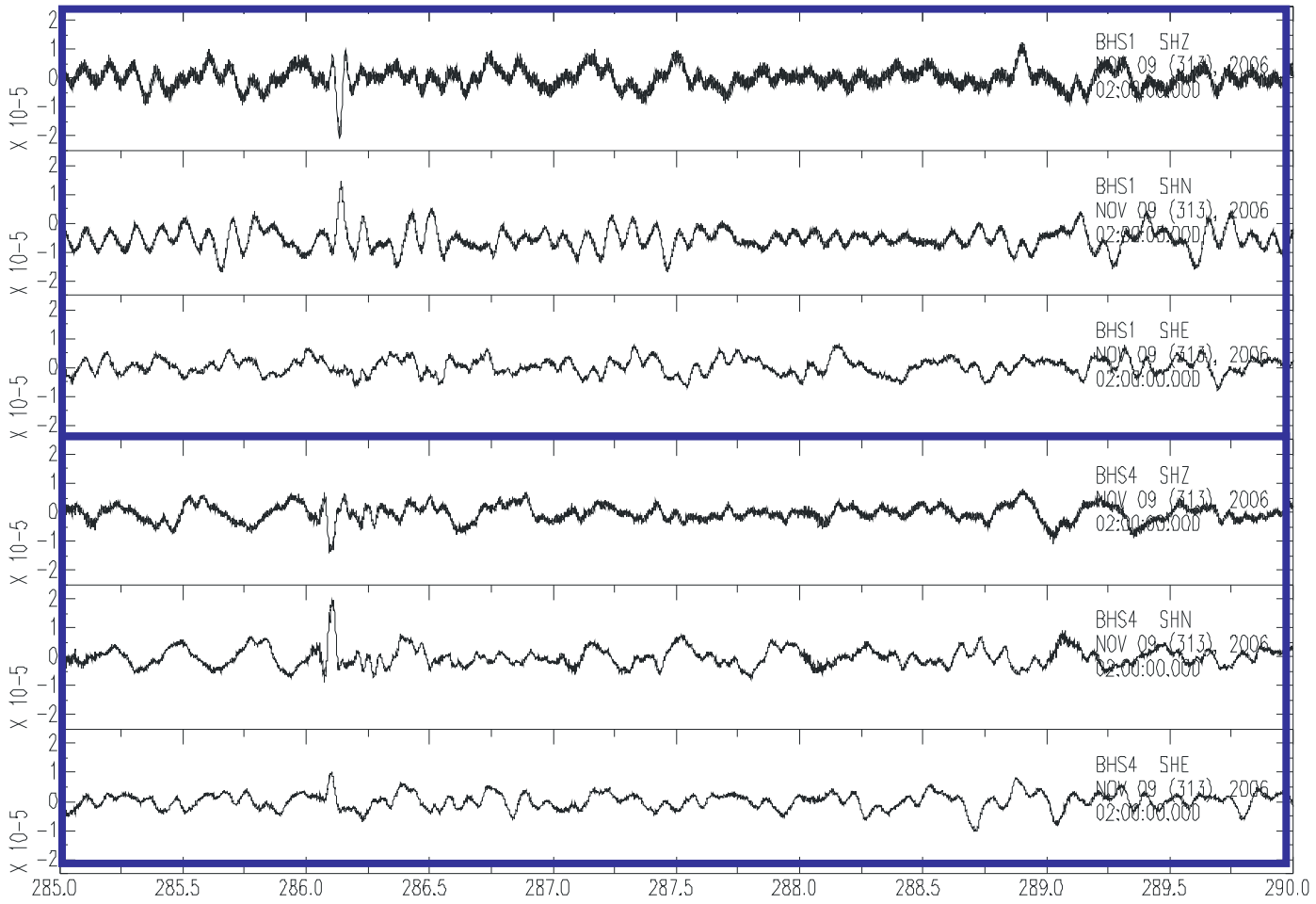
2006/11/09 02:00 Z-Comp (1 sec records)

(upward motion, T~0.05 sec)



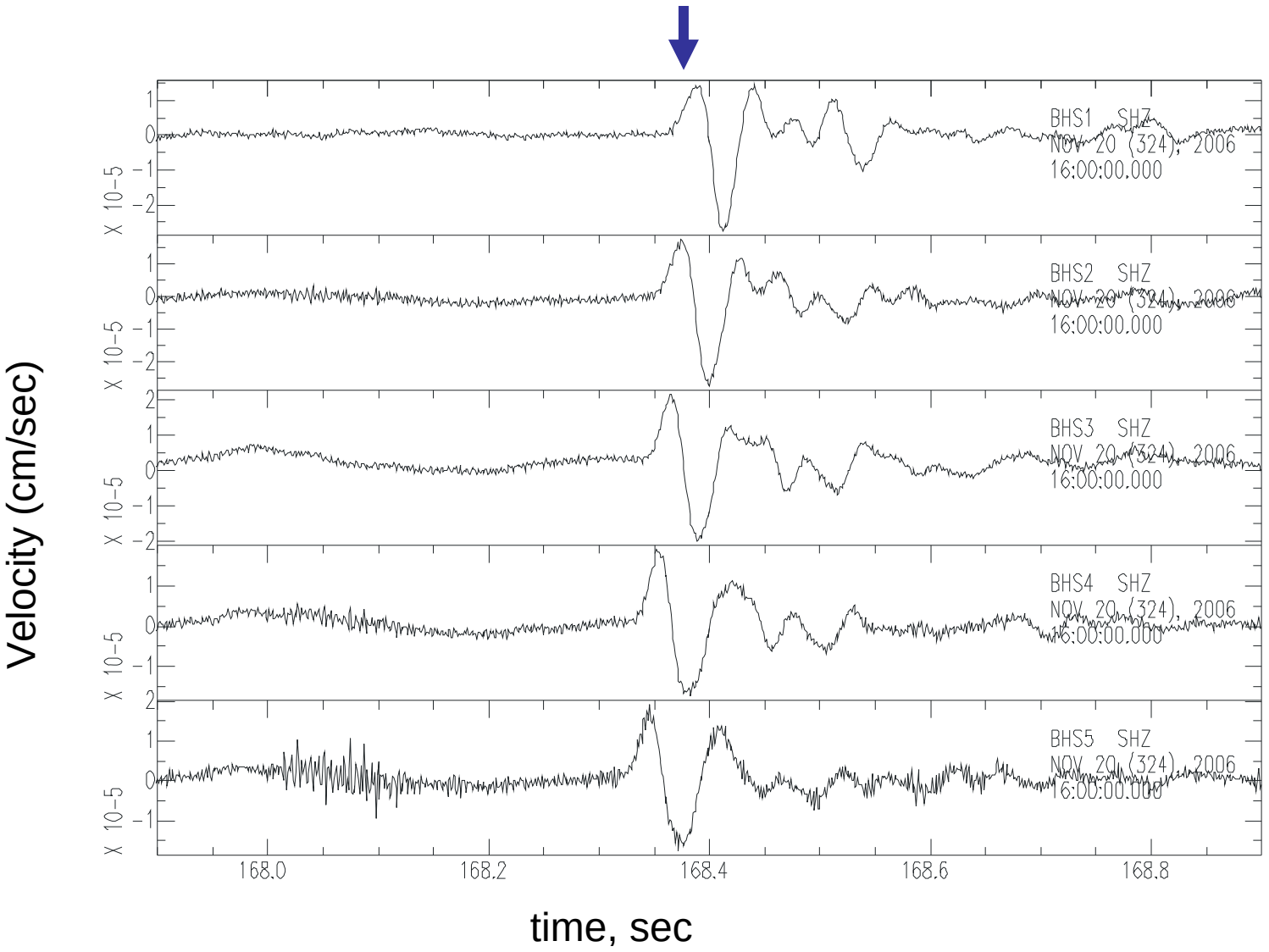
2006/11/09 02:00 Z-Comp
(5 sec records, BHS1; BHS4 Z, N, E)

(No S-wave in horizontal components)



2006/11/20 16:00 Z-Comp (1 sec record)

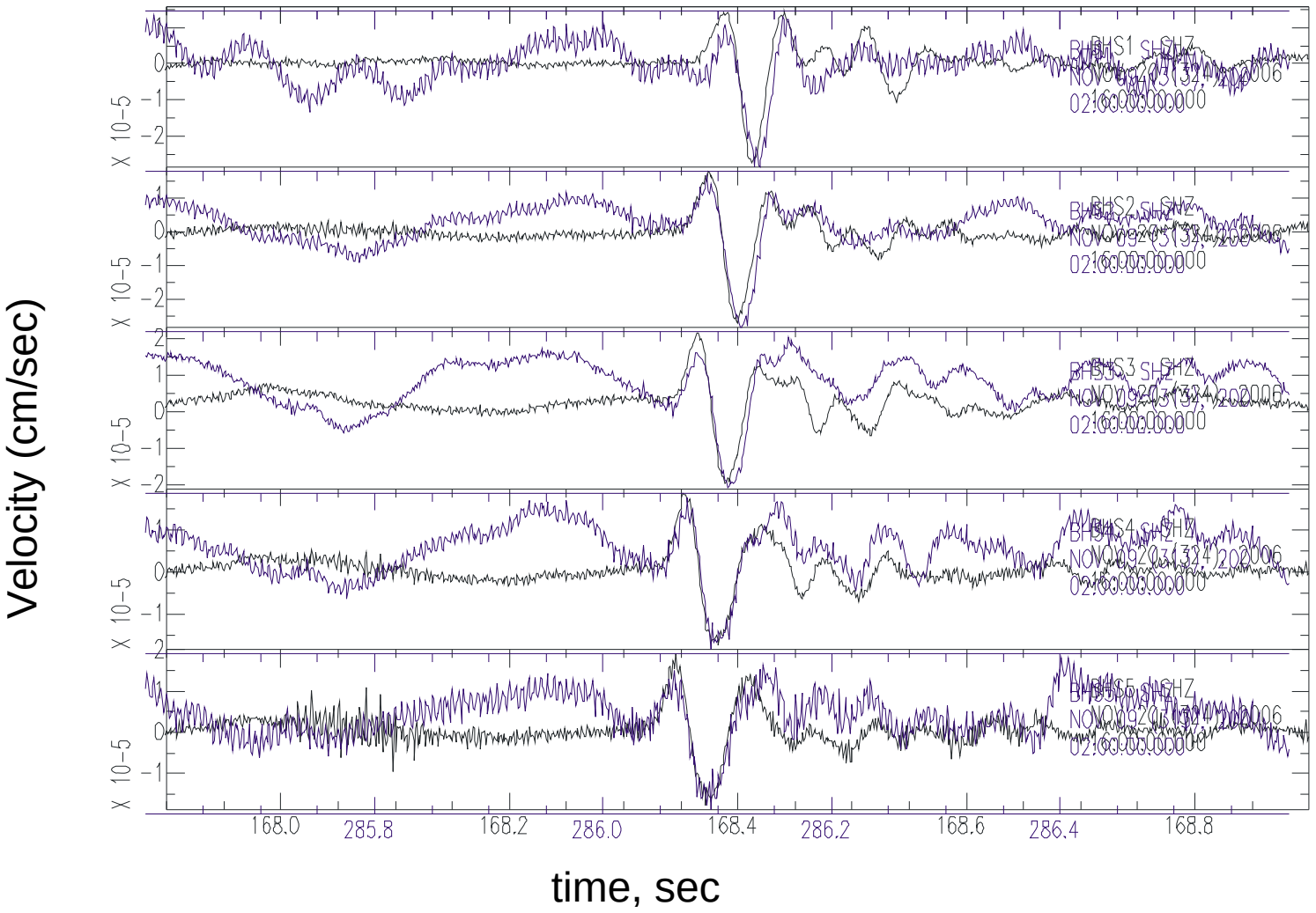
Upward first motion, pulse width~0.05 sec



2006/11/20 16:00 Z-Comp (1 sec record)

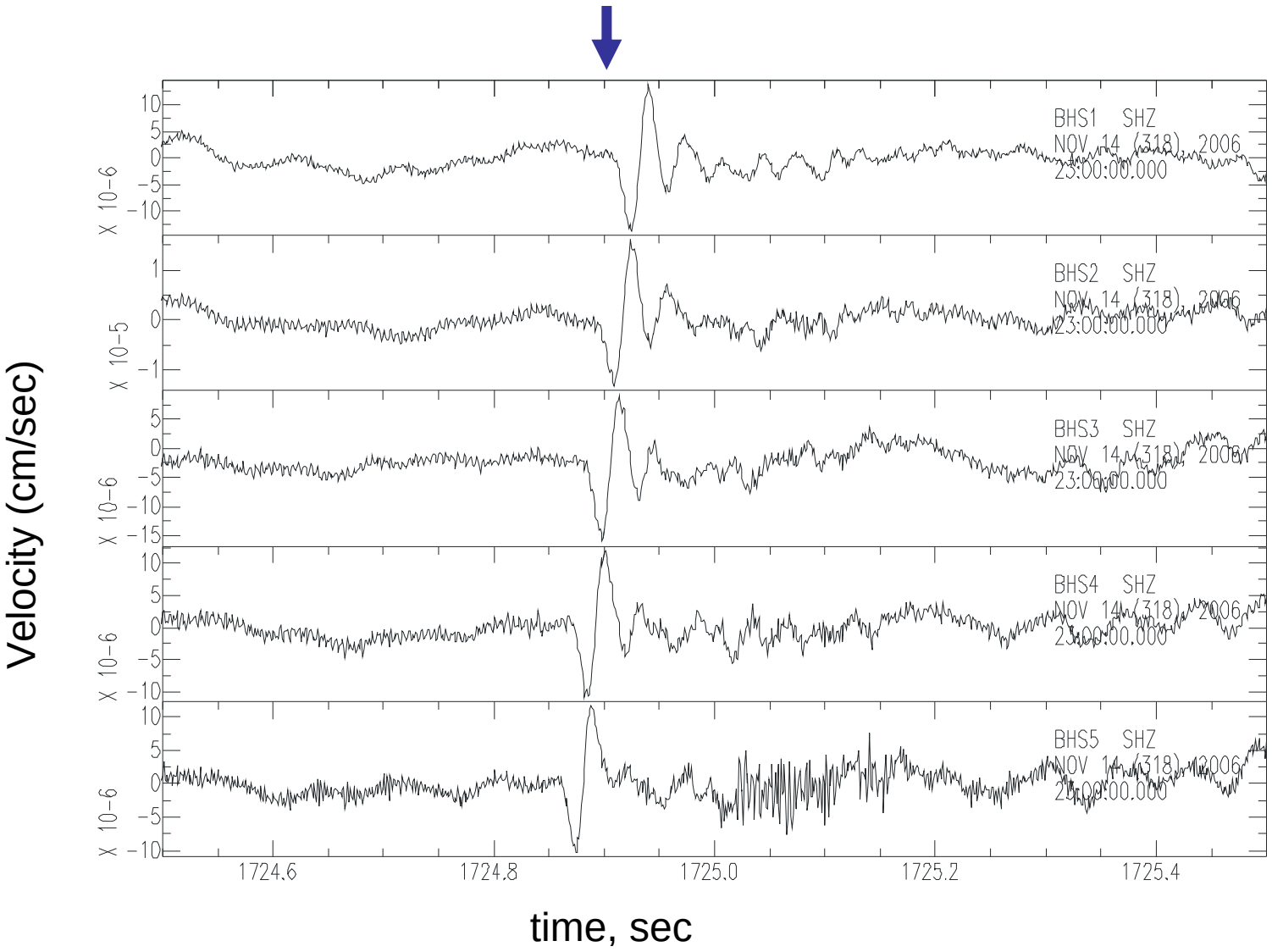
Upward first motion

(compared to 2006/11/09 02:00 records)



2006/11/14 23:00 Z-Comp (1 sec record)

Downward first motion pulse width~0.025 sec



Up						
time			group	Δt1-4	Vapp.	io
date	hour	sec				
20061114	15	179.5	UpC	0.028	5.836	49
20061120	16	168.3	UpA	0.033	4.952	40
20061126	13	781.6	UpA	0.032	5.107	42
20061126	17	1989.55	UpB	0.034	4.806	38
20070105	7	18.3	UpC	0.033	4.952	40
20070124	22	29.85	UpA	0.030	5.447	46
20070124	22	344	UpB	0.031	5.271	44
20070205	9	3042.1	UpA	0.033	4.952	40
20070306	22	1853.92	UpA	0.031	5.271	44
20070326	11	3286.2	UpA	0.033	4.952	40
20070401	20	243.6	UpC	0.033	4.952	40
20070403	01	1913.37	UpC	0.033	4.952	40
Down						
20061105	14	3140	DnC	0.032	5.107	42
20070110	8	1680.5	DnC	0.033	4.952	40
20070110	8	1680.5	DnC	0.033	4.952	40
20070114	1	1671.3	DnB	0.033	4.952	40
20070114	1	1672.25	DnB'	0.031	5.271	44
20070214	4	2461.96	DnC	0.033	4.952	40
20070329	10	2743.75	DnB	0.033	4.952	40
20070404	4	769.632	DnB	0.034	4.806	38

F type: amplitude > 10^{-5} cm/sec

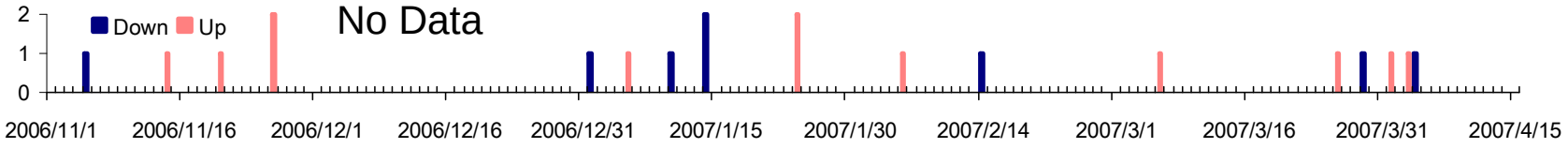
$V_{app.}$~4.95-5.11 km/sec

io~38-49 degree

*Most of the events with io~40 degree

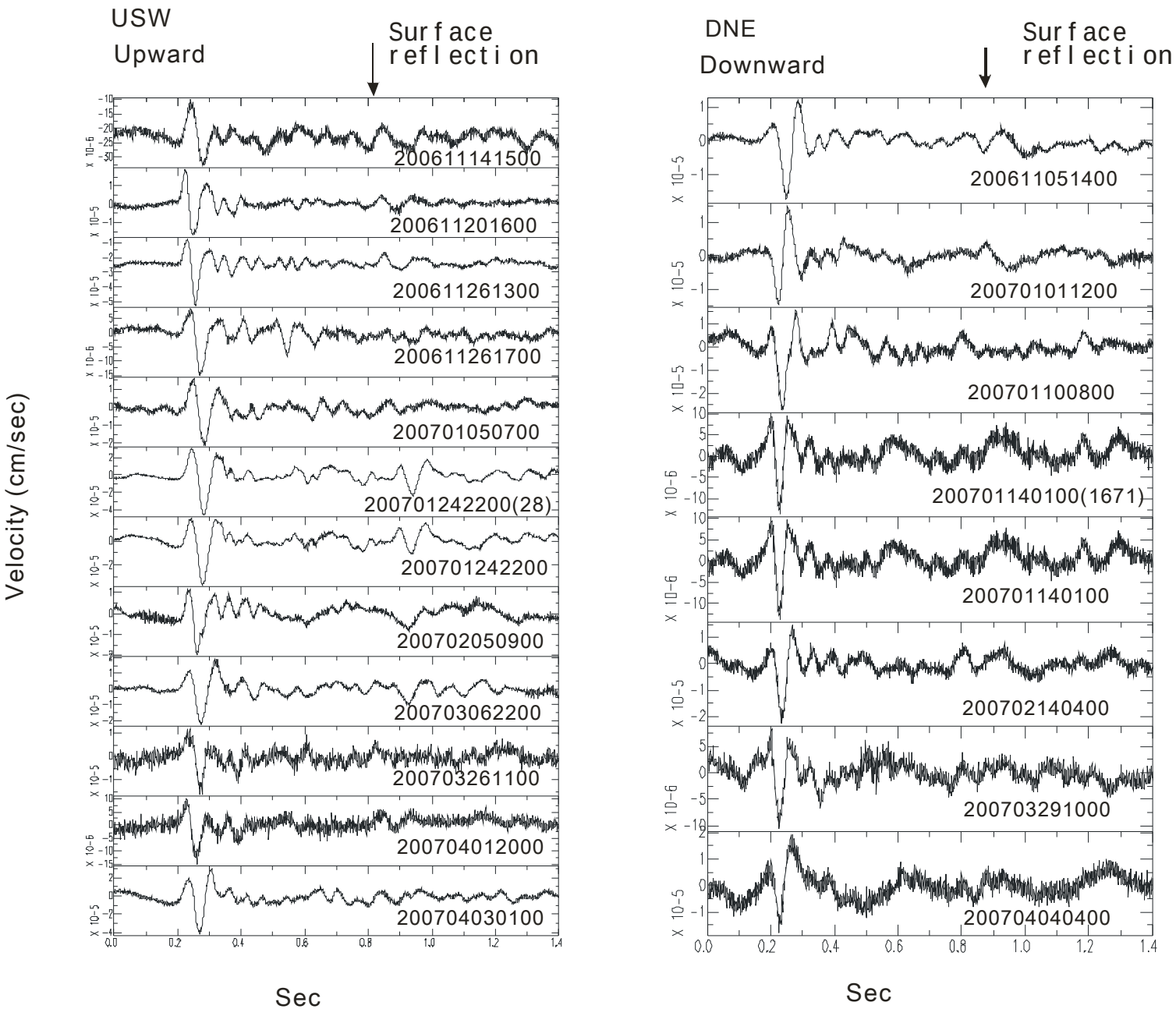
FIT Period:
1st FIT: Nov. 7-11, 2006
2nd FIT: Jan. 23-27, 2007
1st Main-FIT: March
2nd Main-FIT: April

FIT FIT FIT

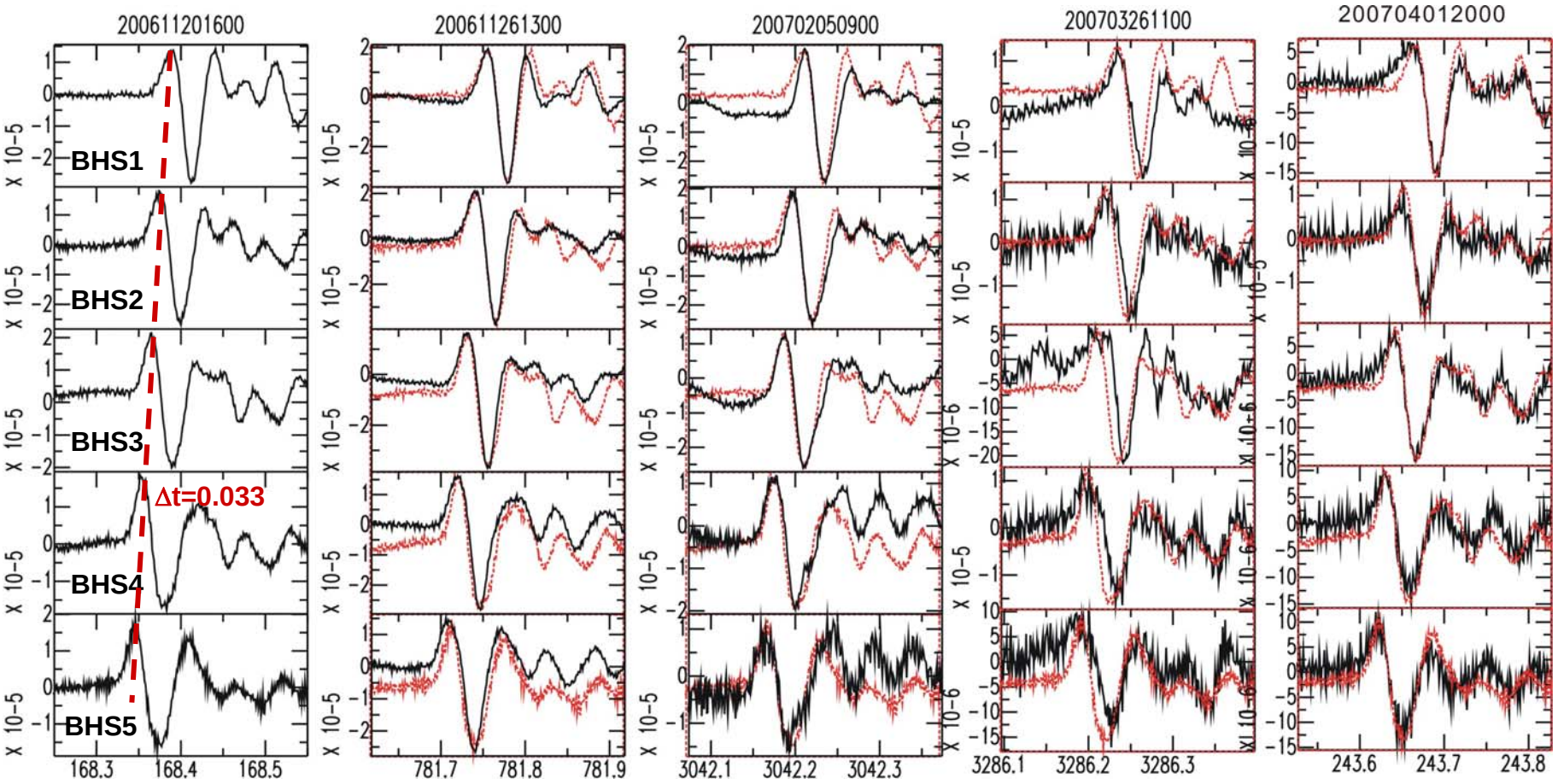


	2006/11/5	2006/11/14	2006/11/20	2006/11/26	2007/1/1	2007/1/5	2007/1/10	2007/1/14	2007/1/24	2007/2/5	2007/2/14	2007/3/6	2007/3/26	2007/3/29	2007/4/1	2007/4/3	2007/4/4
Down	1	0	0	0	1	0	1	2	0	0	1	0	0	1	0	0	1
Up	0	1	1	2	0	1	0	0	2	1	0	1	1	0	1	1	0

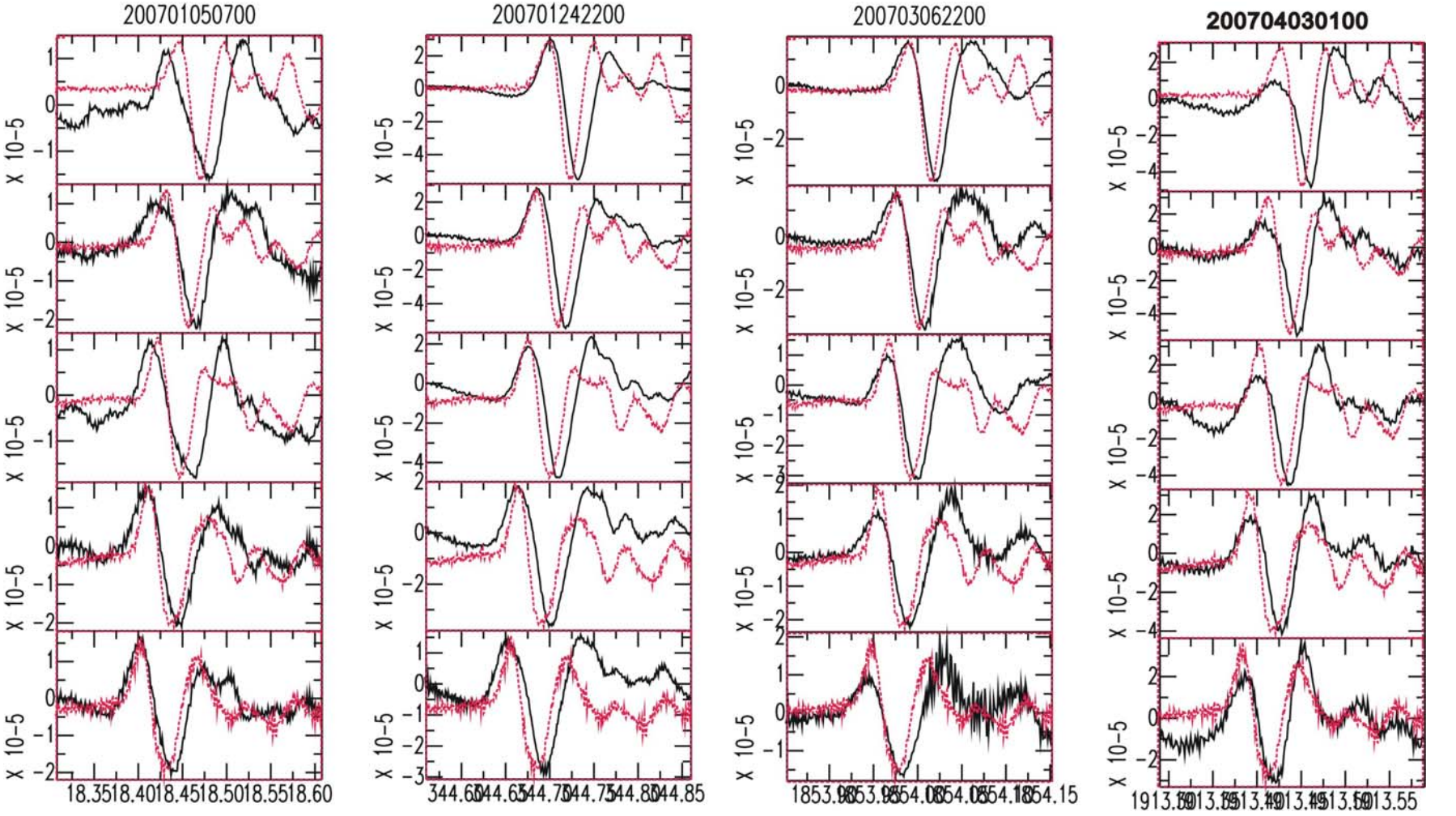
BHS4-Z-Component



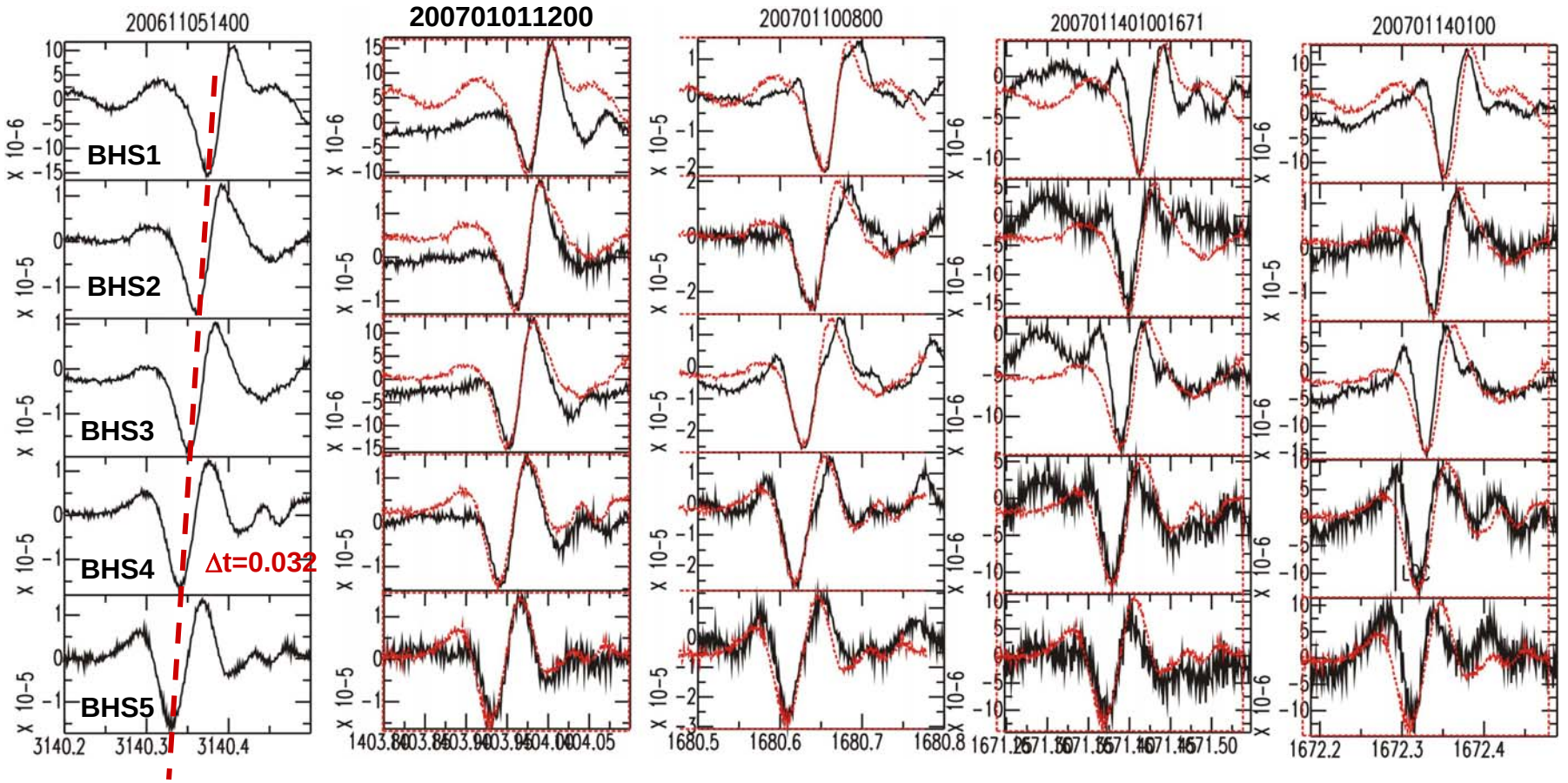
Ftype events comparison (I): Upward motions

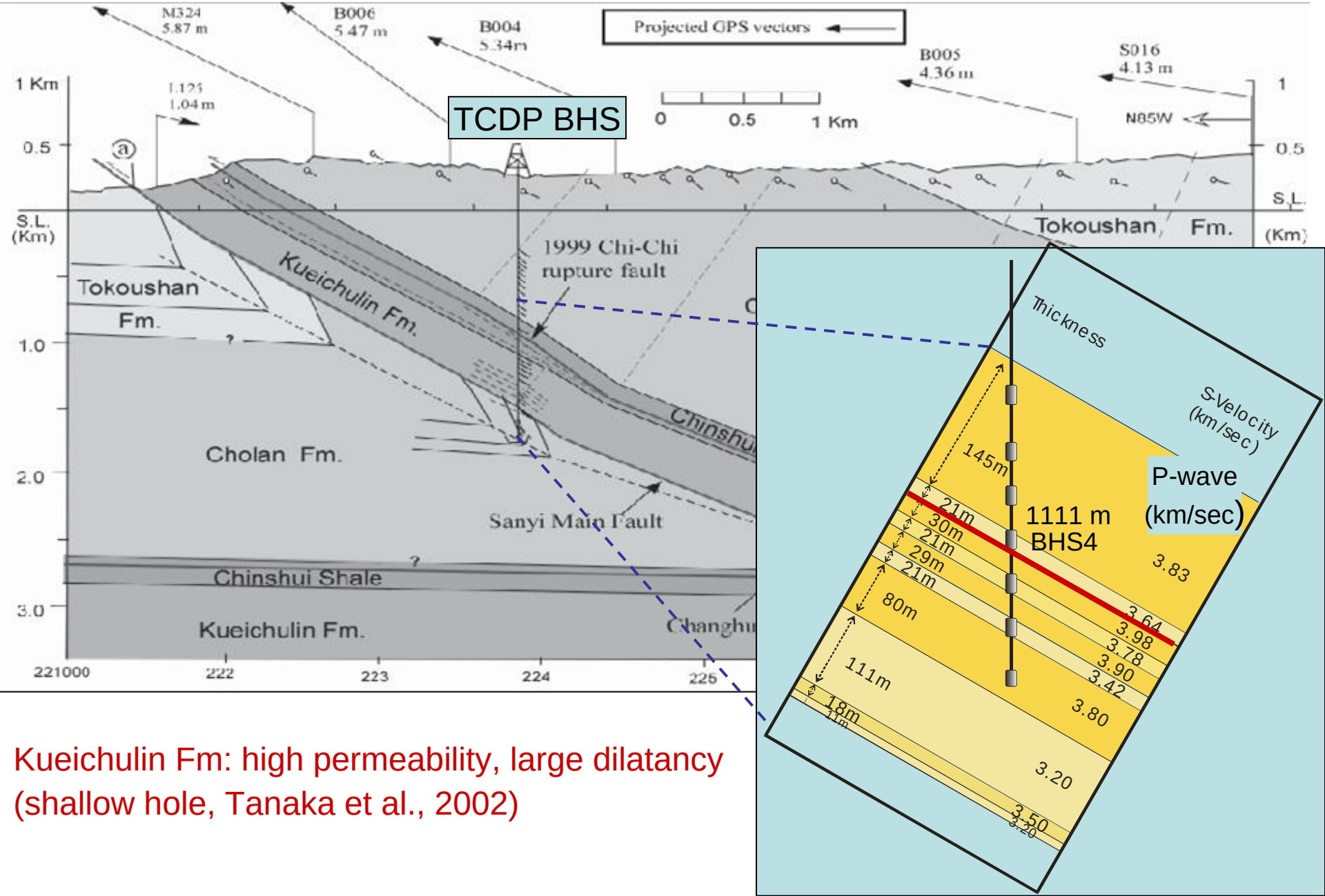


Ftype events comparison (II): Upward motions

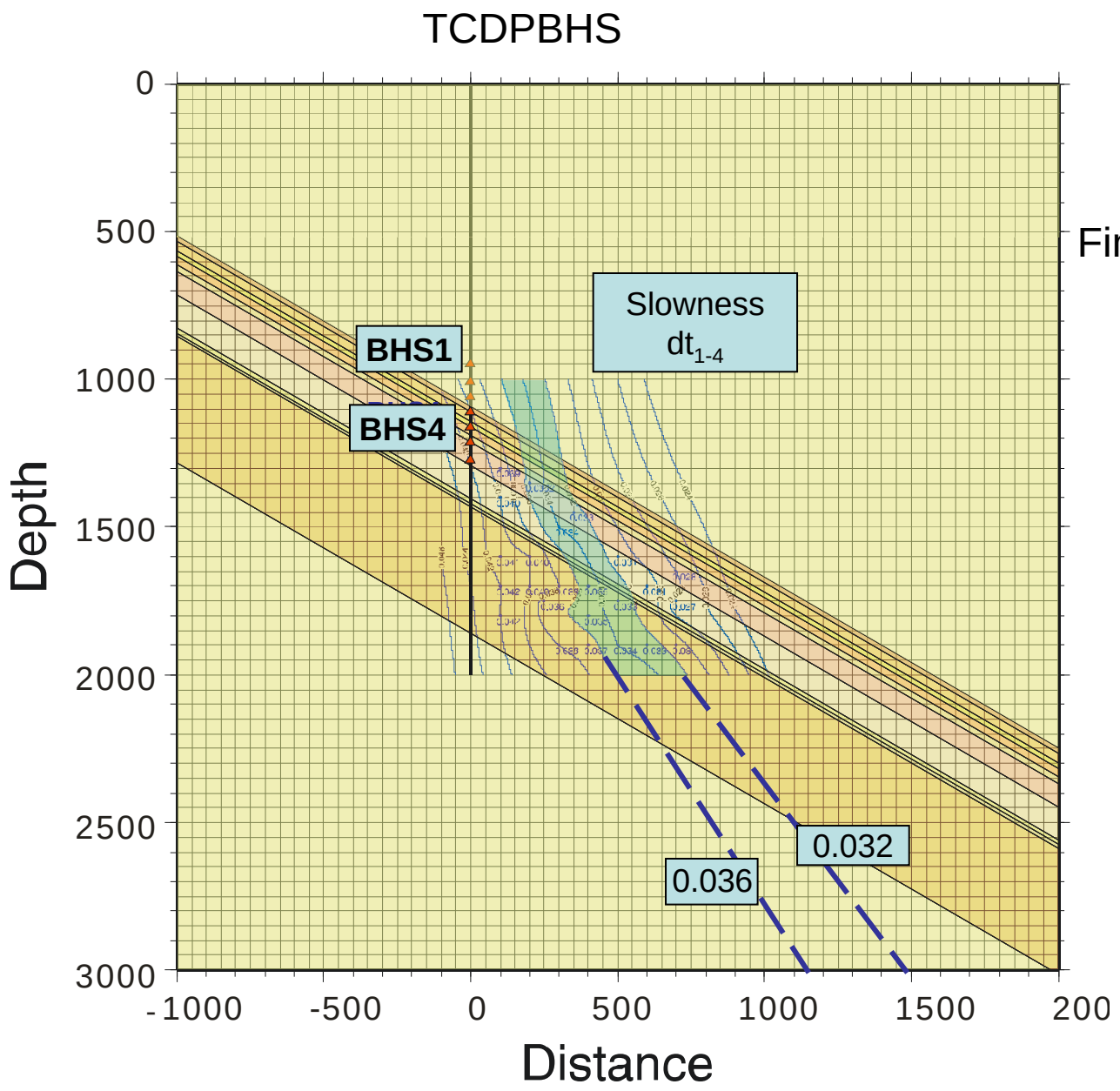


Ftype events comparison: Downward motions





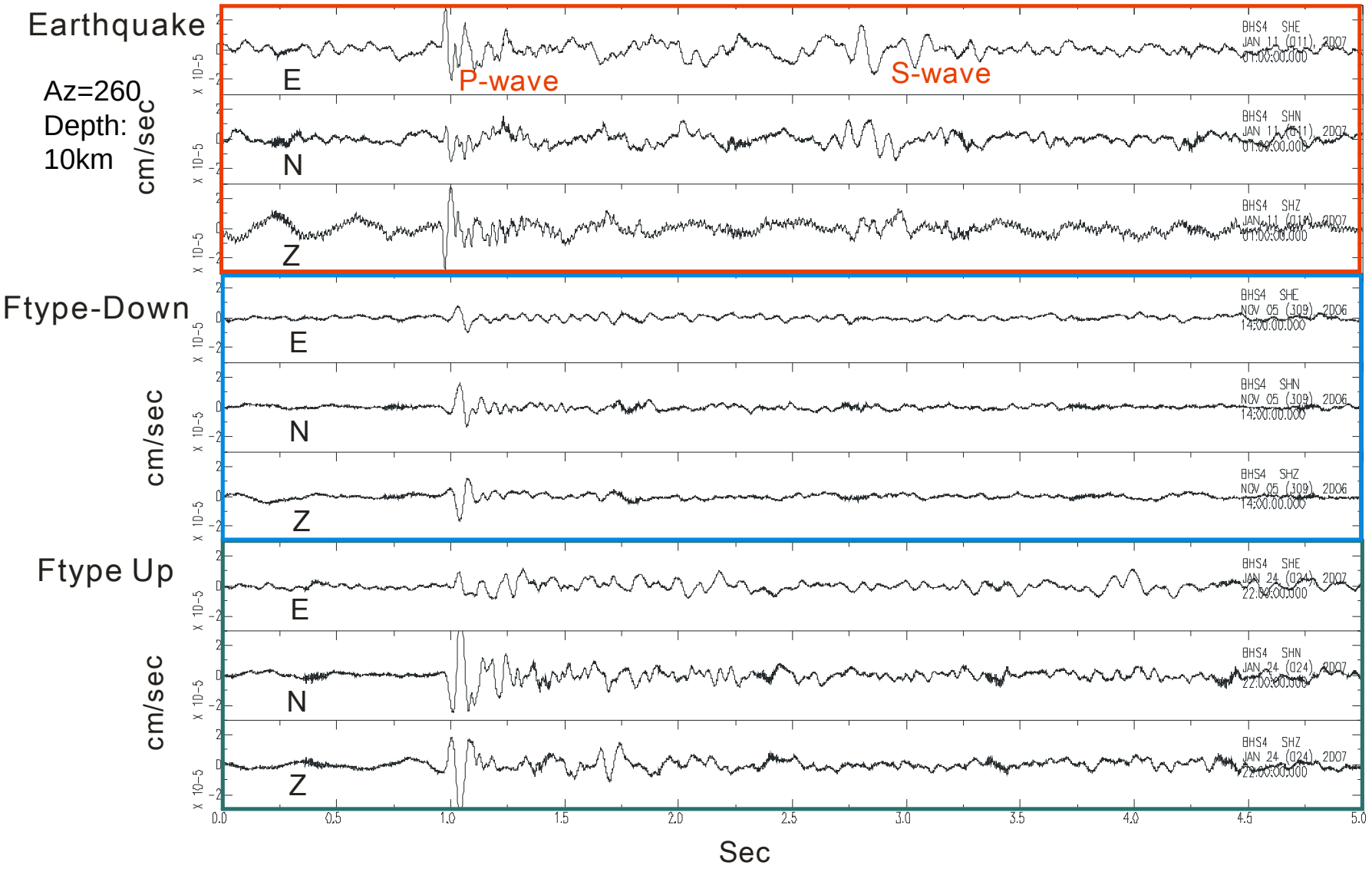
Kueichulin Fm: high permeability, large dilatancy
(shallow hole, Tanaka et al., 2002)



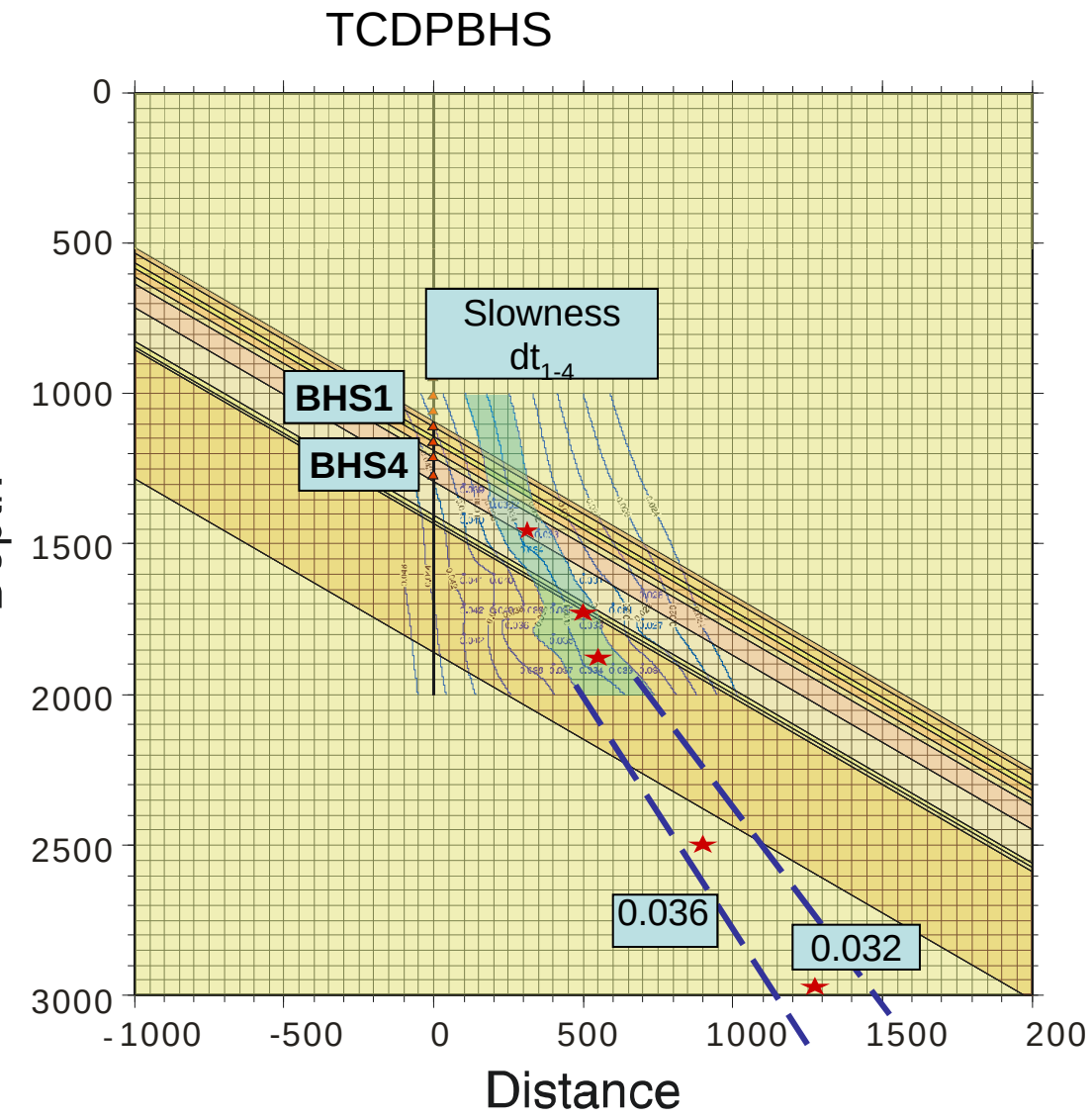
Finite-Difference Modeling

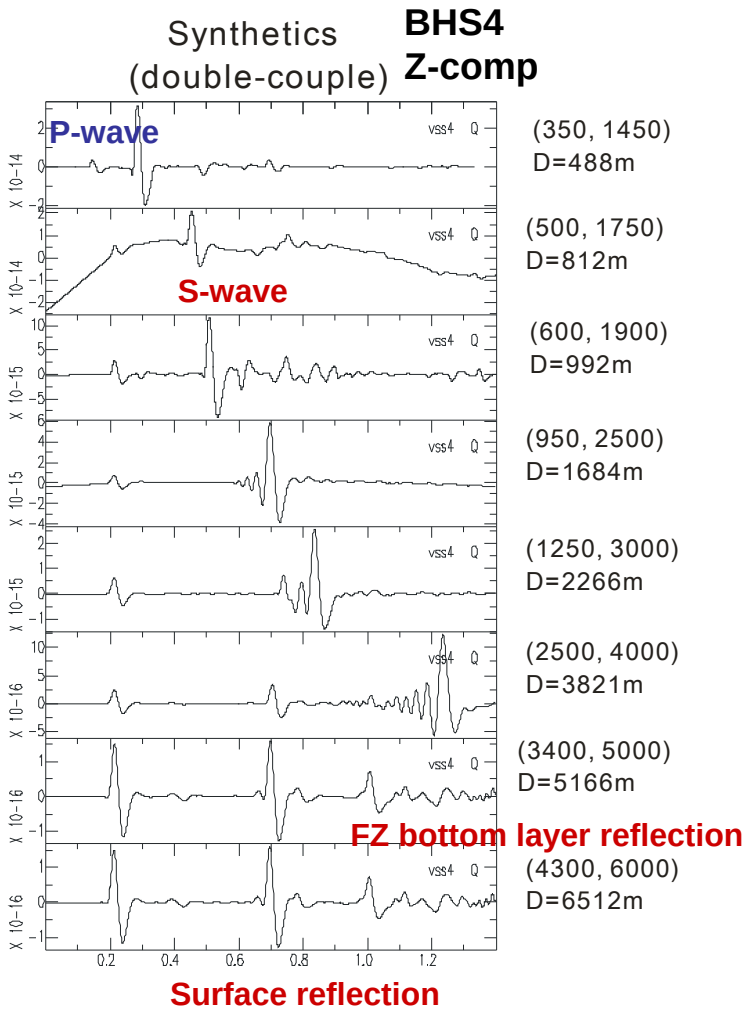
Events: $\Delta t_{1\text{-}4}$=0.033 sec

BHS4 E- N- Z- components 5-sec Records

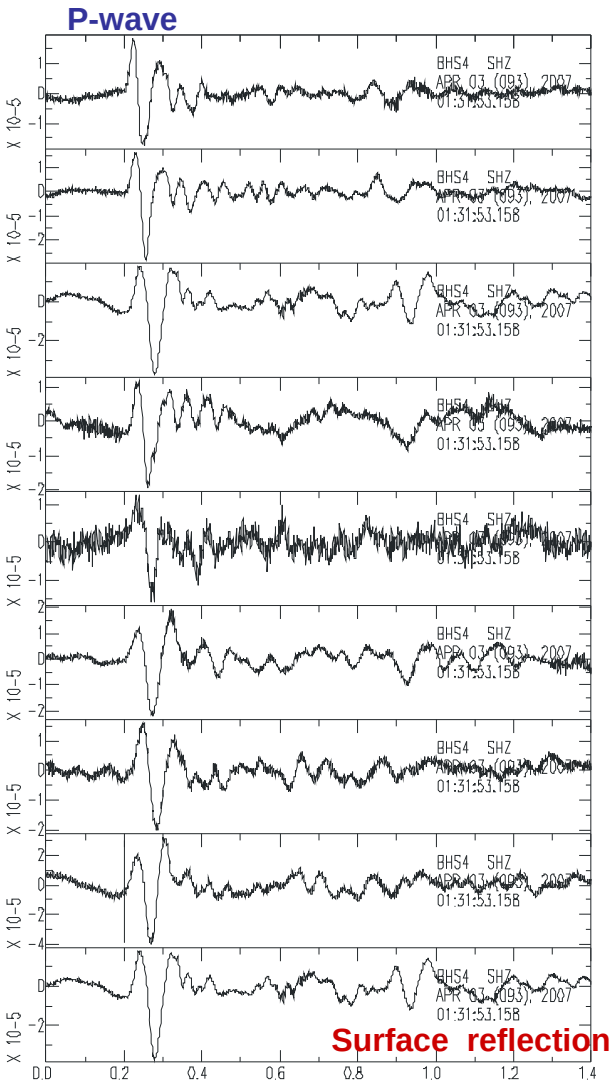


Finite-Difference Simulation:
Double-Couple Events, Strong S-wave

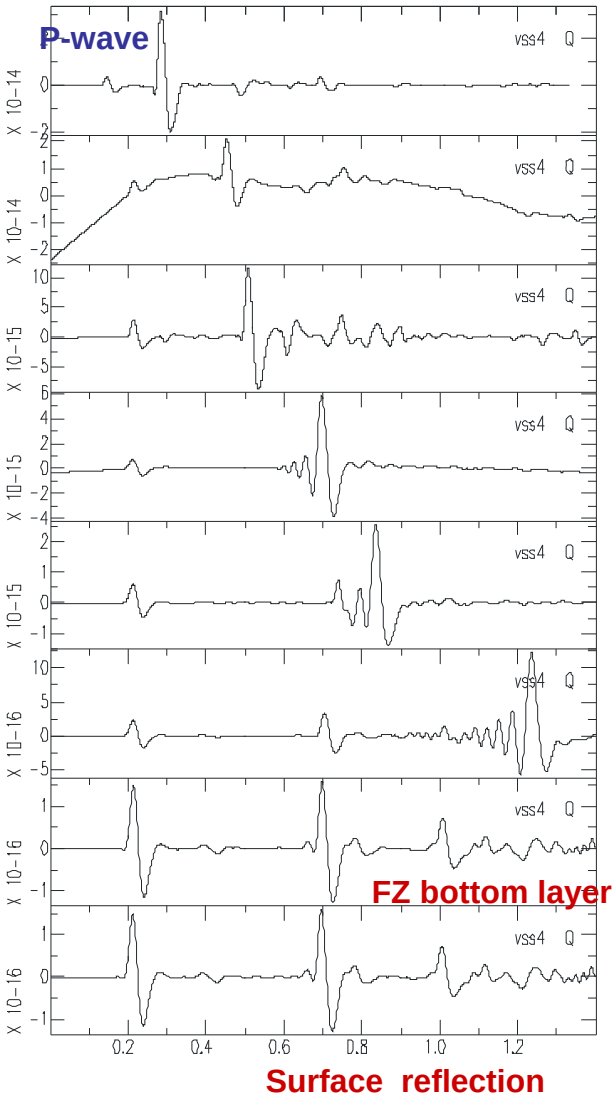




Observation



Synthetics (double-couple)



(350, 1450)
D=488m

(500, 1750)
D=812m

(600, 1900)
D=992m

(950, 2500)
D=1684m

(1250, 3000)
D=2266m

(2500, 4000)
D=3821m

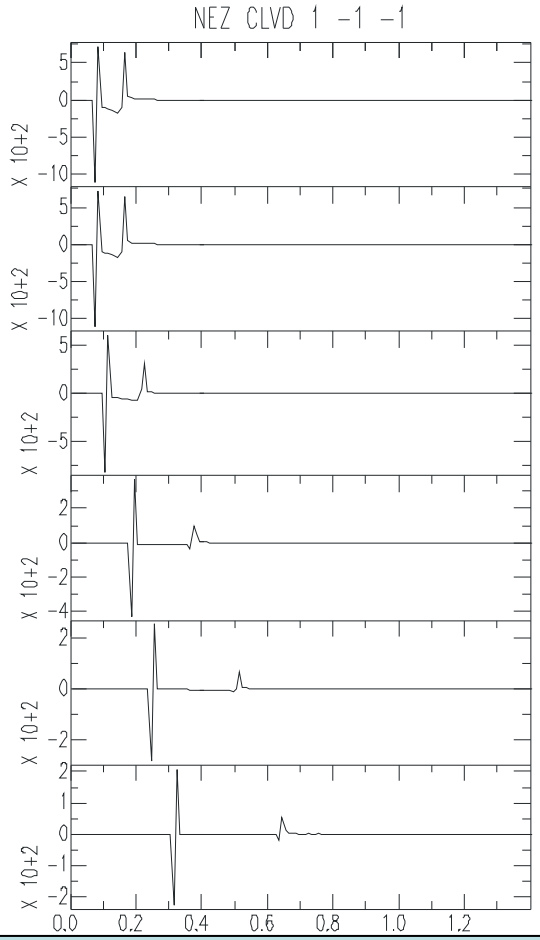
(3400, 5000)
D=5166m

(4300, 6000)
D=6512m

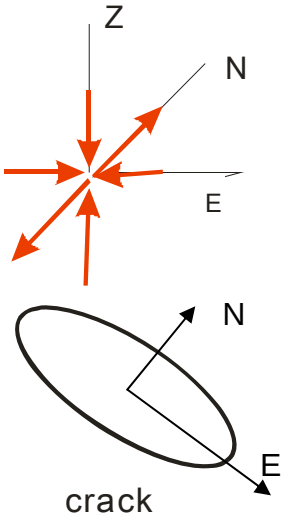
Finite-Difference Simulation: CLVD

Synthetics (CLVD)

Compensated Linear Vector Decomposition

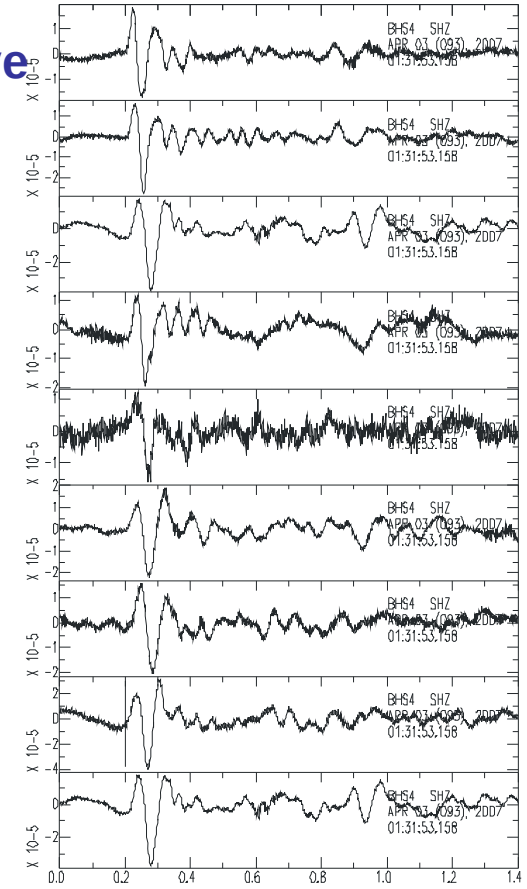


Strong P-wave
Weak S-wave



anisotropy

Observation



Pulse width (τ)~0,05-0.1 sec

τ=2.62 a/β
β=1.6km/sec

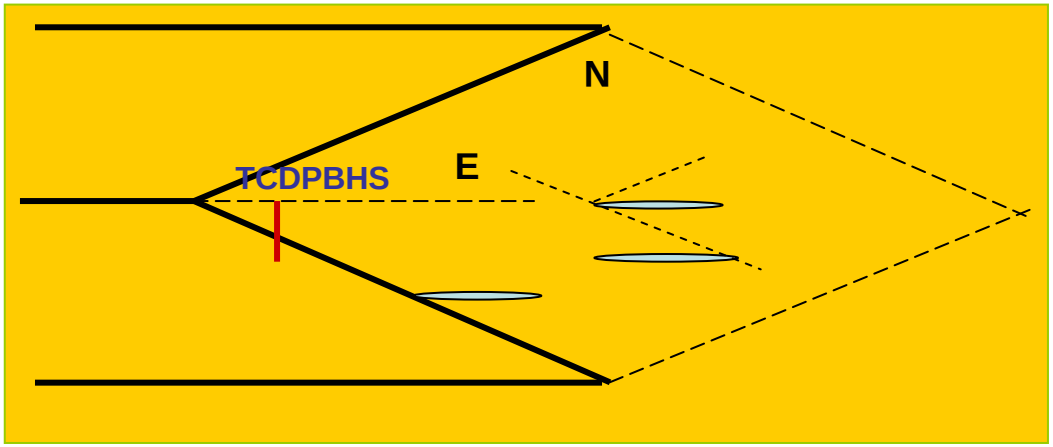
Cohn et al. (1982)
Brune (1970)

a: radius of
a circular fault

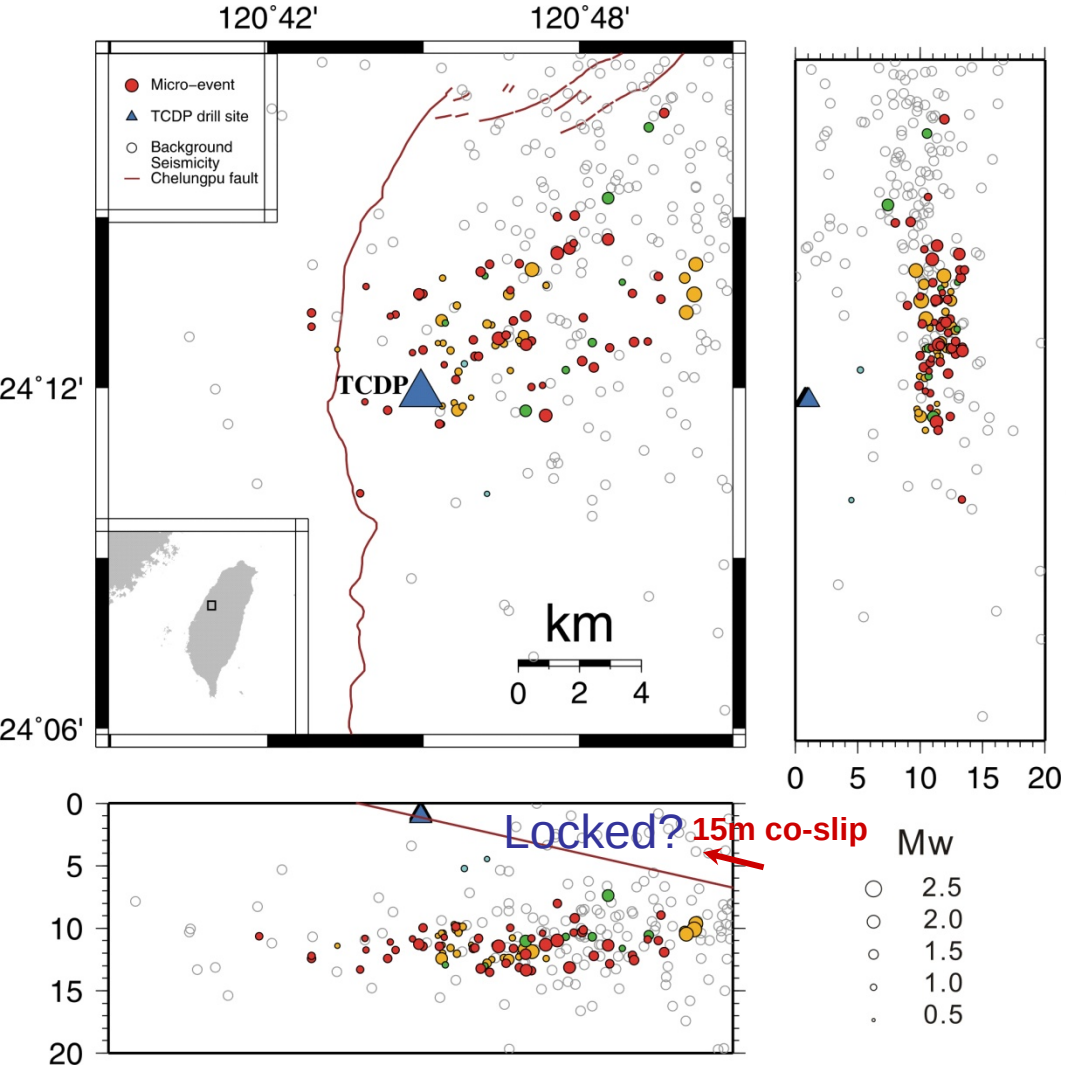
a=30-61m

Elongated crack
Length~100-200m

Schematic Diagram of the Open Cracks

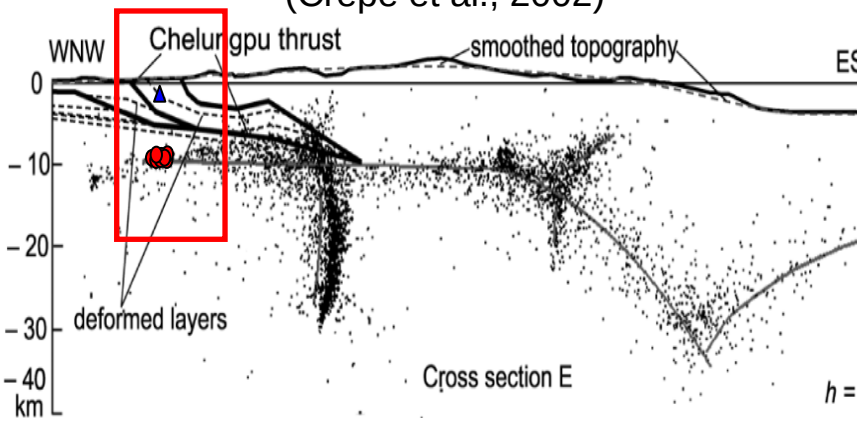


Microevents were from the decollement
No events in the large co-seismic slip region



Aftershock distribution

(Crepe et al., 2002)



2006/11/05~11/30

2006/12/01~12/06

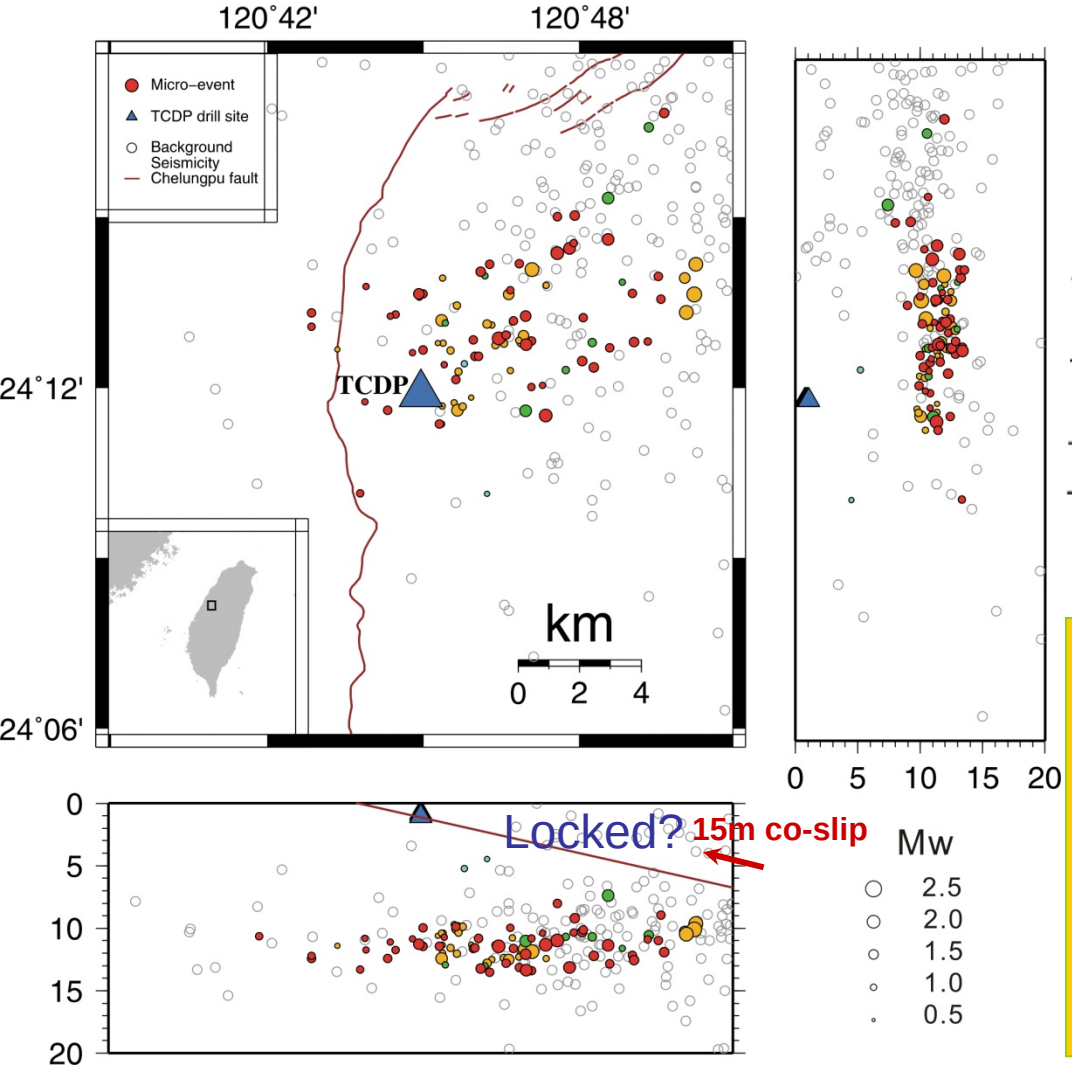
2007/01/01~01/31

Ts-Tp < 1s

Background seismicity
2004~2007 from CWB

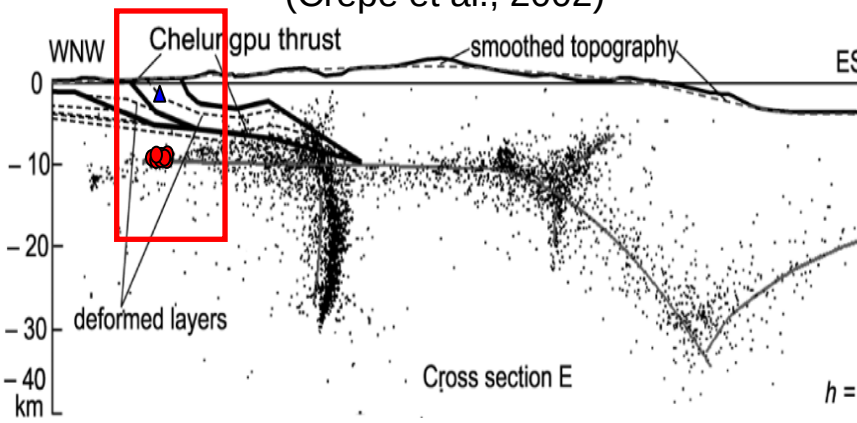
Status of STRESS in the FAULT?

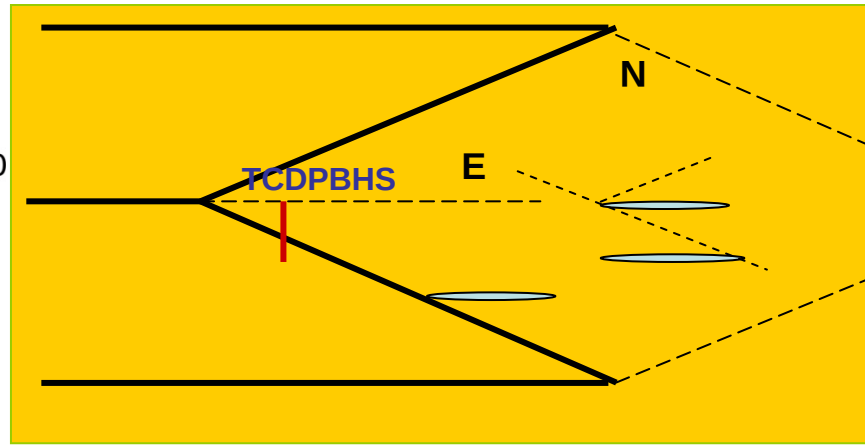
Stress was not released in a form of earthquakes, but from open crack



Aftershock distribution

(Crepe et al., 2002)





Mechanism: stress driven fluid flow?

Fault-Valve Action in Overpressured Crust

Still Exploring?

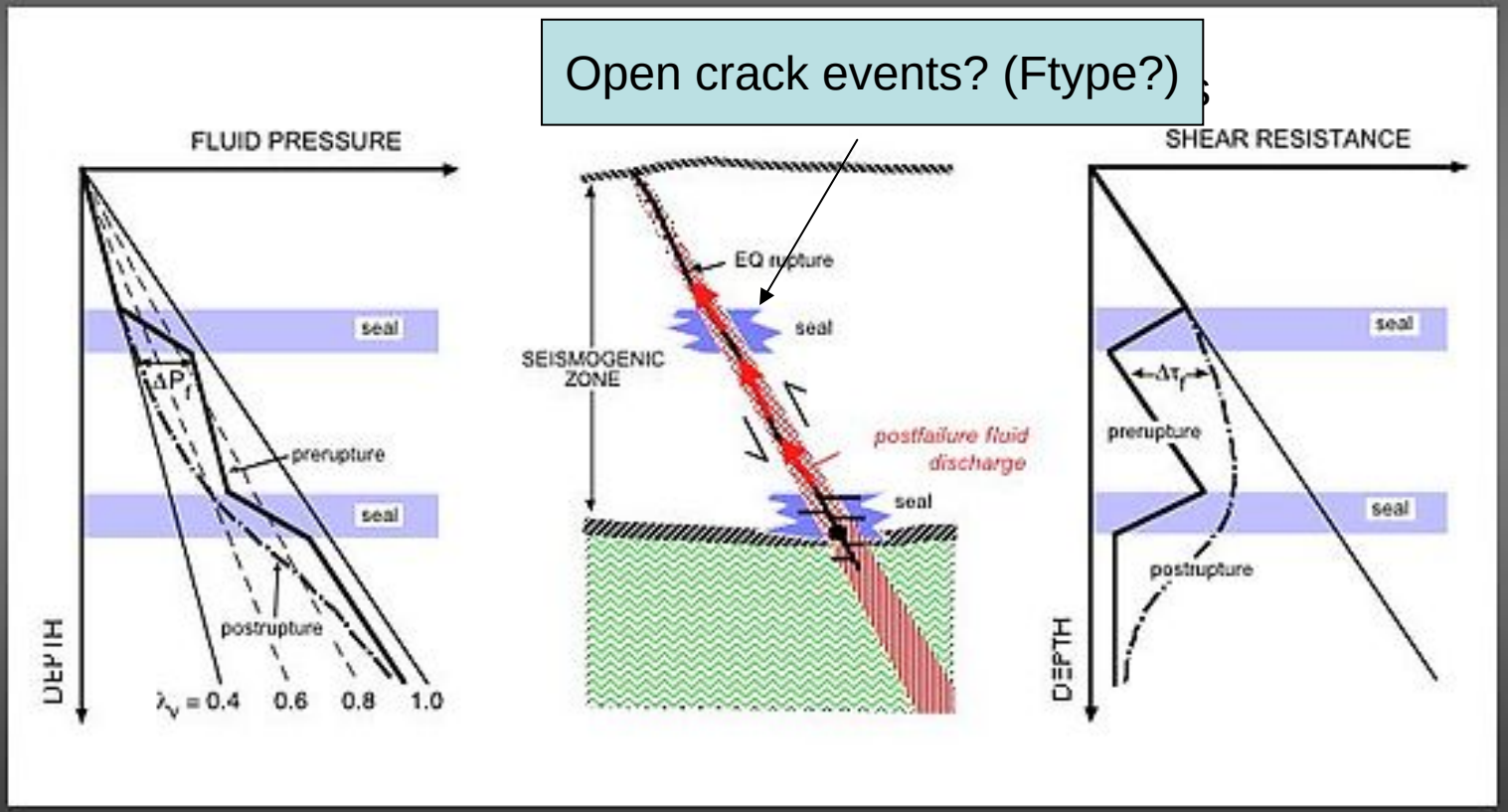


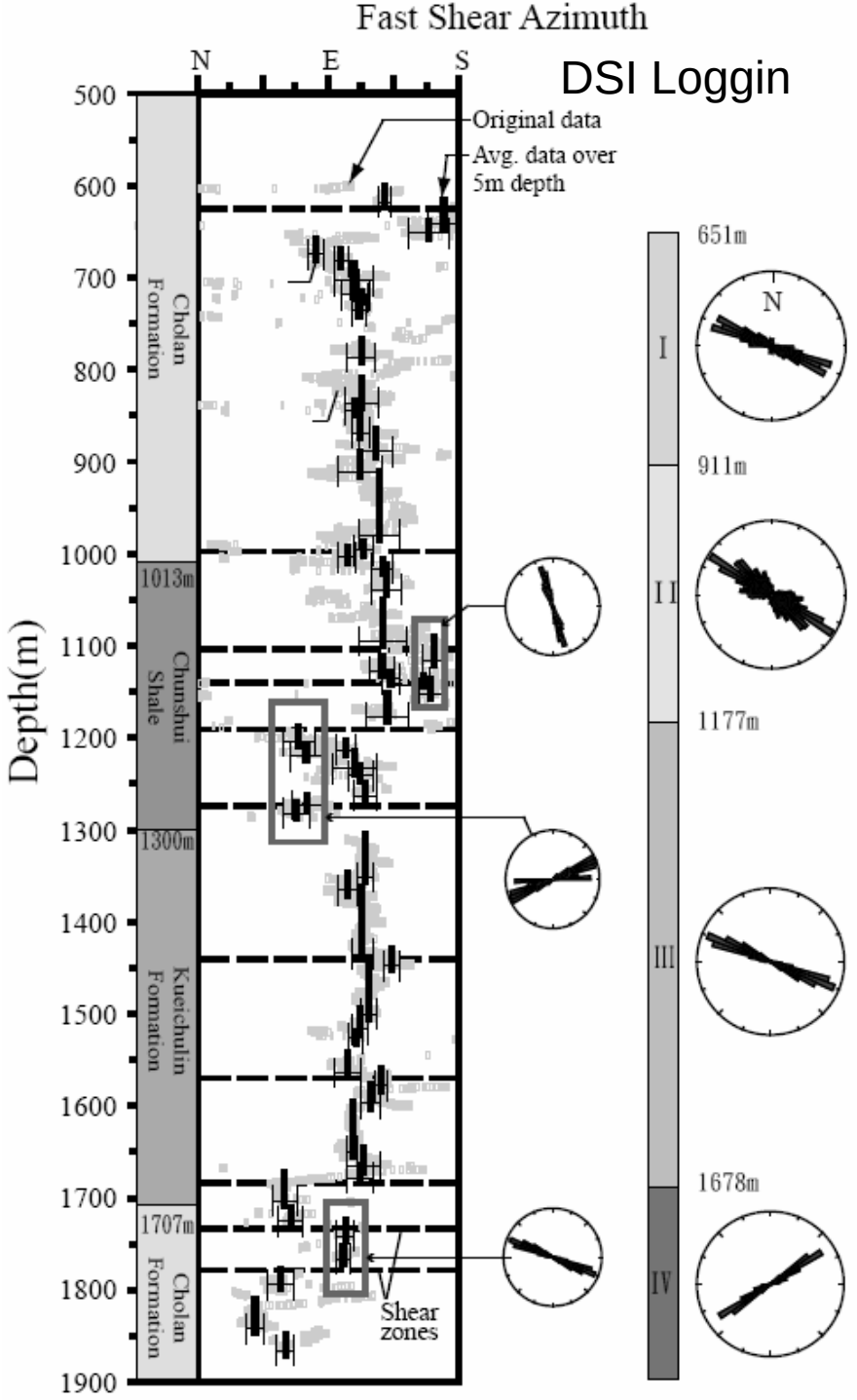
Figure after Rick Sibson

Summary

- P-wave only Ftype events are not from regular double-couple earthquakes
- Events are repeatable, but not identical
- Events might be related to a CLVD mechanism
- Observed events were from existing or/and new open cracks
- Cracks have the dimension of about 100-200m in NS direction (along strike)
- **Mechanism**

  -Role of the fluid in a locked splayed fault, which had anomalous large co-seismic slip

  -Exploring the status of stress on the splayed fault during inter-seismic period



- THANK YOU!

In-Situ TCDP BHS Observatory at Fault Zone: Preliminary Summary

- No any micro-events located within the co-seismic large slip zone => Locked of the splay fault during the inter-seismic period

- P-wave only events are the open crack related events, not faulting
- Observed events were from existing or/and new open cracks in Kueichulin formation?
- Mechanism

  -Fluid driven events?

- Implications ? on going …

More complete data sorting and analysis (locations, modeling)

Data Sorting, November, 2006-April 7, 2007

Sampling rate :
1000p/s before 2008
200p/s after 2008

Flowchart

Filter (only sorting data)
Band reject 58~62 Hz
Band pass 10~100 Hz

Correction :
Galperin rotation
Orientation correction
Remove instrument response
Unit correction to cm/sec

Step 1

Original data

Sorting data hour by hour to find "up going" wave.

Using Z component of all seismometers records

Step 2

Are P & S waves clear?

YES

Estimate Ts-Tp arrival time

A: Local Events
B: Local Events
P-wave amplitude is larger than S-wave

C : Far field event
Ts-Tp > 6 secs

No

E : Unable to identify

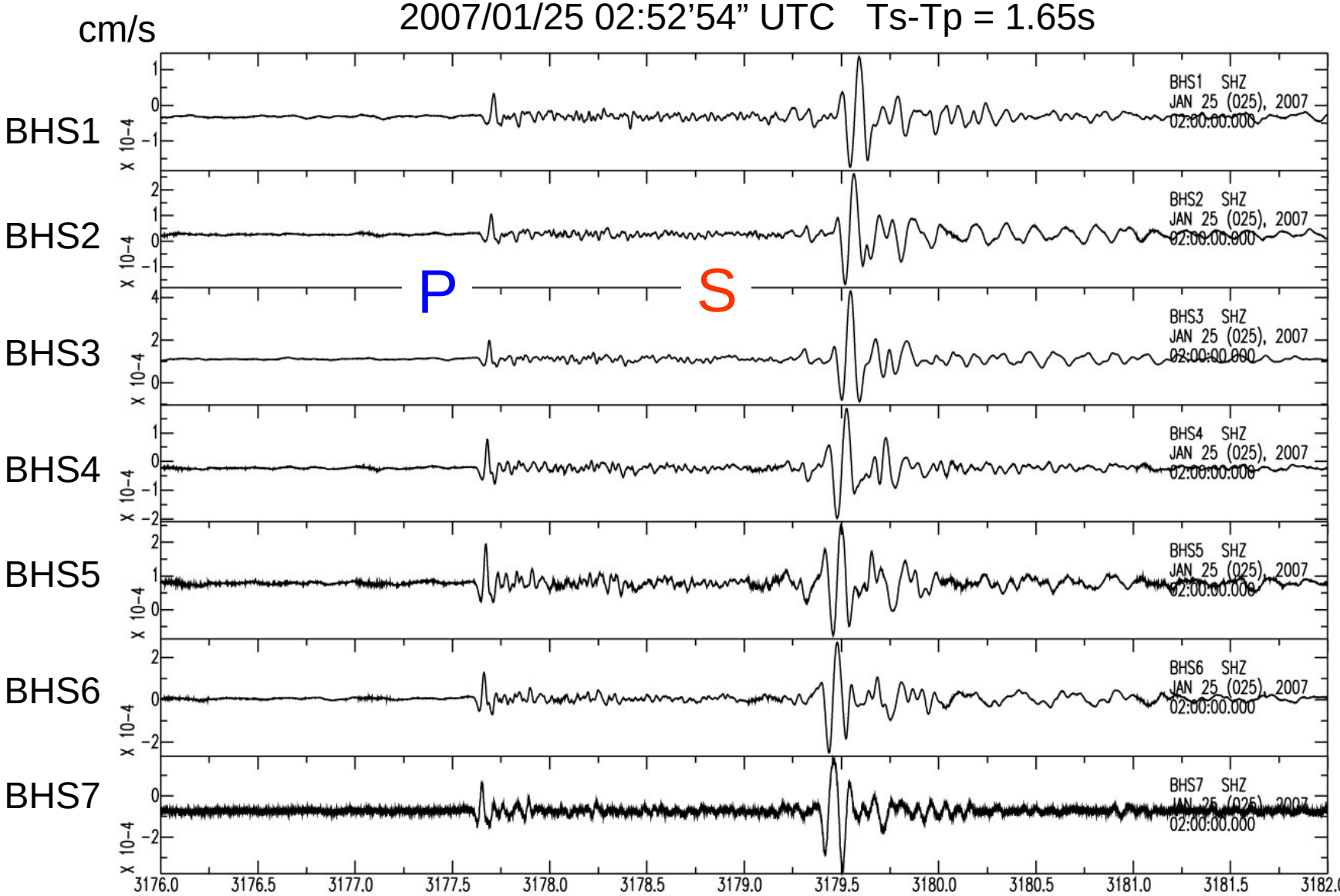
F: One peak event
P-wave only?

G : Tremor (tube wave?)

Only using Z, N and E components of BHS4 records

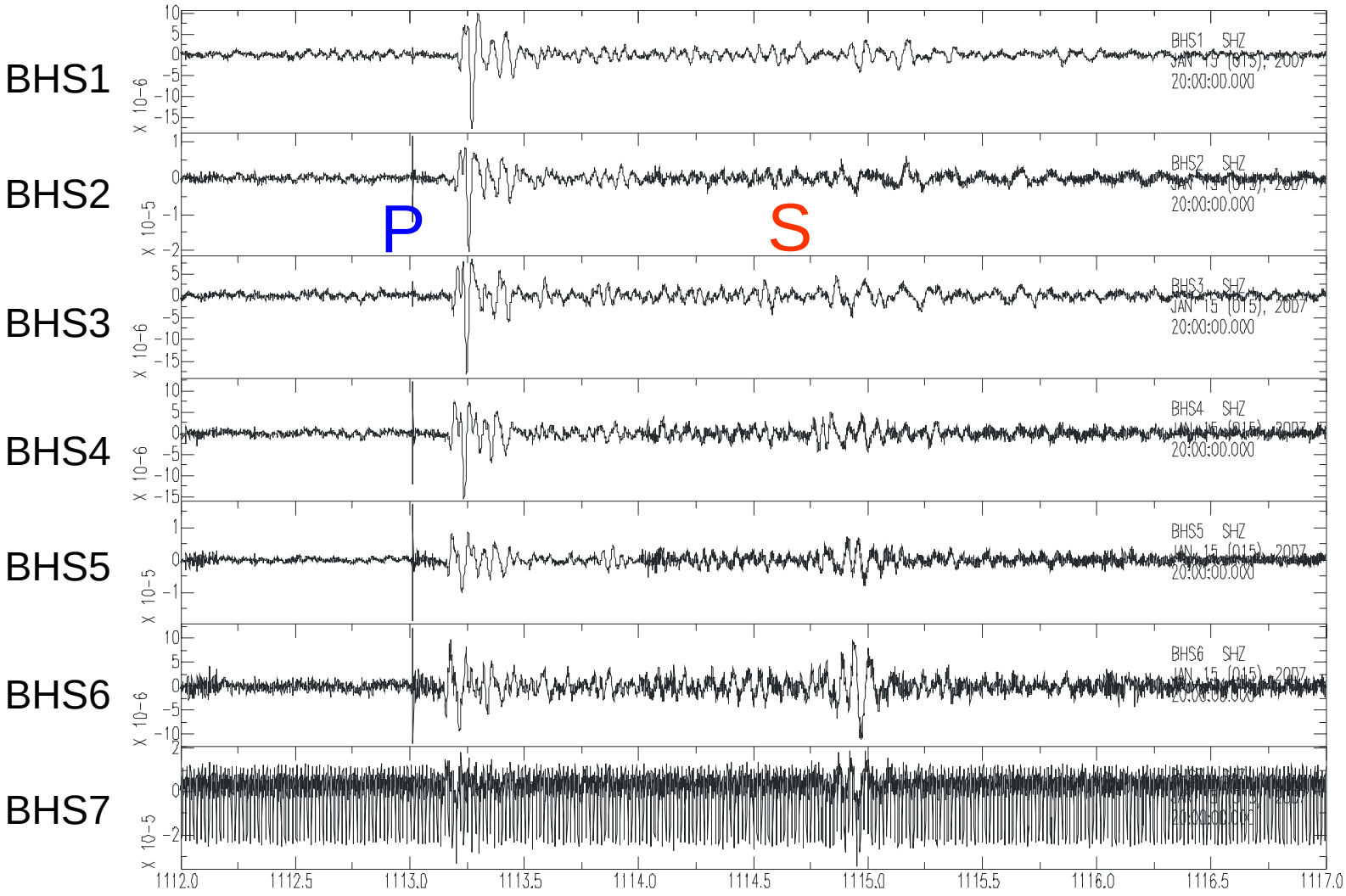
TYPE A (6 seconds record)

2007/01/25 02:52’54” UTC Ts-Tp = 1.65s

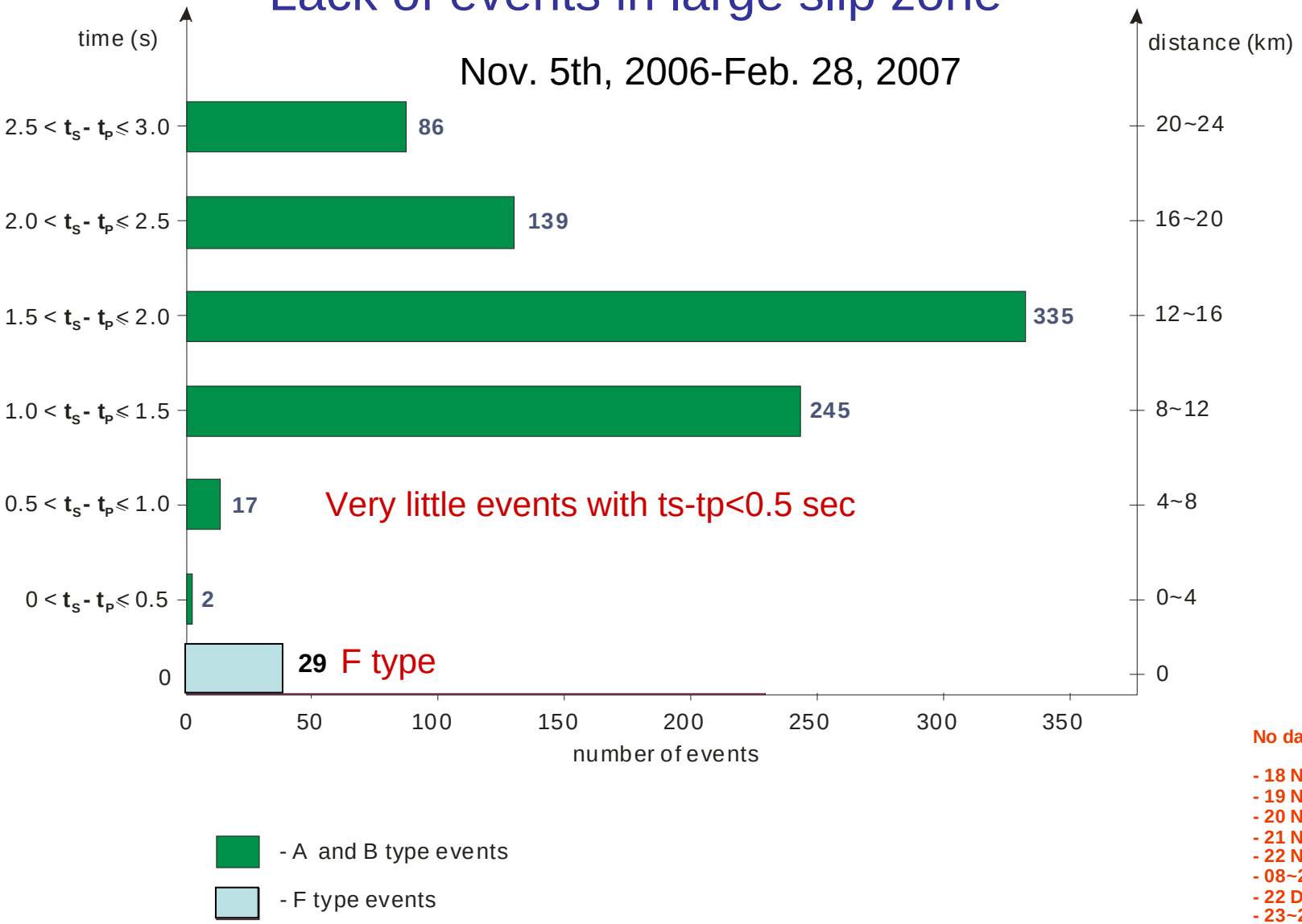


TYPE B(5 seconds record)

2007/01/15 20:18’32” UTC Ts-Tp = 1.3s



Statistics on identified micro-events: Lack of events in large slip zone



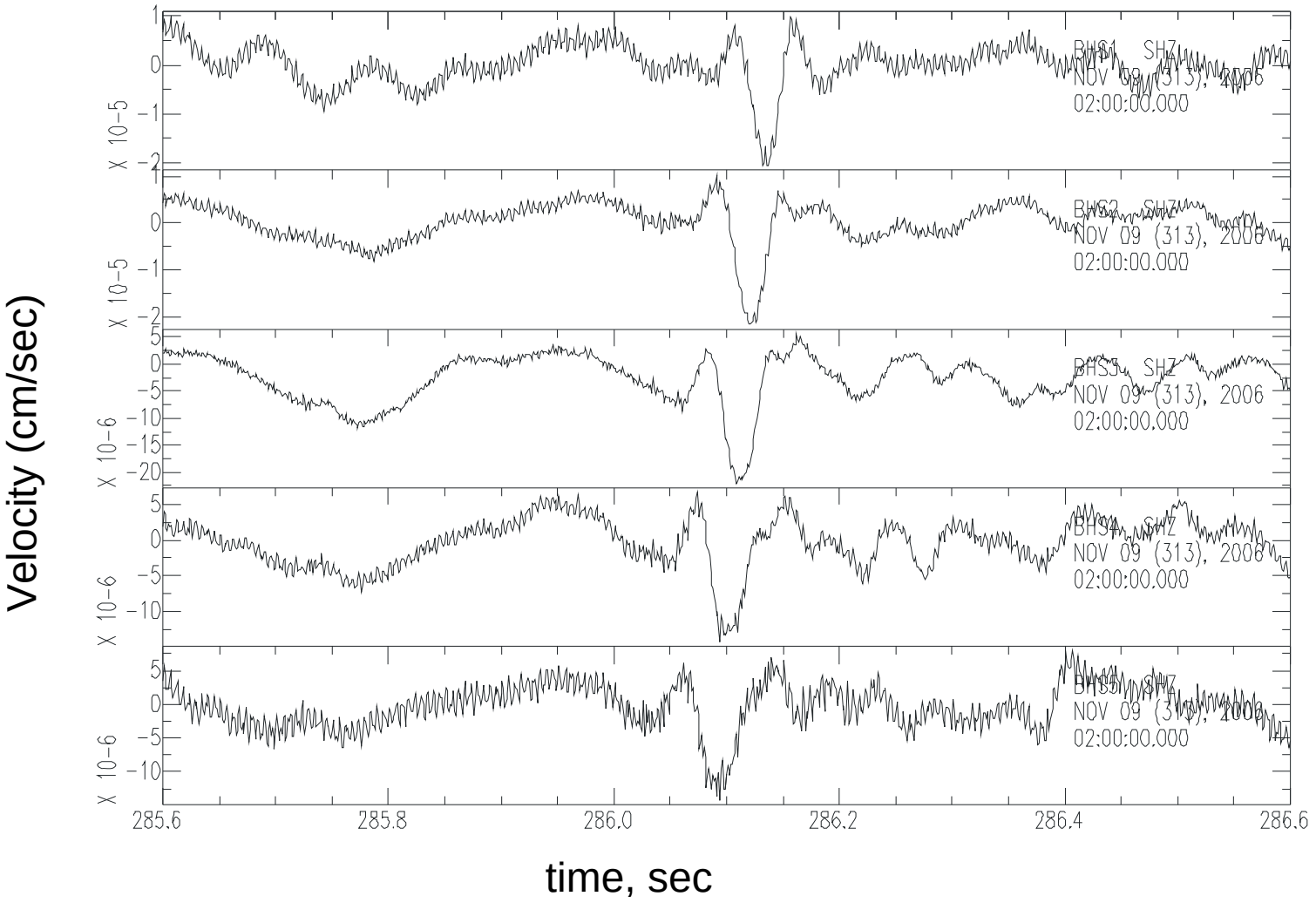
No data:

- 18 Nov 2006 (3~24:00 GMT)
- 19 Nov 2006
- 20 Nov 2006 (0~8:00 GMT)
- 21 Nov 2006 (1~24:00 GMT)
- 22 Nov 2006 (0~2:20 GMT)
- 08~21 Dec 2006
- 22 Dec 2006 (8~24:00 GMT)
- 23~25 Dec 2006
- 27~31 Dec 2006
- 17~22 Feb 2007

F type Event:

2006/11/09 02:00 Z-Comp (1 sec records)

(upward motion, T~0.05 sec)

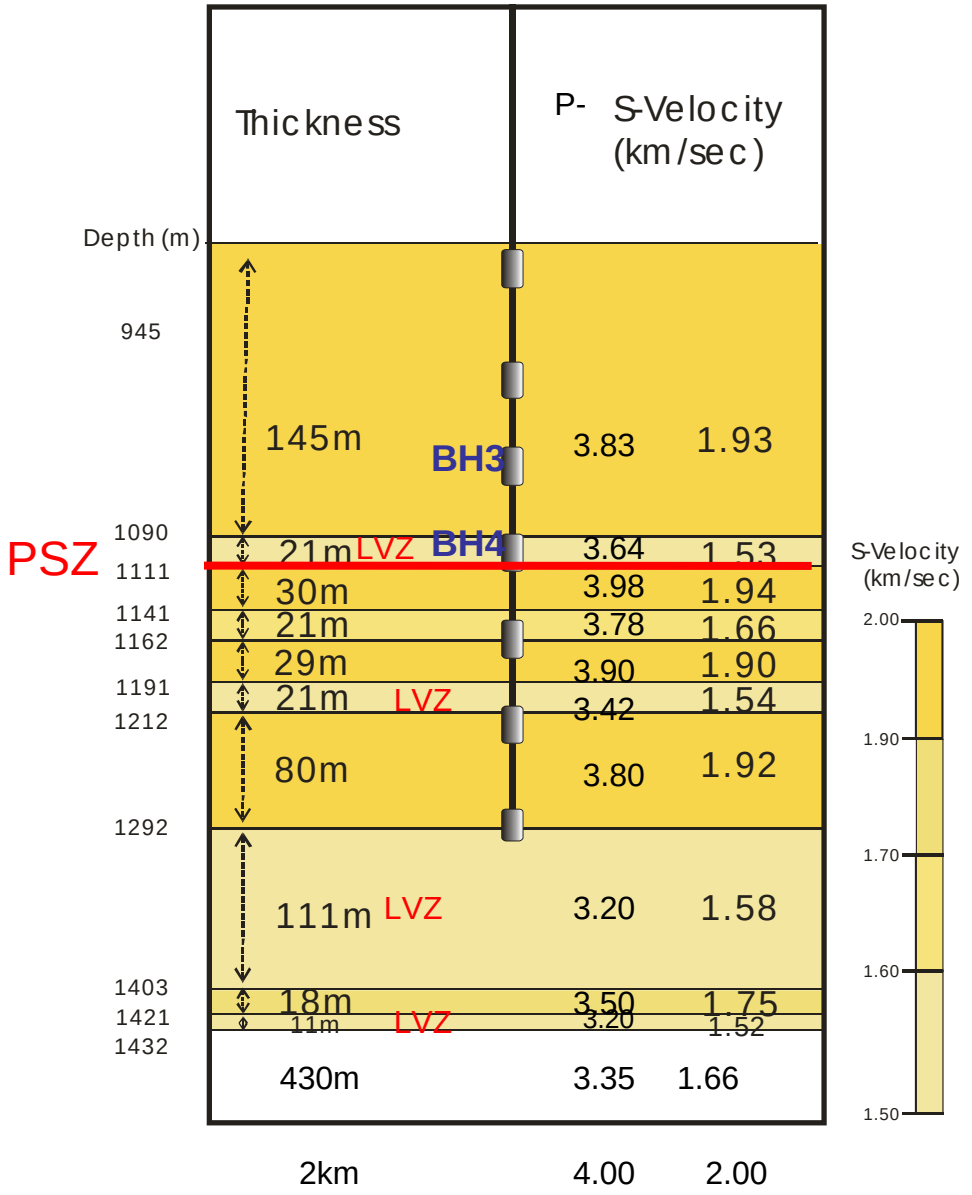


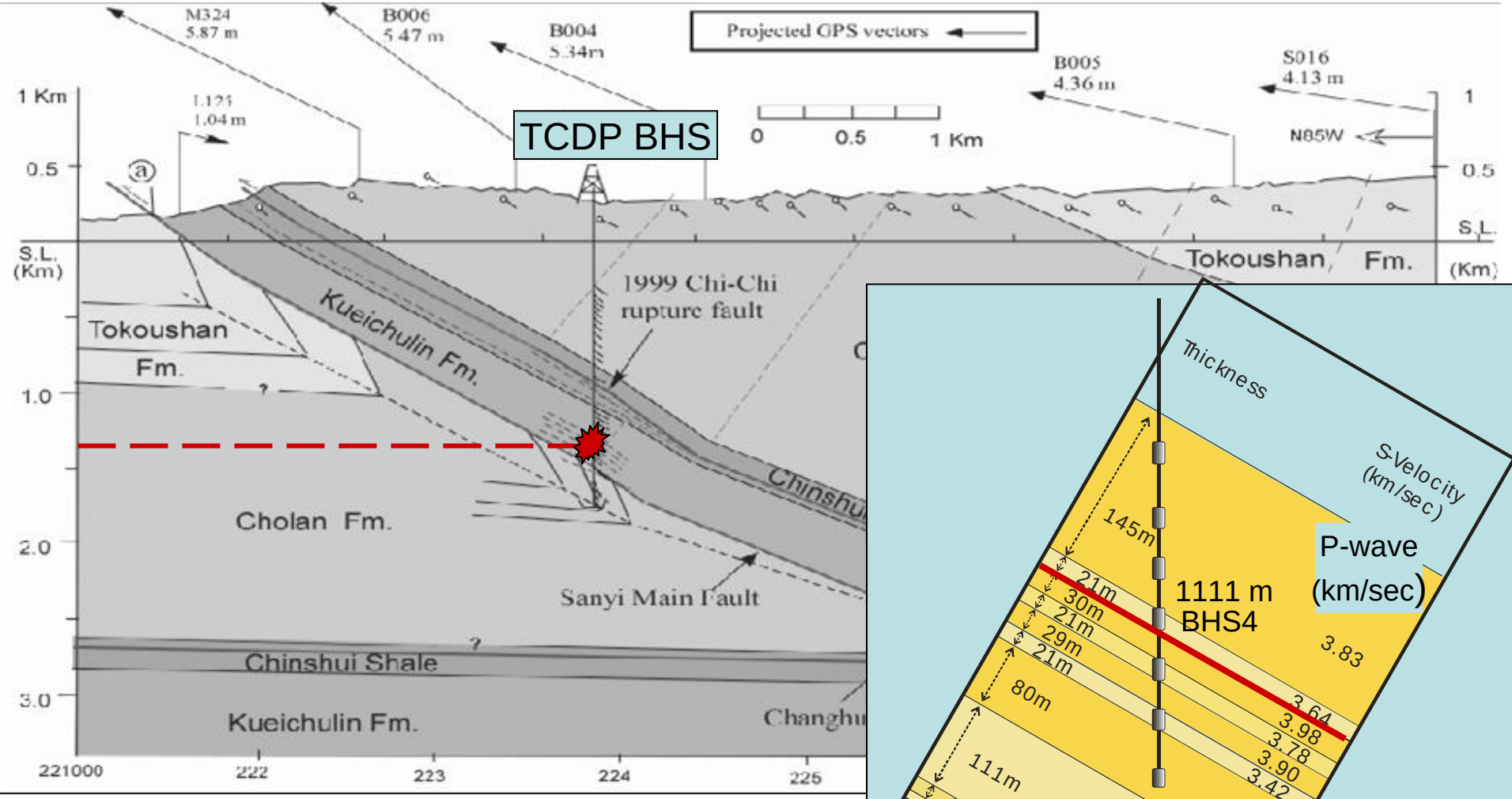
Velocity Structure in the Fault Zone From Login Data

Low Velocity Zone,
Vp~3.20-3.40 km/sec
Vs~1.50-1.60 km/sec

Transition zone
Vp~3.50-3.70km/sec
Vs~1.66-1.75 km/sec

Host Rock
Vp~3.80-4.0 km/sec
Vs~1.90-2.00 km/sec



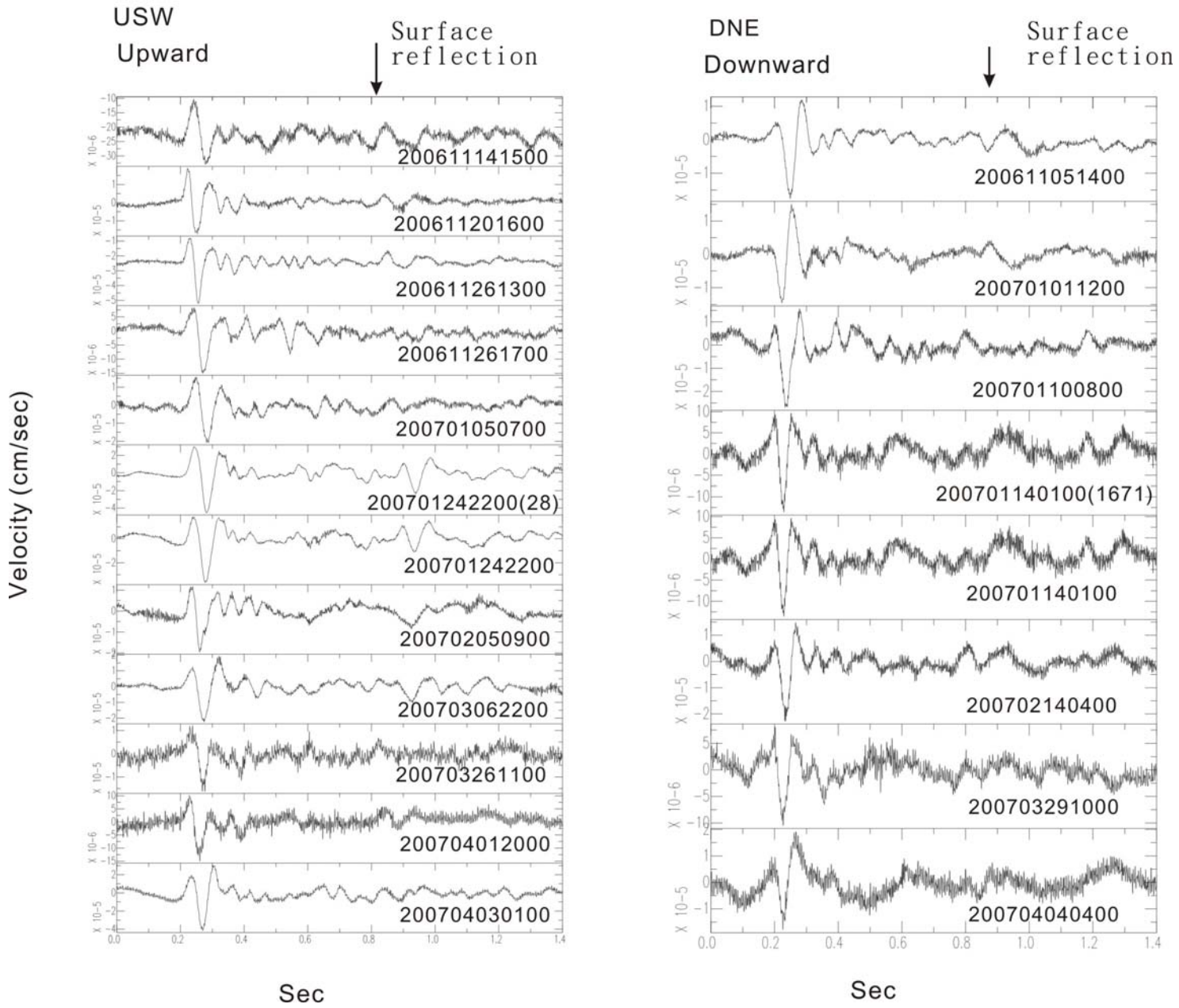


Preliminary Locations

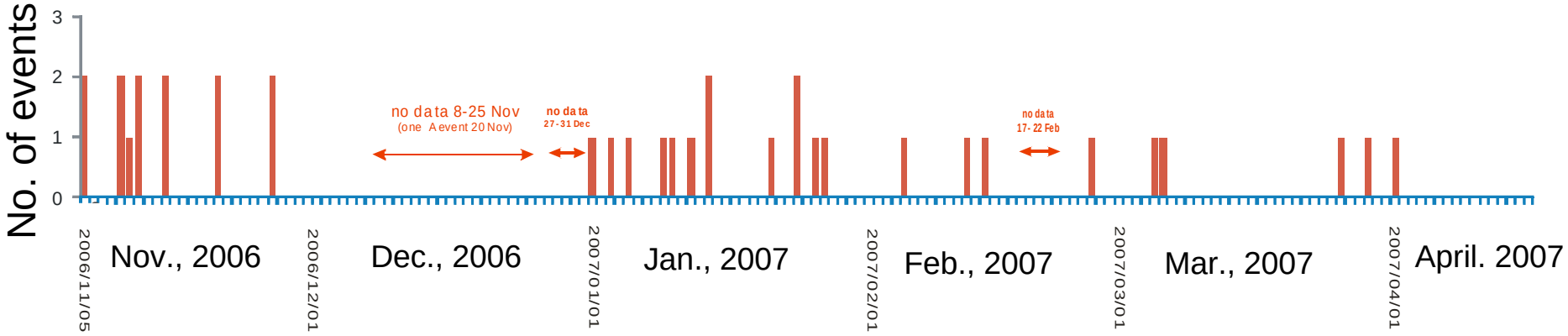
Events from Kueichulin Fm. Below Chinshui Shale

Kueichulin Fm: high permeability, large dilatancy (shallow hole, Tanaka et al., 2002)

BHS4-Z-Component

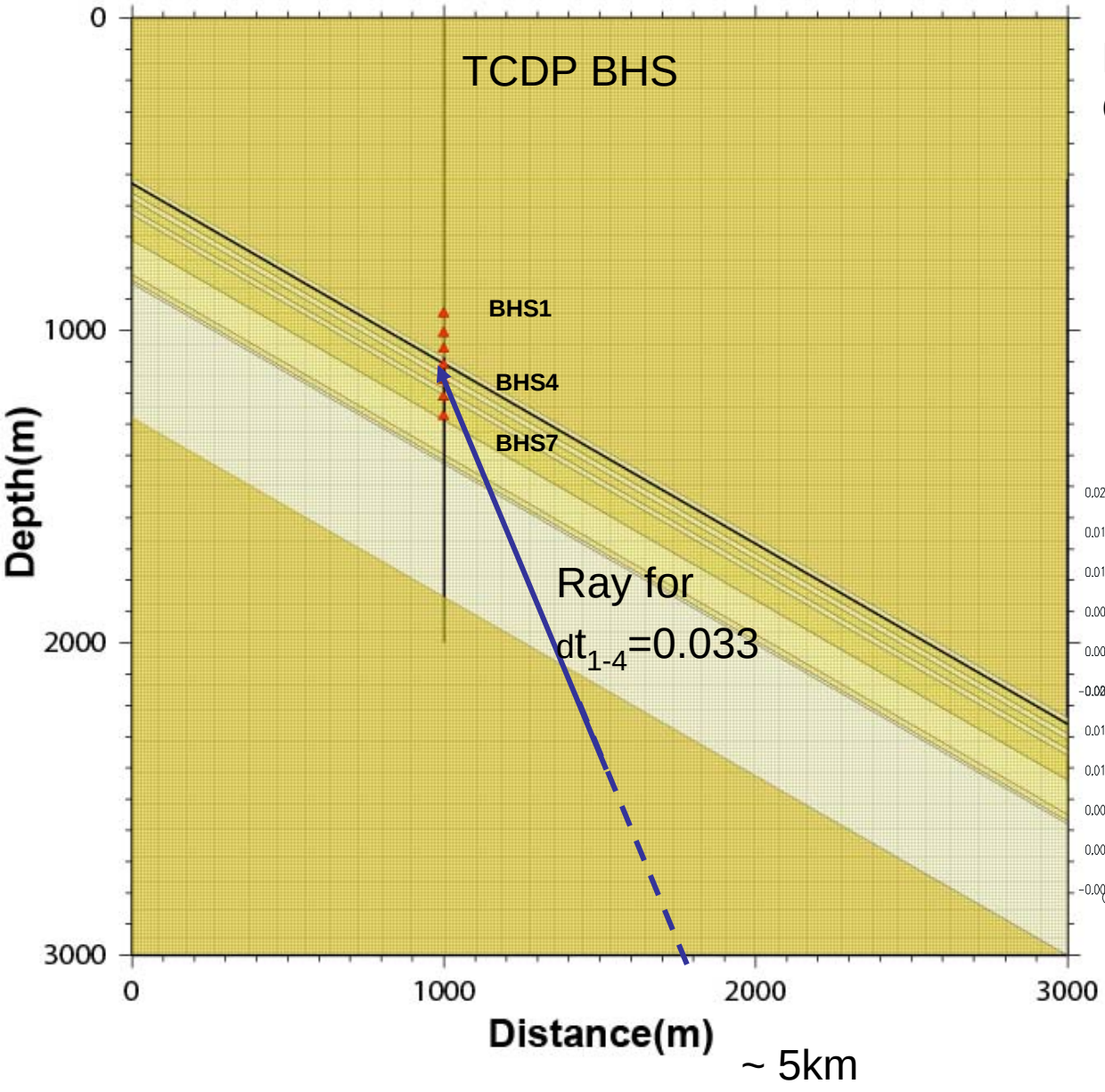


F type events occurrence



Questions on F type Events:

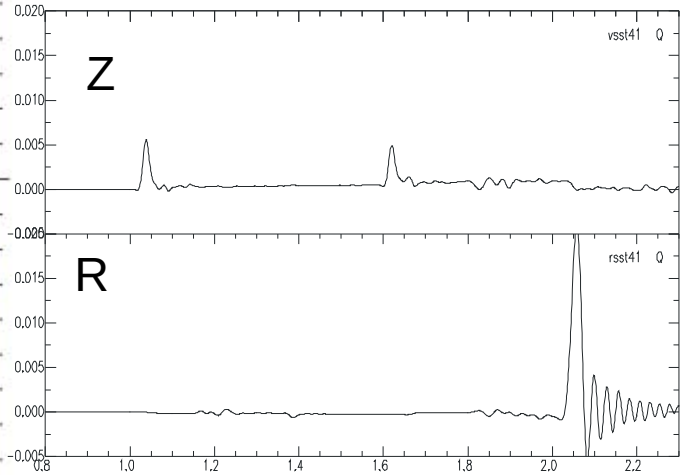
-P-wave only
or
-S-wave nodal



Finite-Difference Modeling
On-going

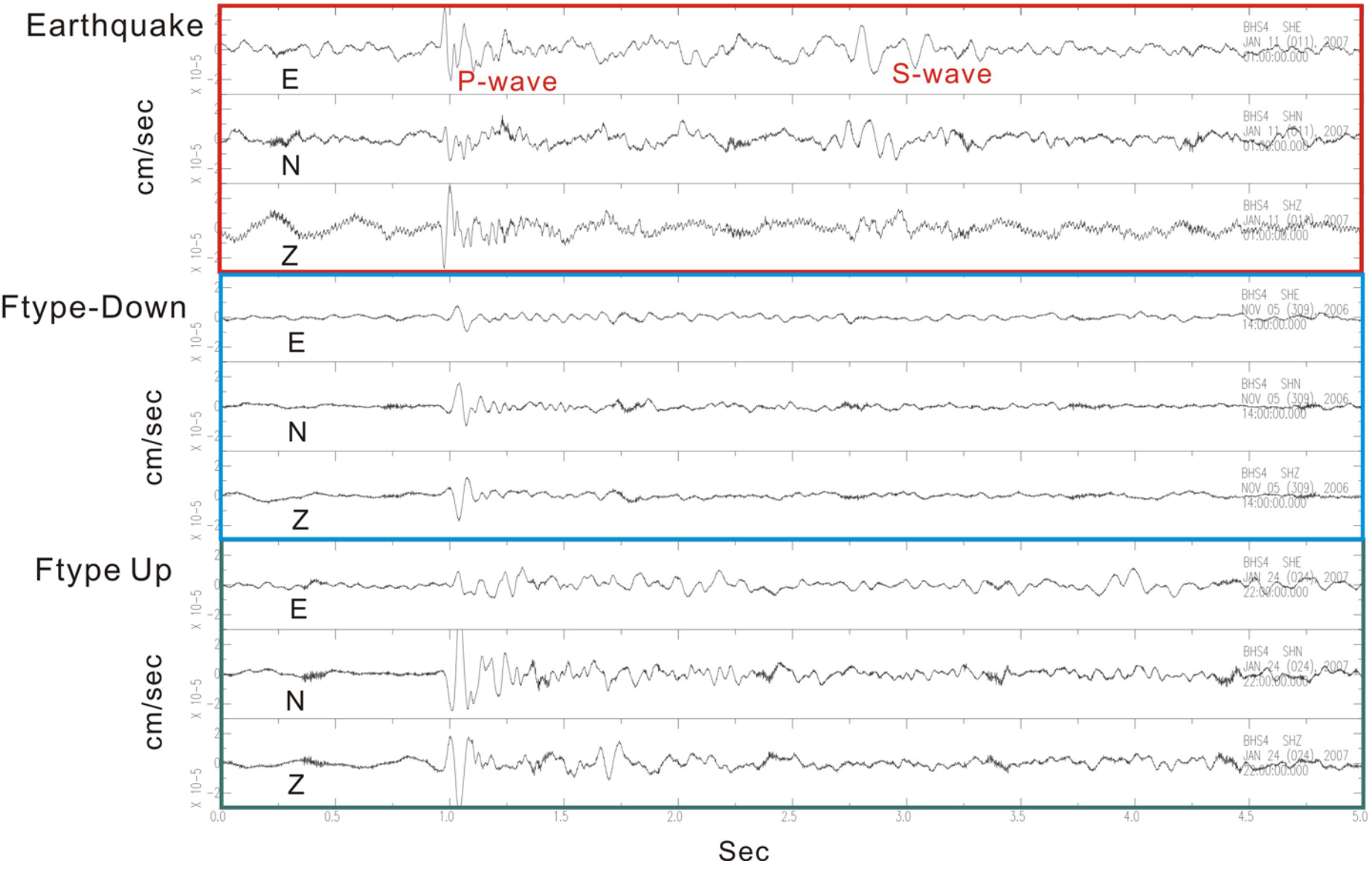
1km to the east to the TCDP
Depth 5km
Synthetic Displacement at BHS4

Strike0 dip30 rake 90

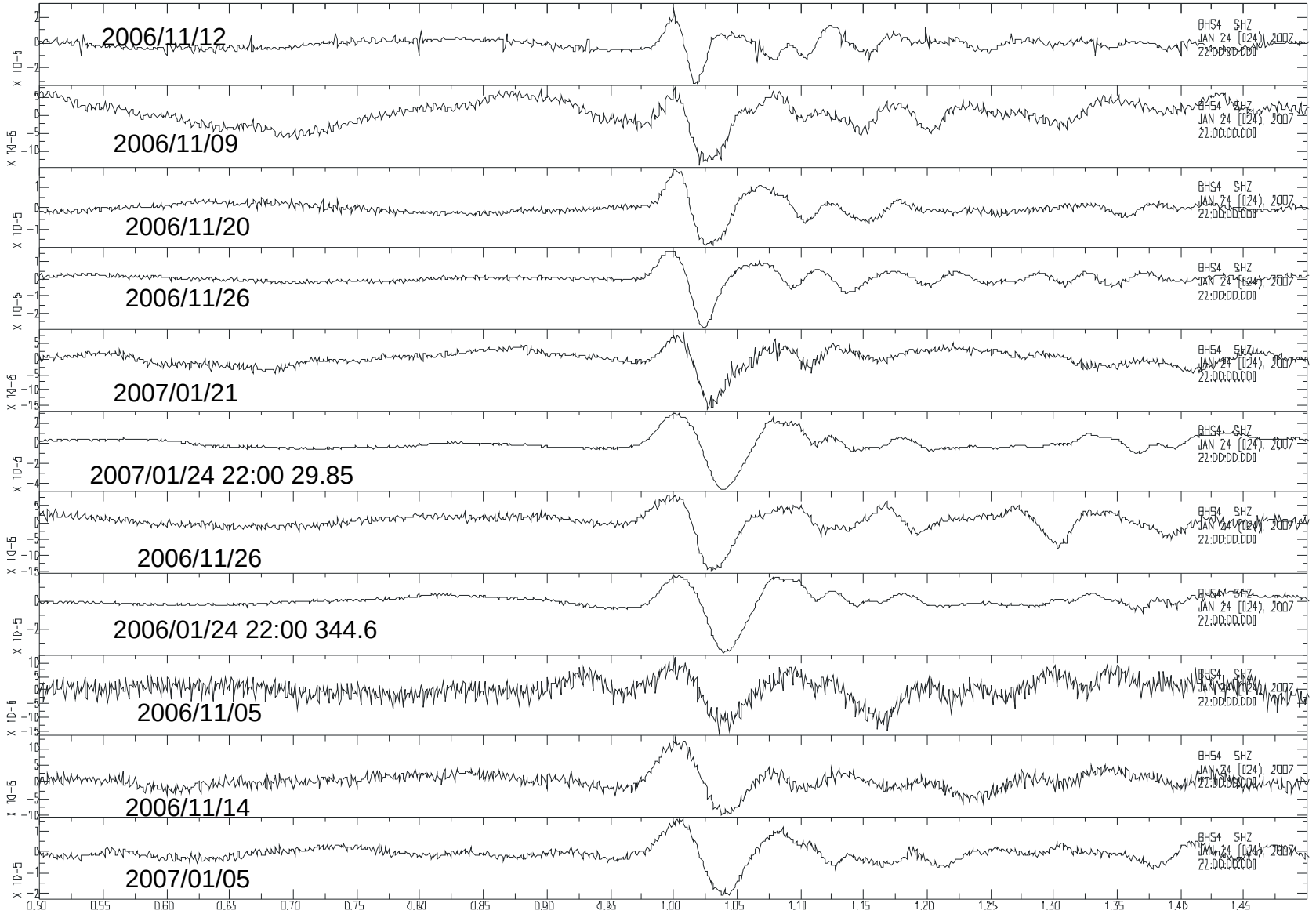


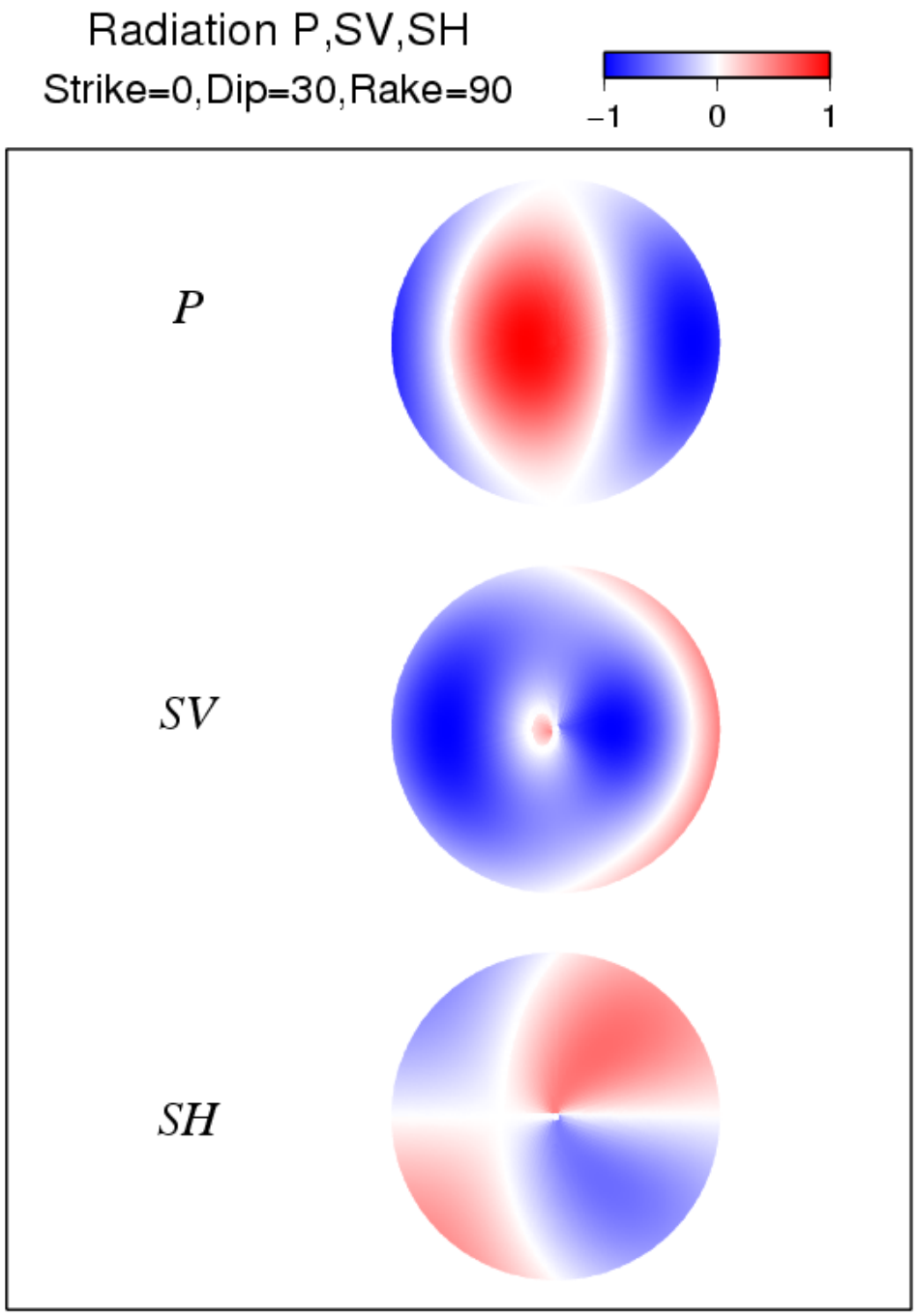
~ 5km

BHS4 E- N- Z- components 5-sec Records



Upward phases at BHS4: Repeatable





Clear P and SV for io~40 degree

No Observed SV: indication of only P-wave event

F Type Events:
Open Crack events?

Modeling on progress…..

Applications Places System 1:51 PM

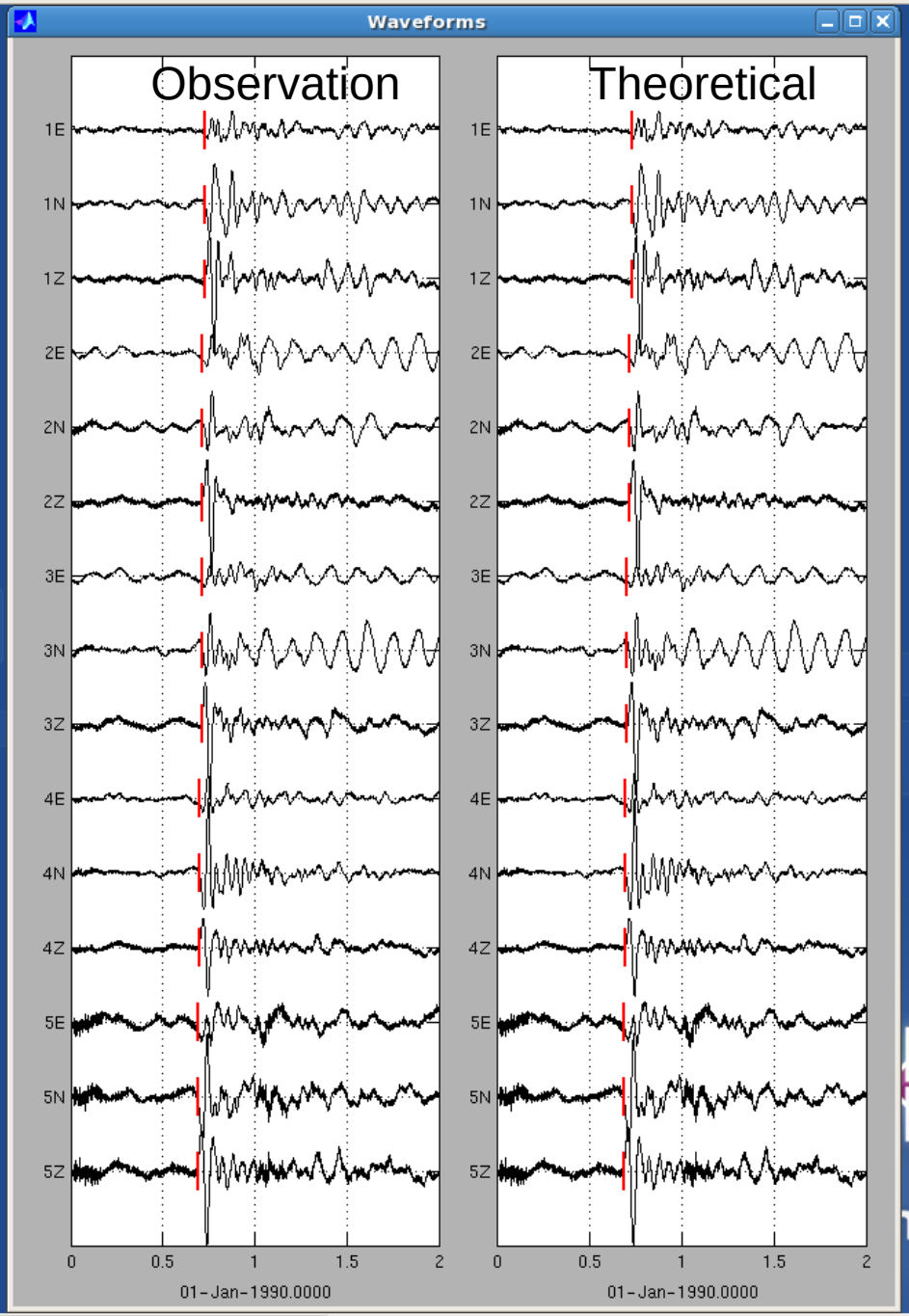
Computer

fong's Home

Trash

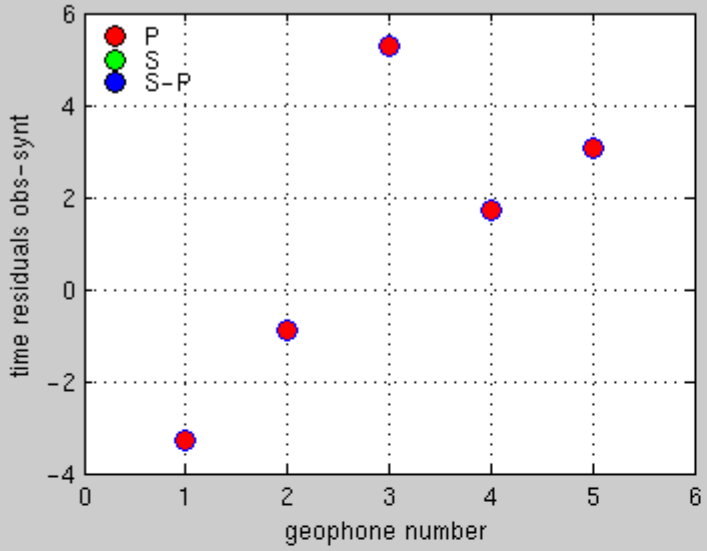
Preliminary locations of the F type events (MIMO, Oye and Roth, 2003)

Using P-wave travel time and polarization

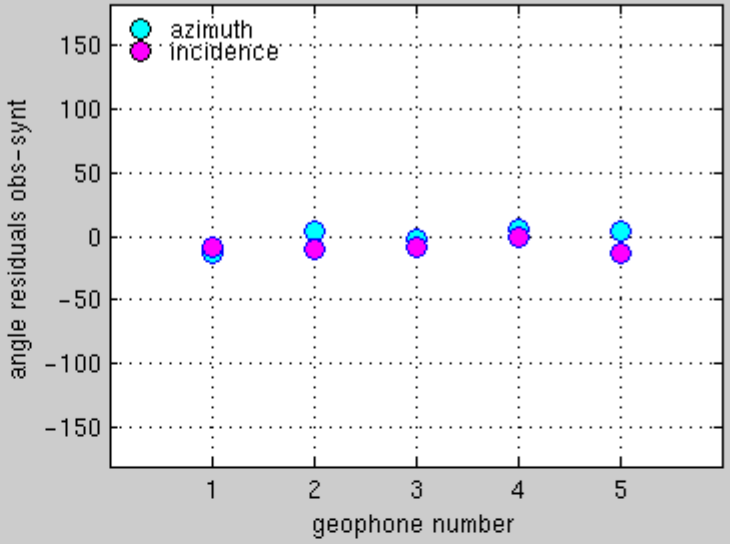


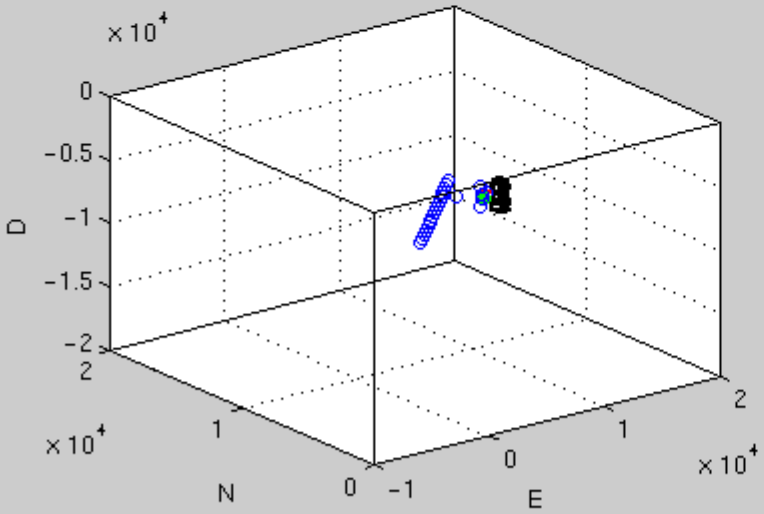
Waveforms Polarization

Time residual (msec)



Azimuth/incidence residual





Event 1:

t0 = 505.41 +- 3269 msec

x = 58.734 +- 610.79

y = 462.73 +- 17668

z = -1442.5 +- 12033

rms location error = 12347

data residual = 3.2173

model residual = 2.9612e-14

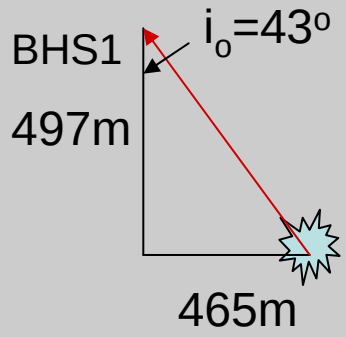
X=59m

Y=463m

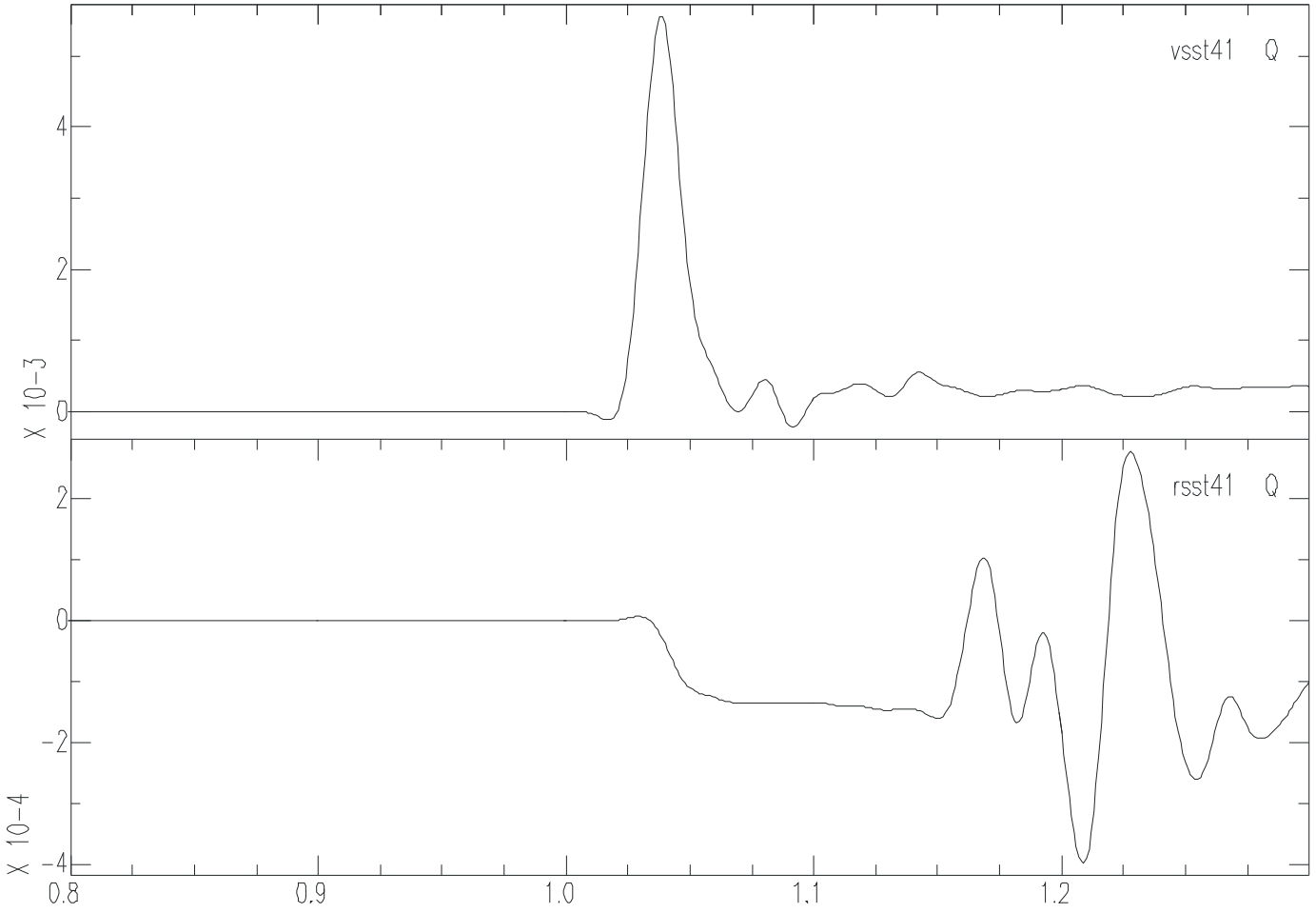
Z=1443m

-498 m below BHS1

-332 m below BHS4



1.5 sec displacement records



- FD slowness

Applications Places System 7:08 PM

MIMO

Session Setup Calibration Automatic processing Manual Processing Visualization

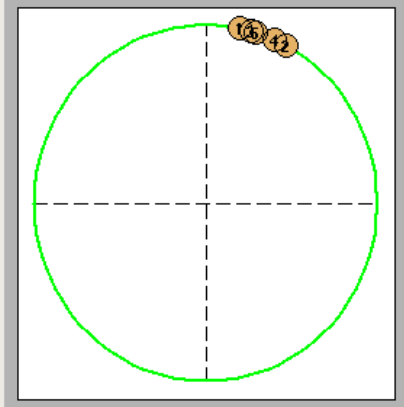
NORSAR

Microseismic Monitoring

MIMO 1.1

Current session: Event 200611122136

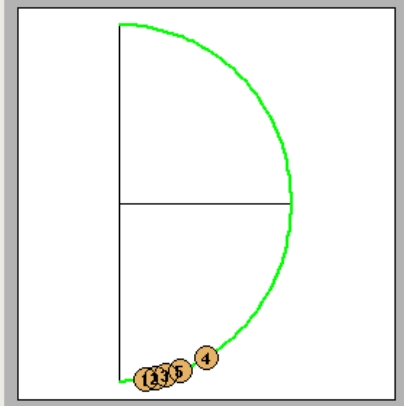
Polarization



Event number 1

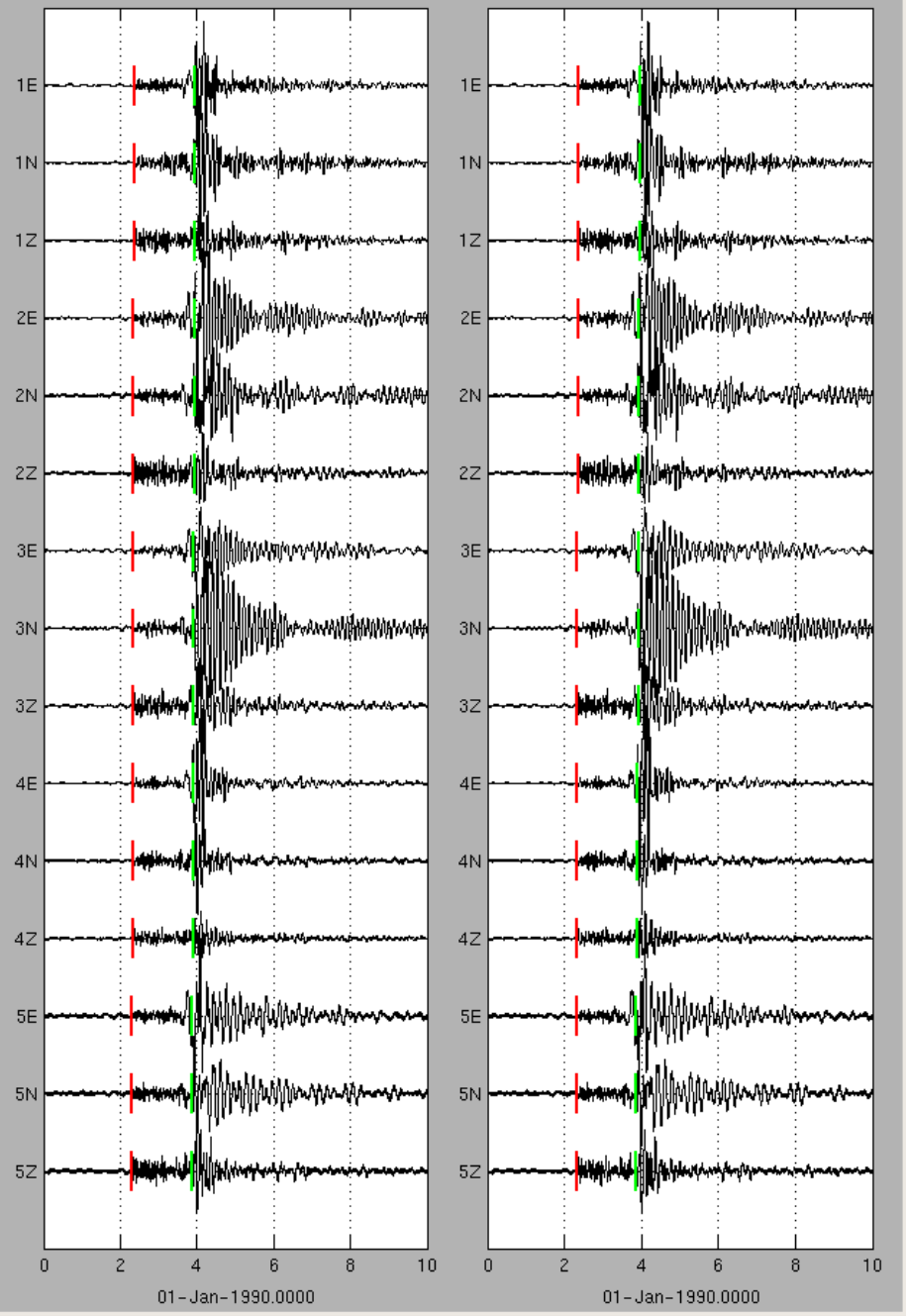
geo	azim	inci	Q1	Q2
1	11.2	8.3	0.96	1.00
2	27.9	11.8	0.99	0.91
3	15.7	15.6	1.00	0.95
4	23.9	30.1	1.00	0.50
5	17.1	20.4	1.00	0.88

Azimuth



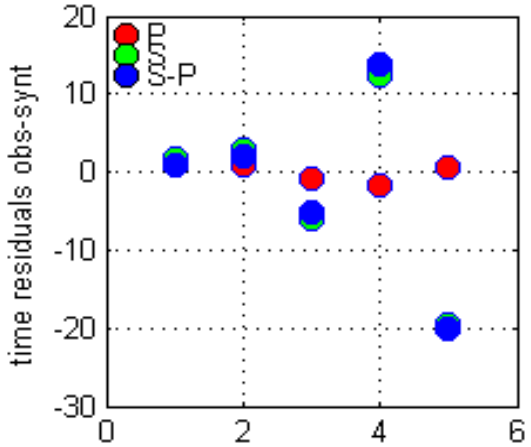
Incidence

Waveforms

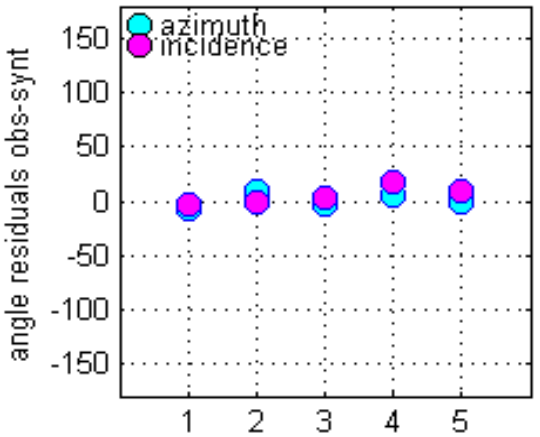


nycticorax@Seis... nycticorax@Seis... MIMO [Step by step] Waveforms Polarization [Figure 1]

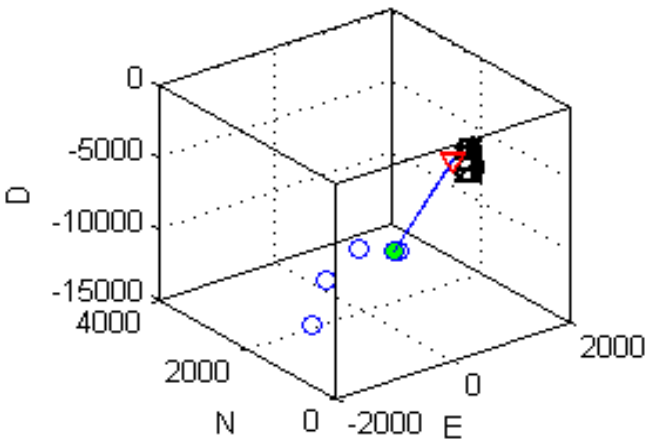
Residue of the location



(ms)



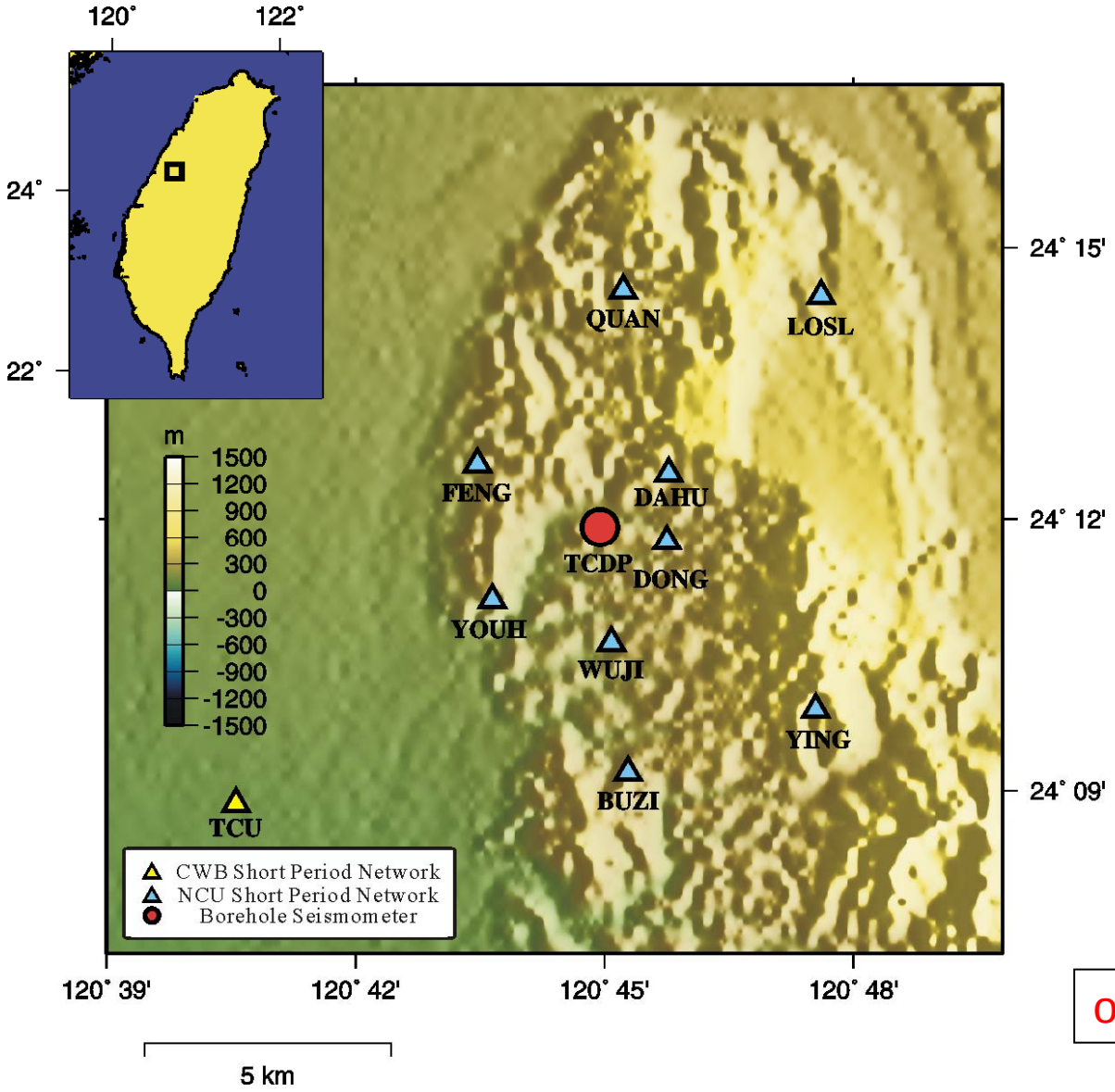
(degree)



Event 1:
t0 = -465.53 +- 4.501 msec
x = 726.86 +- 17764
y = 2245 +- 1.0038e+05
z = -12214 +- 4886.2
rms location error = 58920
data residual = 8.9928
model residual = 1.0455e-06

Event 200611122136

Short period surface network

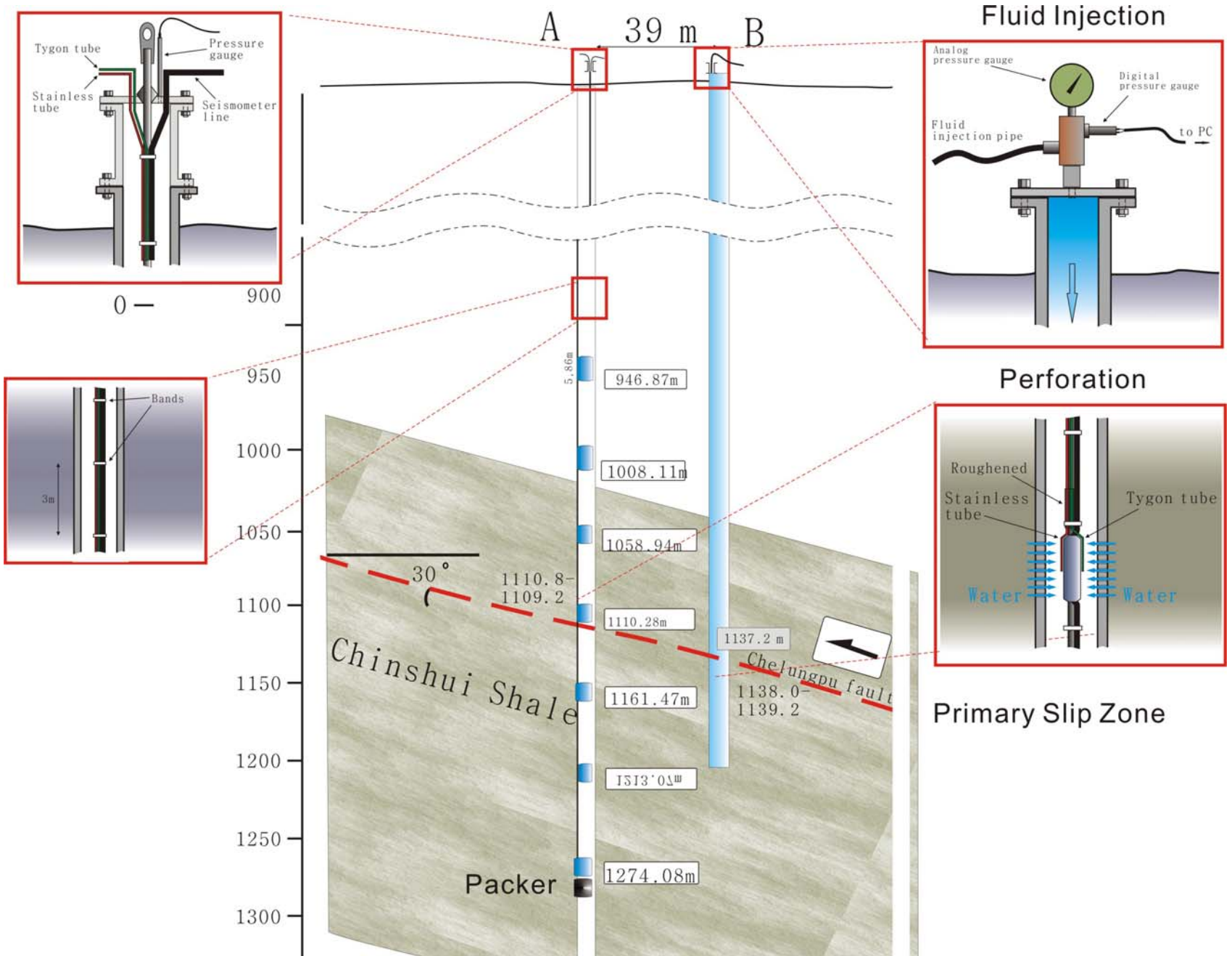


ongoing

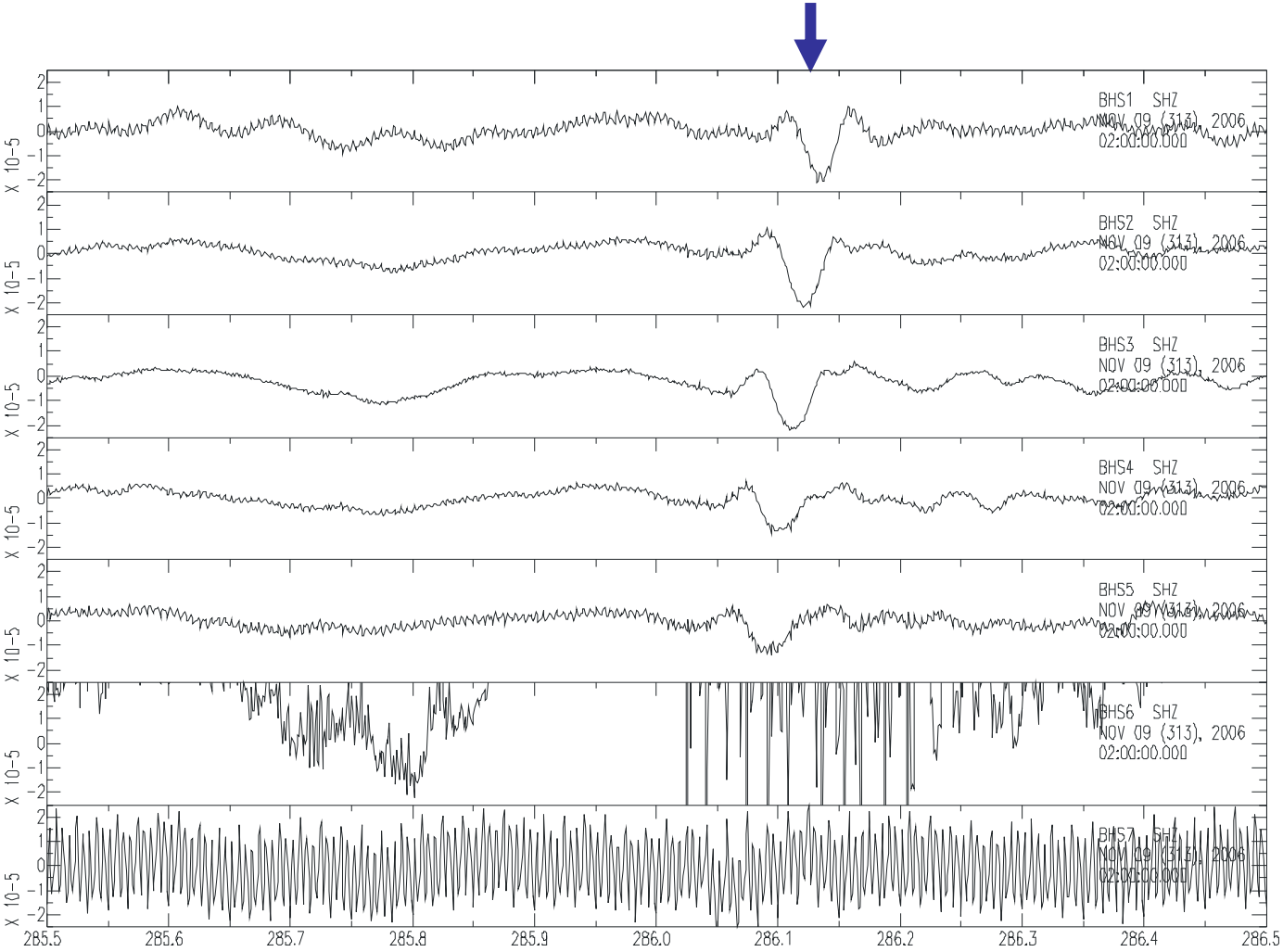
Location of micro events

- Time 2006/11/04~2007/01/31
- 89 events were located.
- S/N > 4
- Notch filter was used only.
- Ts-Tp arrival time less than 2 seconds
- The records of surface network were not used.

Chelunpu Fault FIT, Nov., 2006, Jan., and March, 2007



2006/11/09 Z-Comp
(1 sec records)

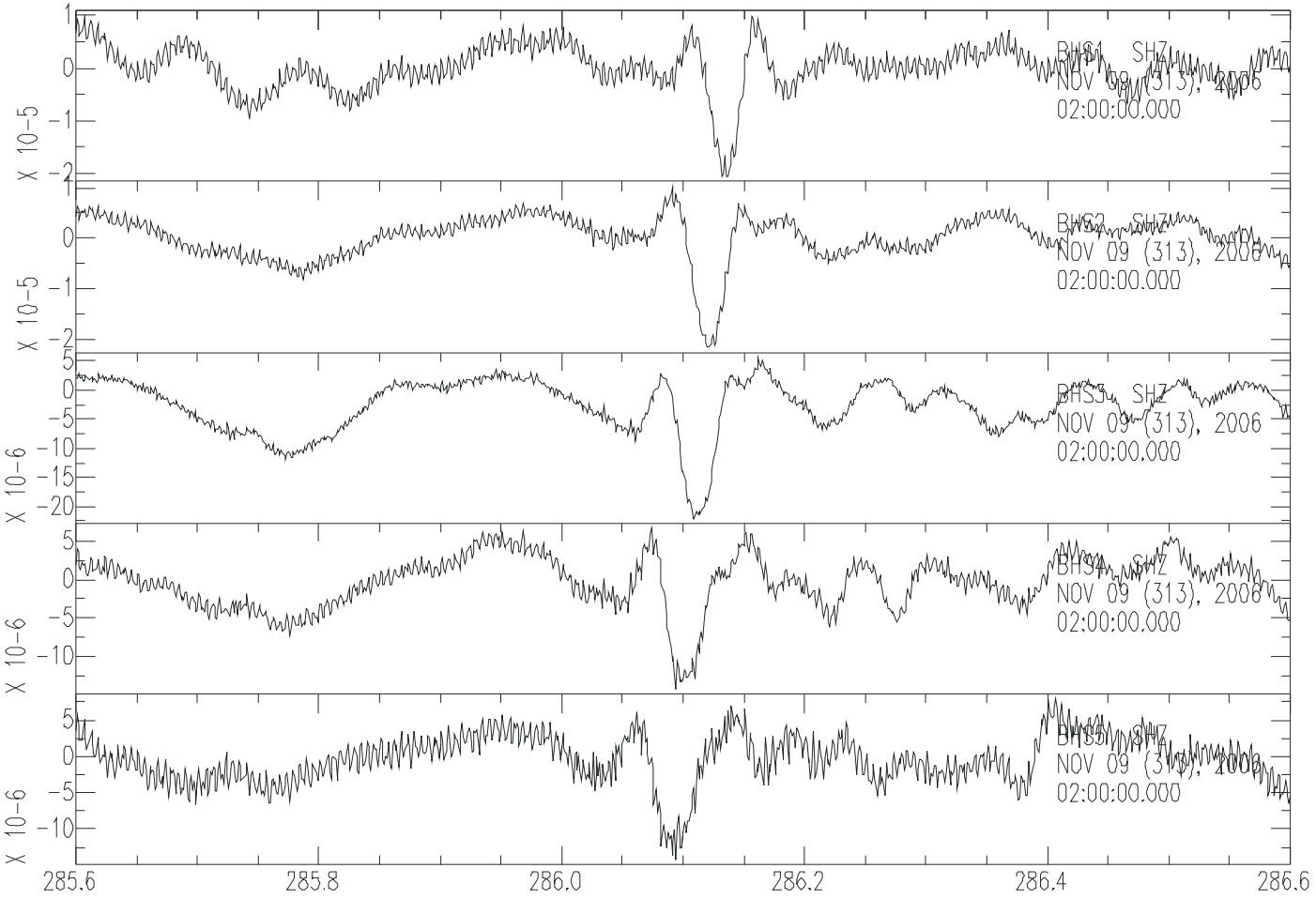


Velocity (cm/sec)

time, sec

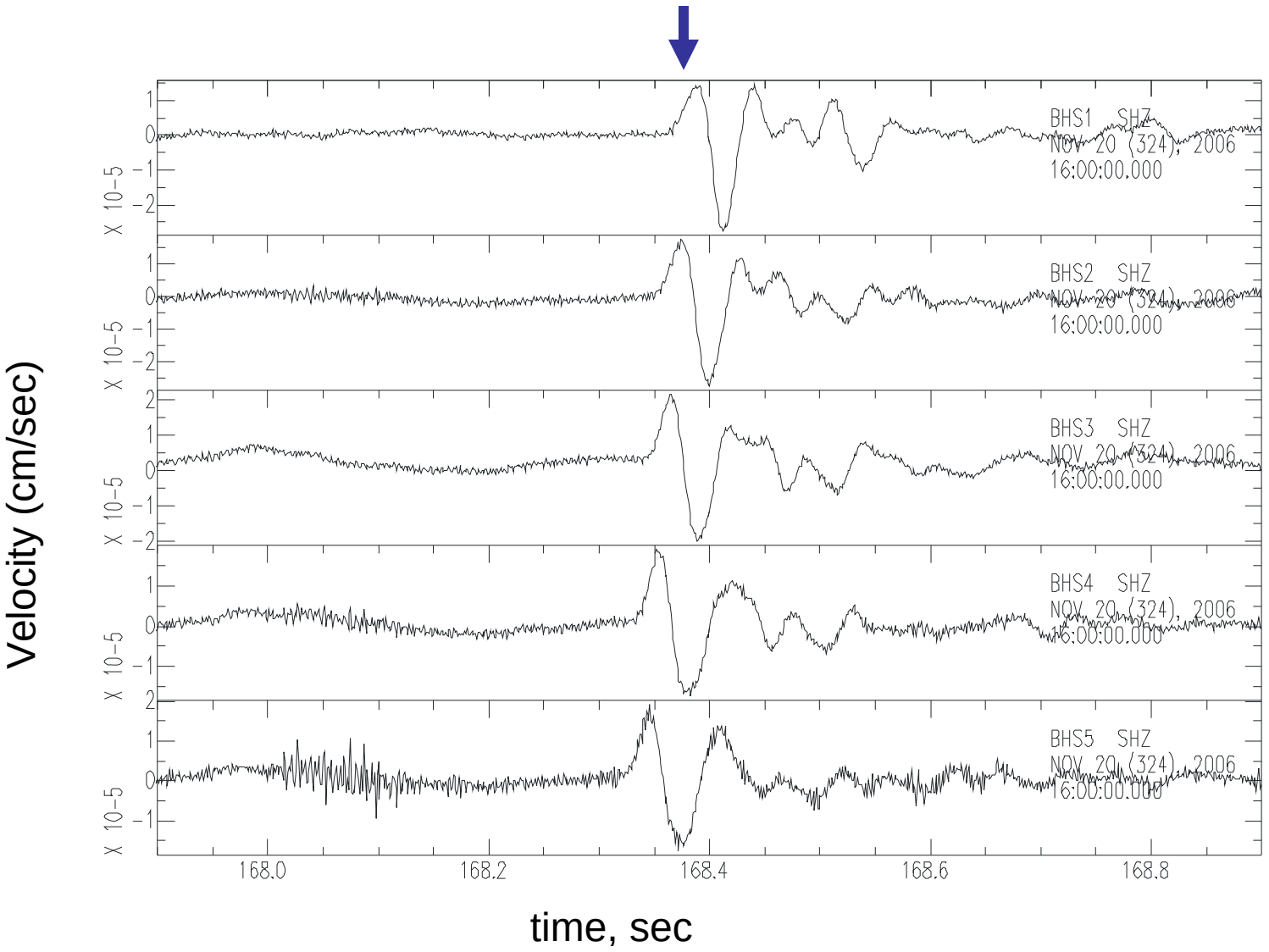
2006/11/09 02:00 Z-Comp
(1 sec record)

(upward motion, T~0.05 sec)



2006/11/20 16:00 Z-Comp (1 sec record)

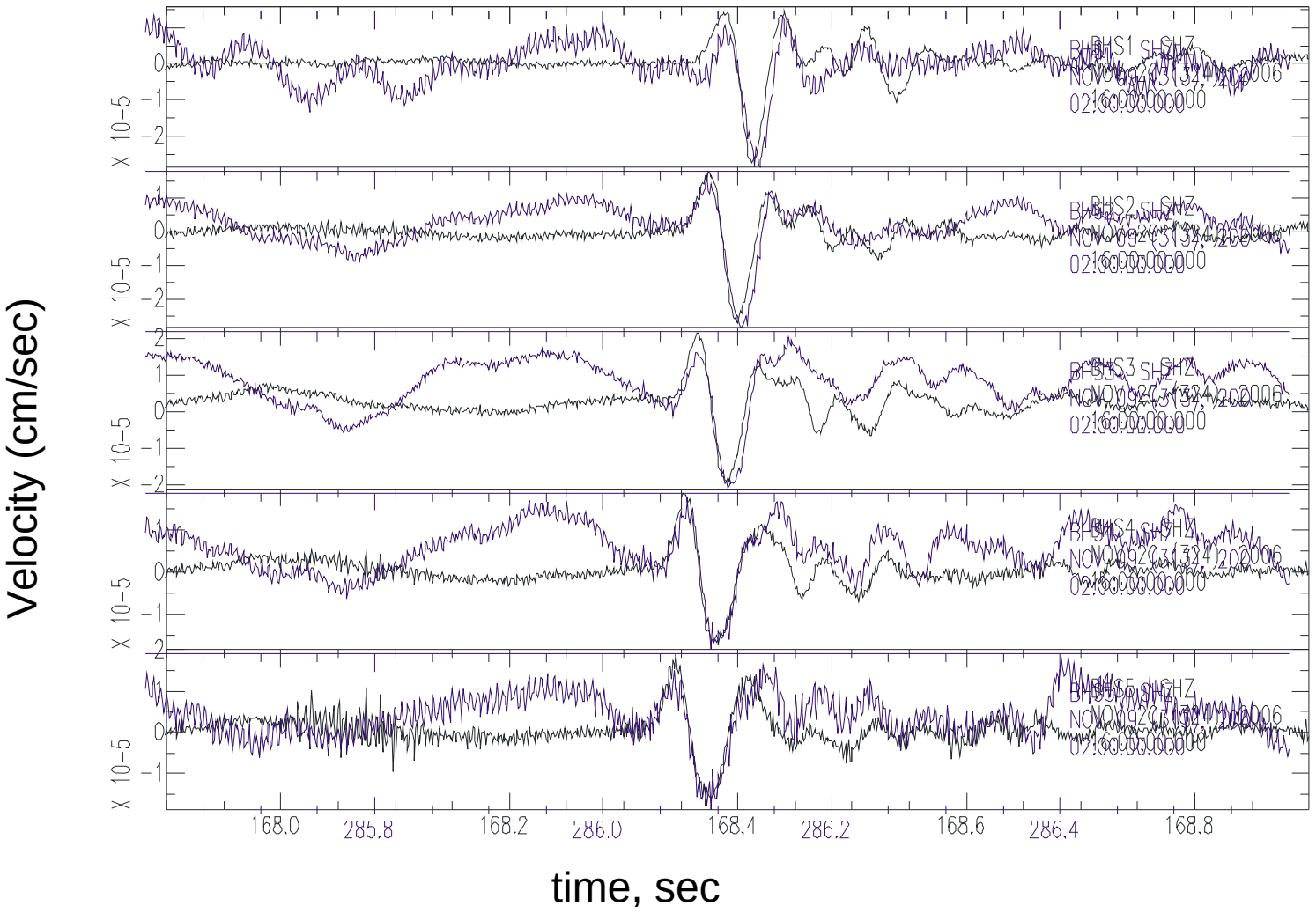
Upward first motion, pulse width~0.05 sec



2006/11/20 16:00 Z-Comp (1 sec record)

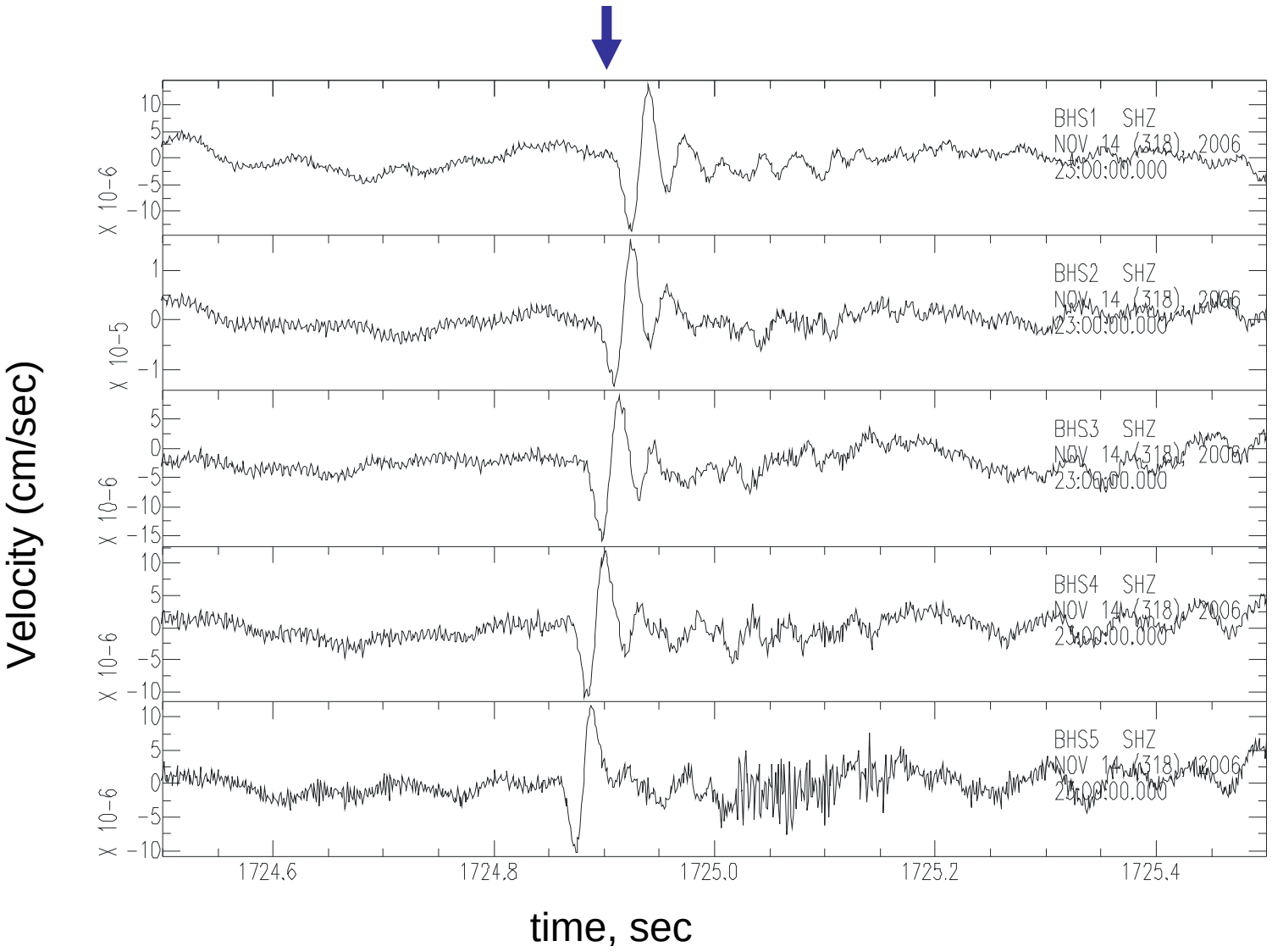
Upward first motion

(compared to 2006/11/09 02:00 records)



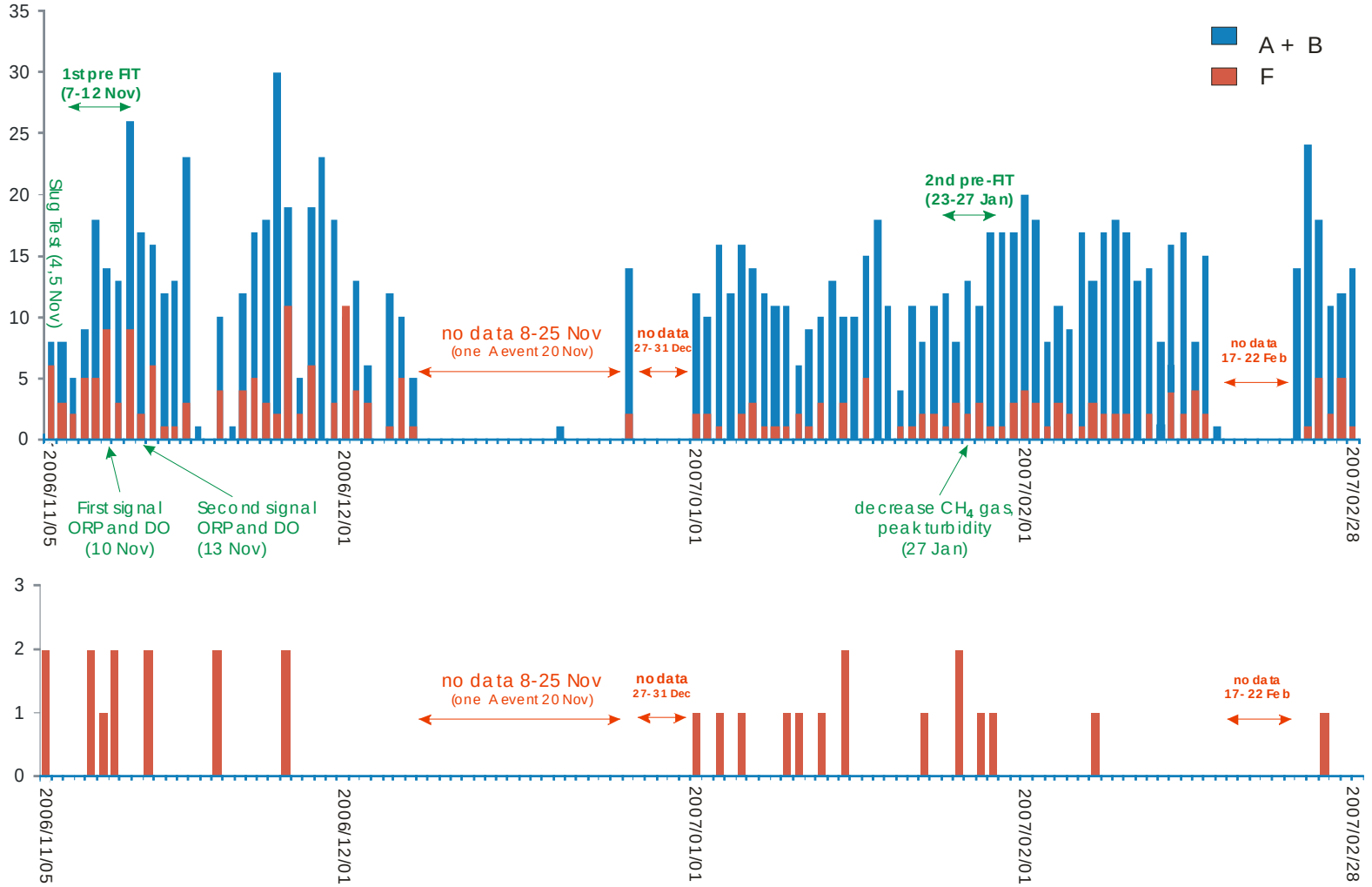
2006/11/14 23:00 Z-Comp (1 sec record)

Downward first motion pulse width~0.025 sec



Statistics A+B and F (FIT time, and arrival of ORP and DO signals)

Nov. 3rd, 2006-Feb. 28, 2007



Preliminary locations of the open crack events

- *Estimated from $V_{apparent}$*
  - i_o (incident angle) $= cos^{-1} (V_{real}/V_{apparent})$
  - $V_{apparent}=\Delta_{(BHS4-BHS1)} / \Delta t$

    $V_{real}=3.8$ km/sec

    larger Δt=> smaller V_{app}=> smaller i_o (closer event)

- Location by MIMO (Oye and Roth, 2003)
  - P-wave particle motions
  - travel times between receivers

Micro events location

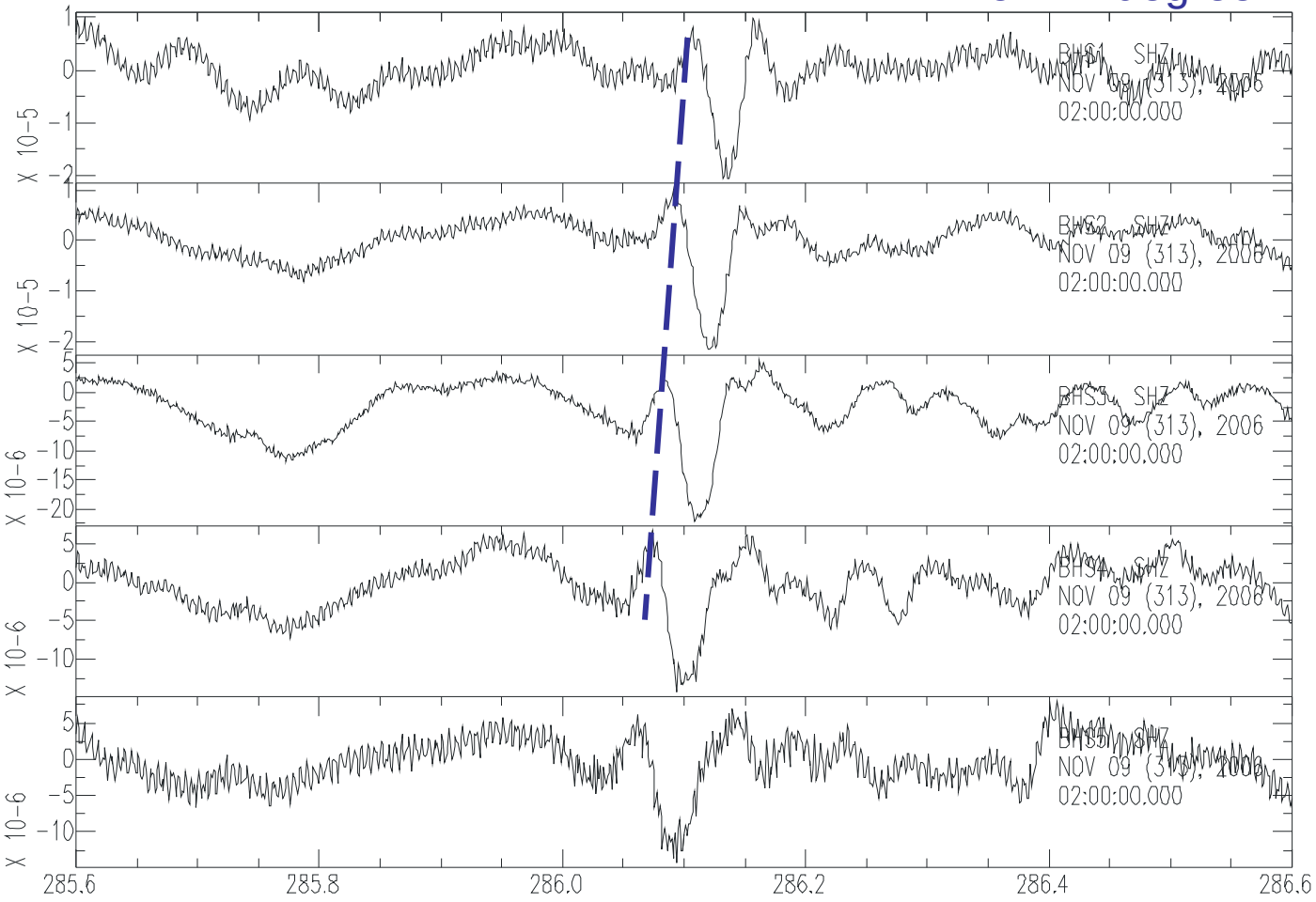
- Polarization
- P and S-wave onset time
- Linear inversion for homogeneous velocity models

The velocity model we used is the homogenous model which is the average velocity from Kim's 3D-model (Kim et al., 2005).
Vp = 4064 m/s
Vs = 2601 m/s

(Oye,V & M. Roth, 2003)

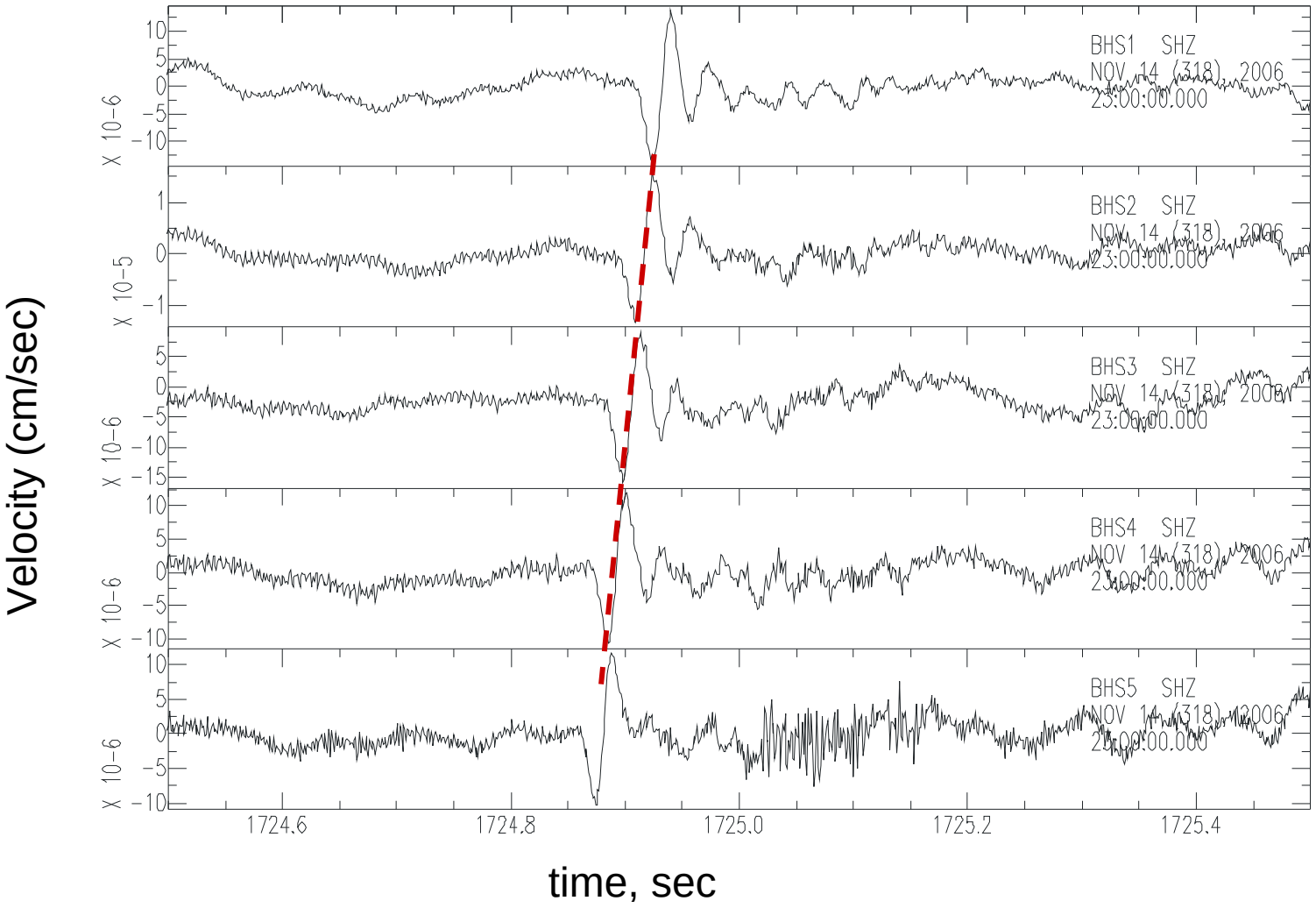
2006/11/09 02:00 Z-Comp
(1 sec records)

Δt=0.032 sec
Vap= 5.11 km/sec
Io= 42 degree



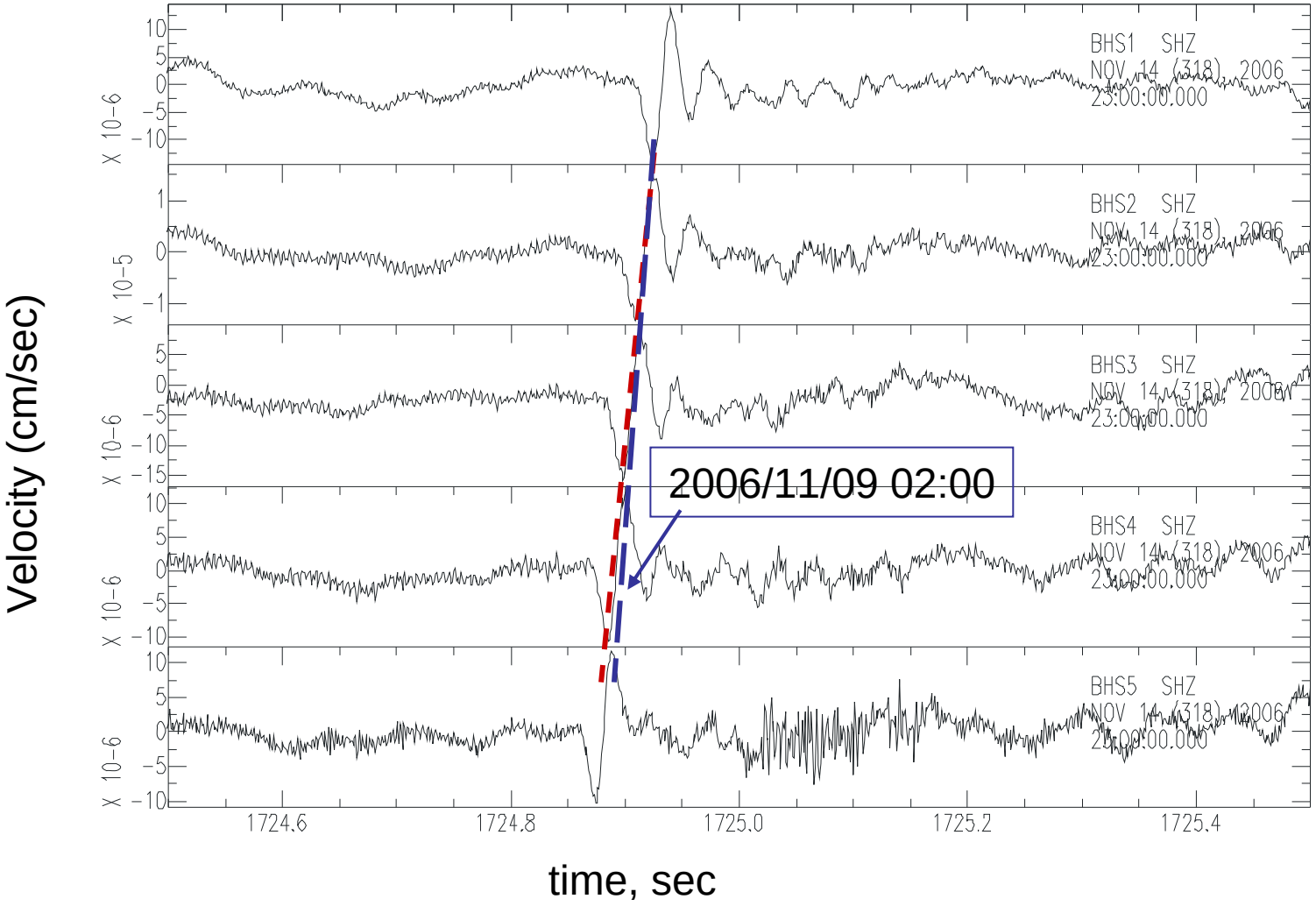
2006/11/14 23:00 Z-Comp
(1 sec record)

Δt=0.034 sec
Vap= 4.8 km/sec
Io=37.65 degree



2006/11/14 23:00 Z-Comp

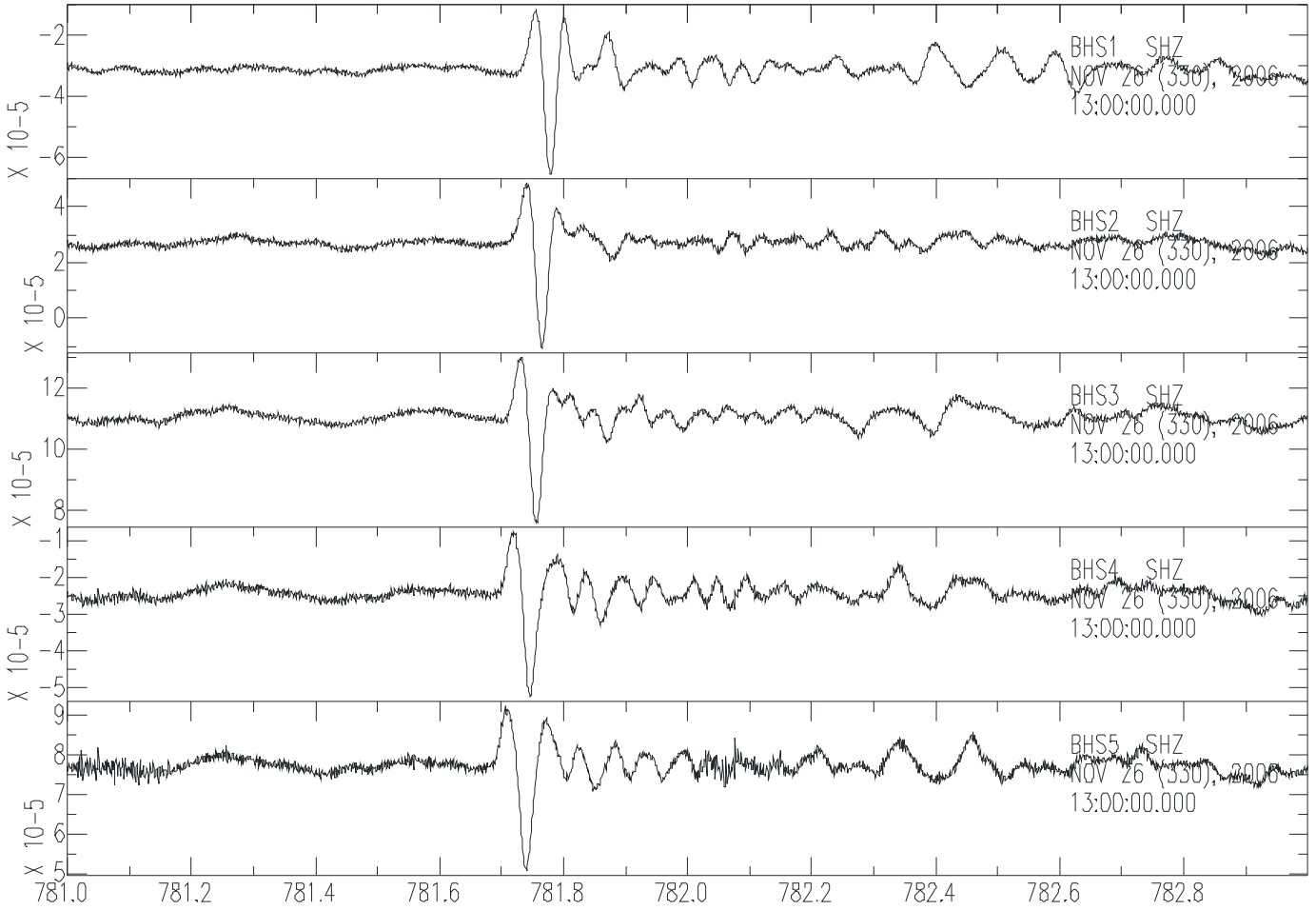
2006/11/09 02:00 Z-comp



2006/11/26 13:00

Vapp=4.95 km/sec

io=39.85

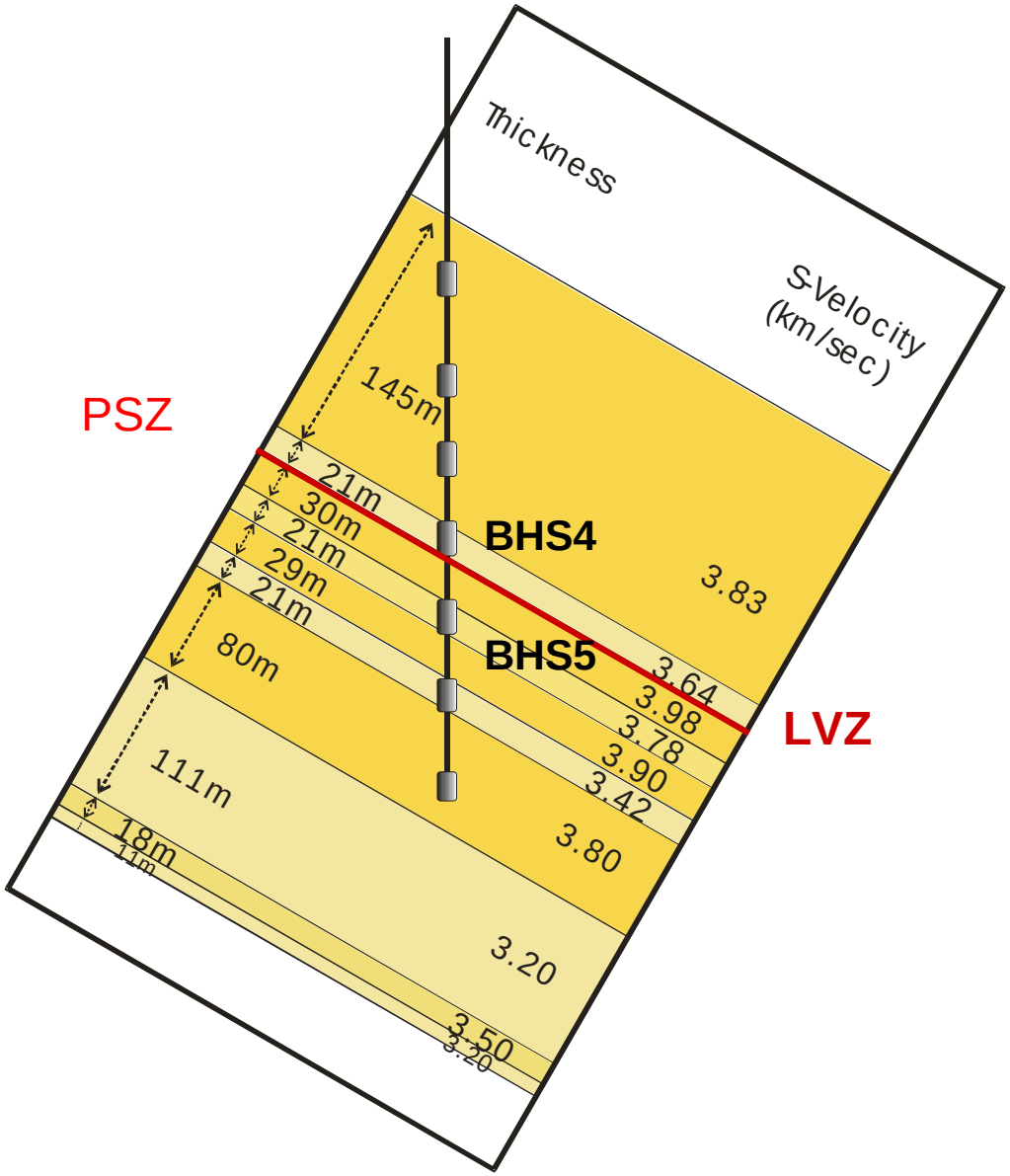


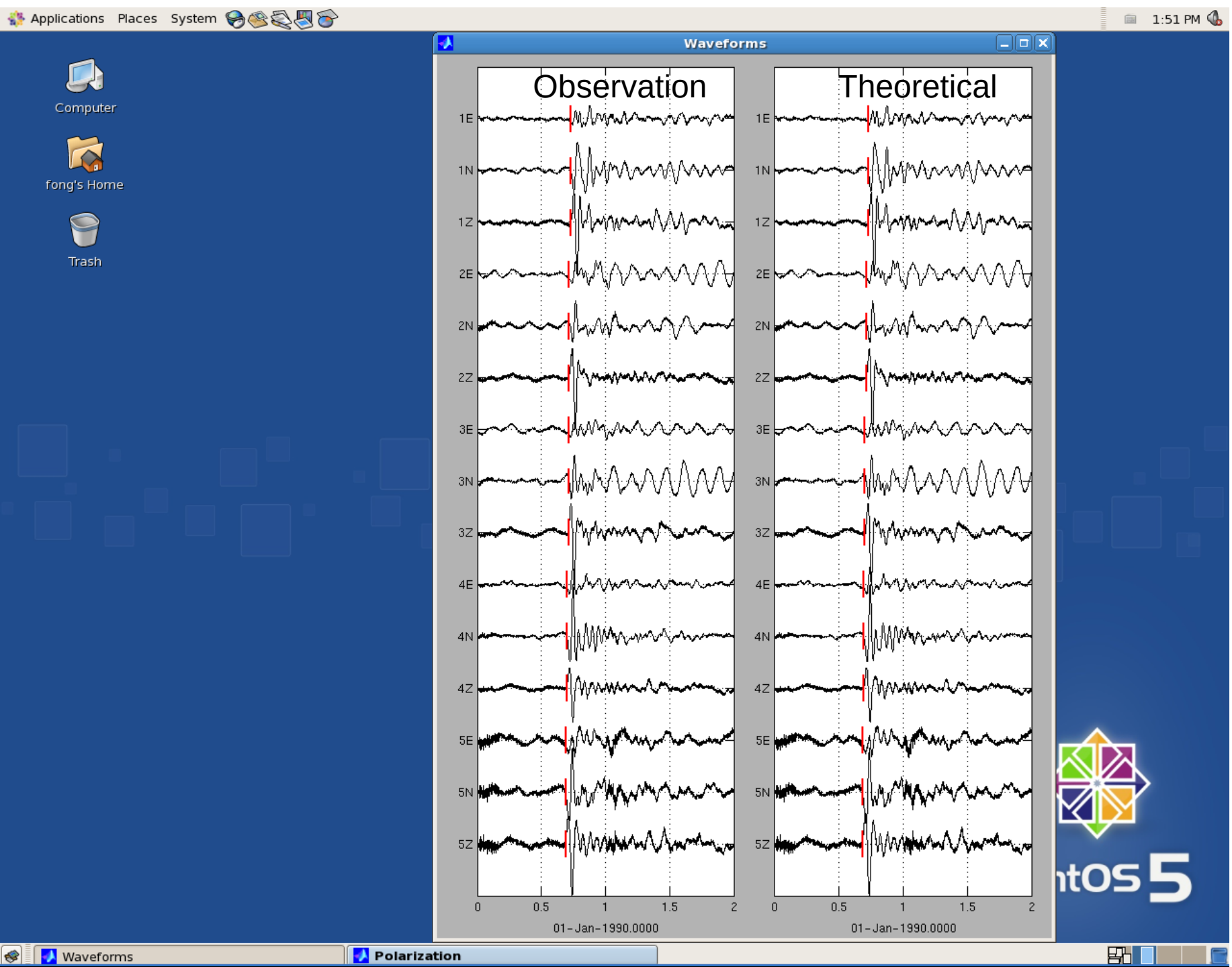
Small Arrivals from head waves traveling along the faster layer below LVZ?

Low Velocity Zone,
Vp~3.20-3.40 km/sec
Vs~1.50-1.60 km/sec

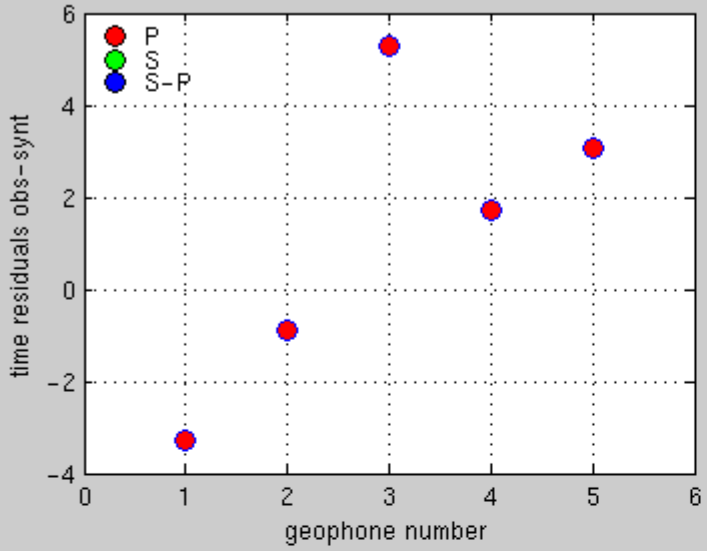
Transition zone
Vp~3.50-3.70km/sec
Vs~1.66-1.75 km/sec

Host Rock
Vp~3.80-4.0 km/sec
Vs~1.90-2.00 km/sec

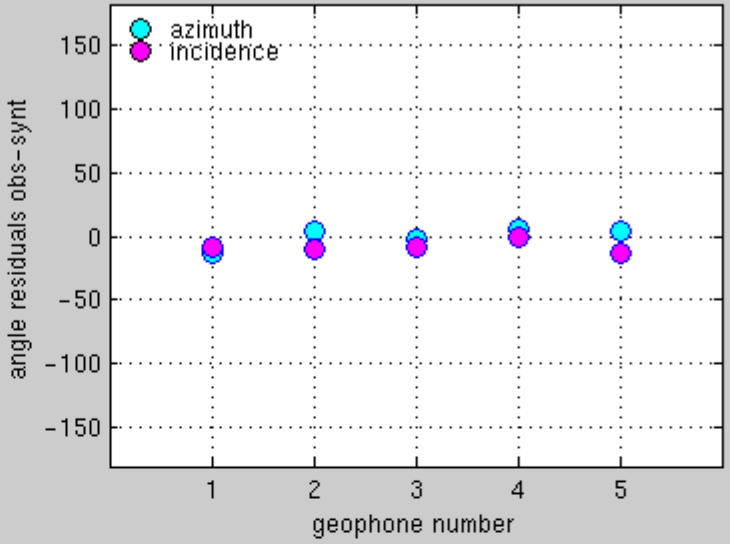


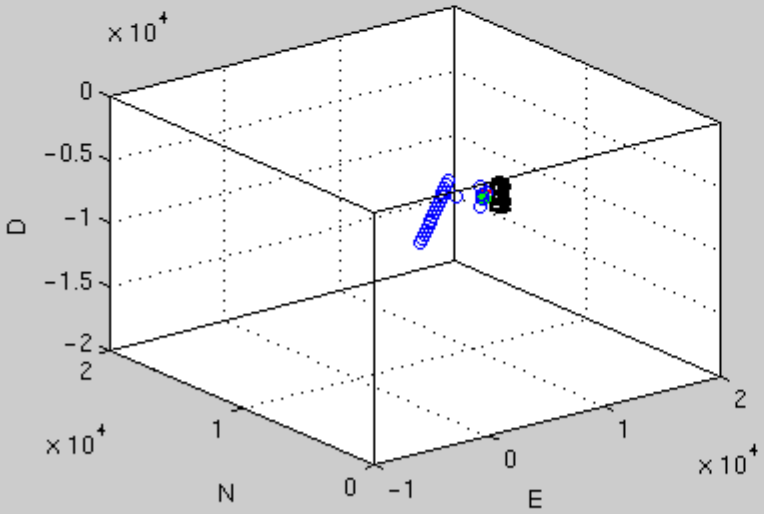

Applications
Places
System
1:51 PM
Computer
fong's Home
Trash
Waveforms
Observation
Theoretical
1E
1N
1Z
2E
2N
2Z
3E
3N
3Z
4E
4N
4Z
5E
5N
5Z
0
0.5
1
1.5
2
01-Jan-1990.0000
01-Jan-1990.0000
Waveforms
Polarization

Time residual (msec)



Azimuth/incidence residual





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rms location error = 12347

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model residual = 2.9612e-14

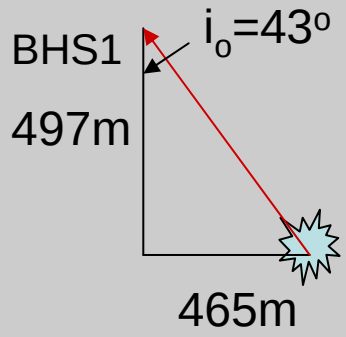
X=59m

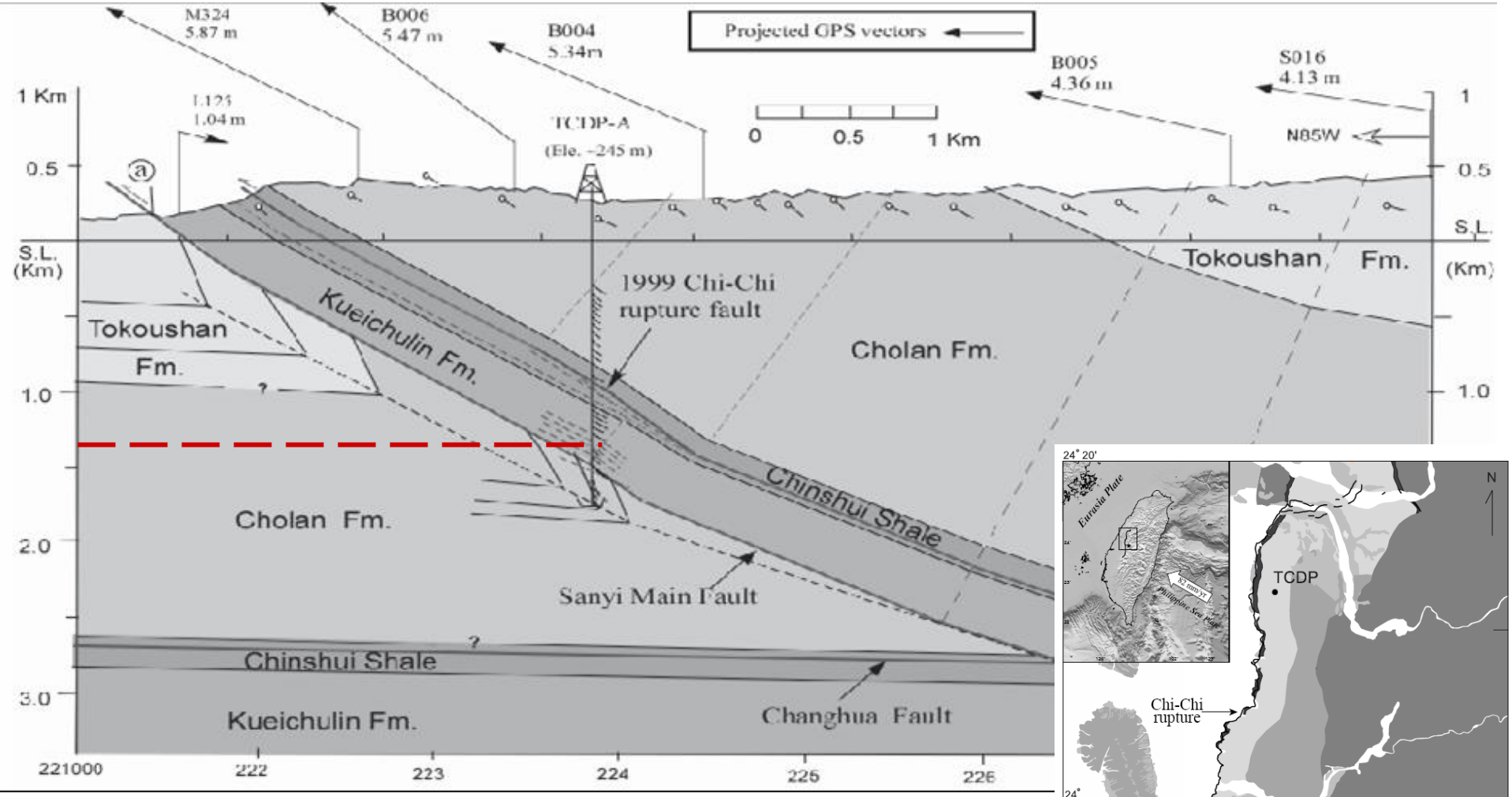
Y=463m

Z=1443m

-498 m below BHS1

-332 m below BHS4





Preliminary Locations

Events from Kueichulin Fm. Below Chinshui Shale

Kueichulin Fm: high permeability, large dilatancy (shallow hole, Tanaka et al., 2002)

Preliminary Summary

- P-wave only events are the open crack related events, not faulting
- Observed events were from existing or/and new open cracks in Kueichulin formation
- Mechanism

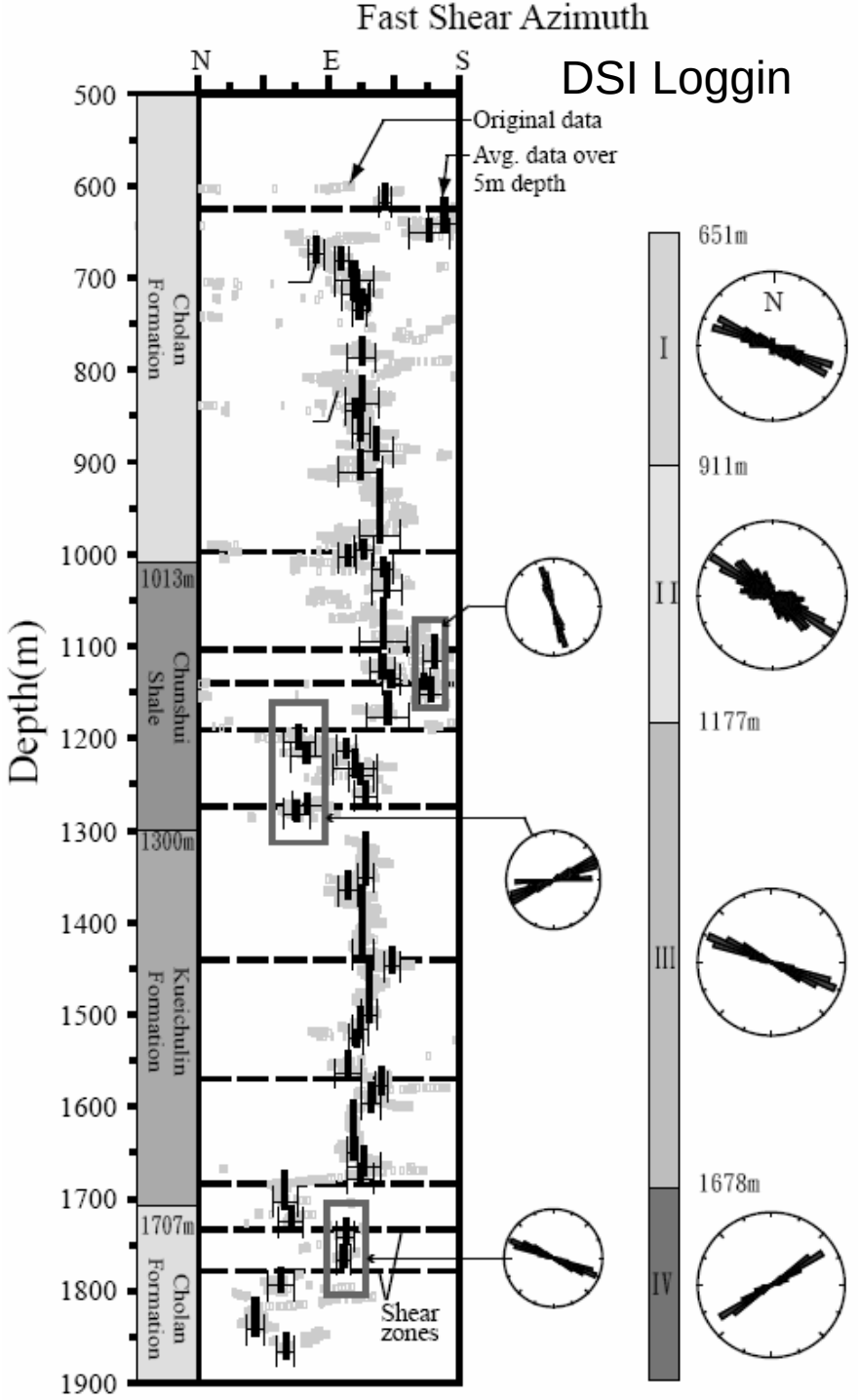
  FIRST OBSERVED NATURE MODE I RUPTURE ?

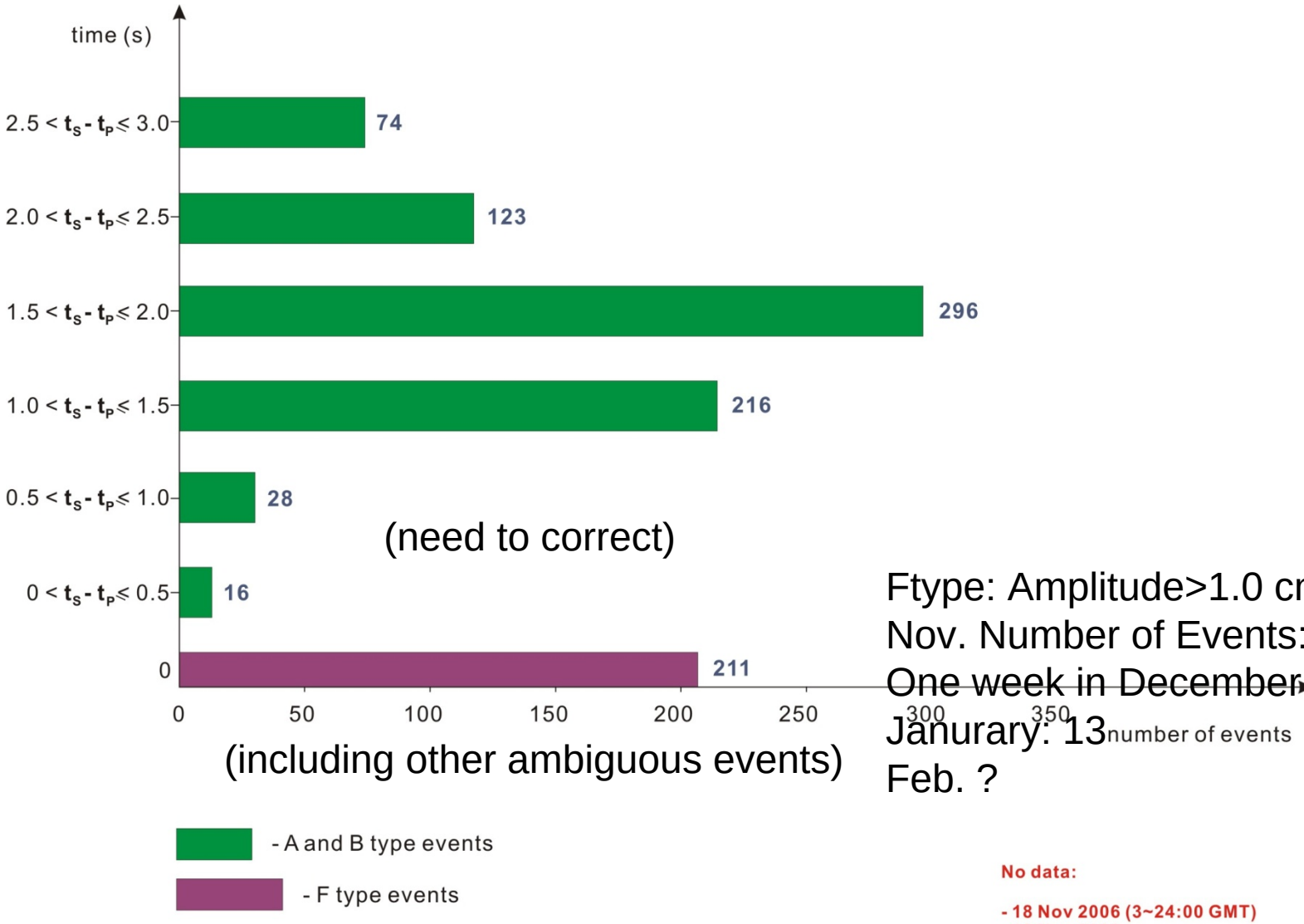
  -Fluid Flow in the Kueichulin formation?

  -Induced by FIT?
- Implications

  on going …

More complete data sorting and analysis (locations, modeling)





(need to correct)

(including other ambiguous events)

Ftype: Amplitude>1.0 cm/sec
Nov. Number of Events: 13
One week in December: 0
Janurary: 13
Feb. ?

No data:

- 18 Nov 2006 (3~24:00 GMT)
- 19 Nov 2006
- 20 Nov 2006 (0~8:00 GMT)
- 21 Nov 2006 (1~24:00 GMT)
- 22 Nov 2006 (0~2:20 GMT)
- 08~21 Dec 2006
- 22 Dec 2006 (8~24:00 GMT)
- 23~25 Dec 2006
- 27~31 Dec 2006
- 17~22 Feb 2007

Ftype after correction (also ORP DO observations, FIT related?)

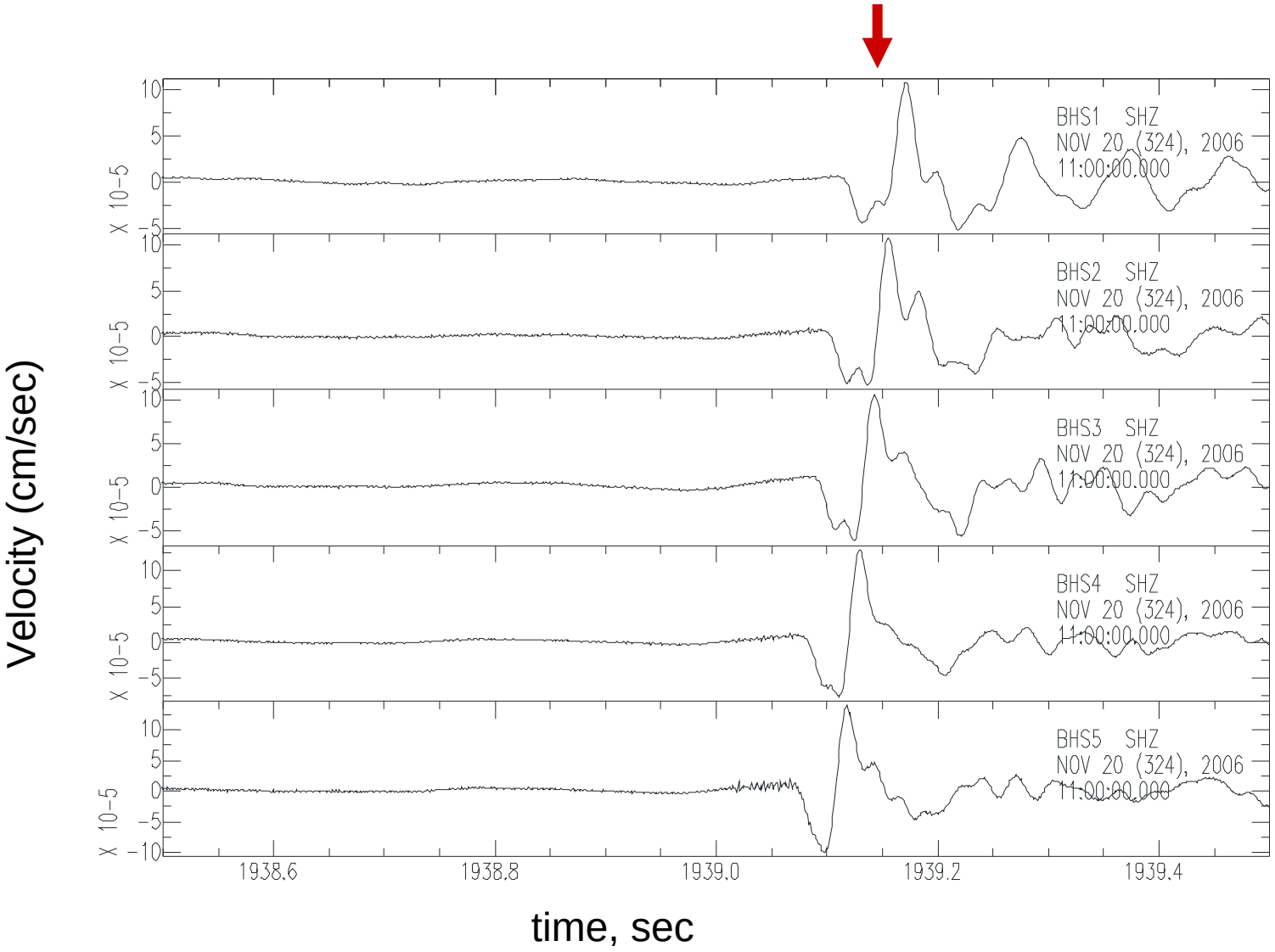
18 Oct, 12:00 temperature measurement at holeB
4 Nov, 16:55 start slug test
5 Nov, 10:00 finish slug test
7 Nov, 22:00 start 1st pre-FIT
10 Nov, 18:27 a first signal of ORP and DO in chemical measurement
12 Nov, 08:30: finish 1st pre-FIT, temperature measurement at hole B
13 Nov, 21:34: a second signal of ORP and DO in chemical meaurement
15 Nov, 10:50 increase turbidity
17 Nov, ~19:00 water flood at hole A

23 Jan, 18:25 start 2nd pre-FIT
24 Jan, 13:05: electricity power failure
27 Jan, 01:00: decrease CH4 gas, peak turbidity
31 Jan, 11:30: pressure release, temperature measurement at hole B

Ftype: Nov. #13, Dec., None, Jan. #13

2006/11/20 11:00 Z-Comp (1 sec record)

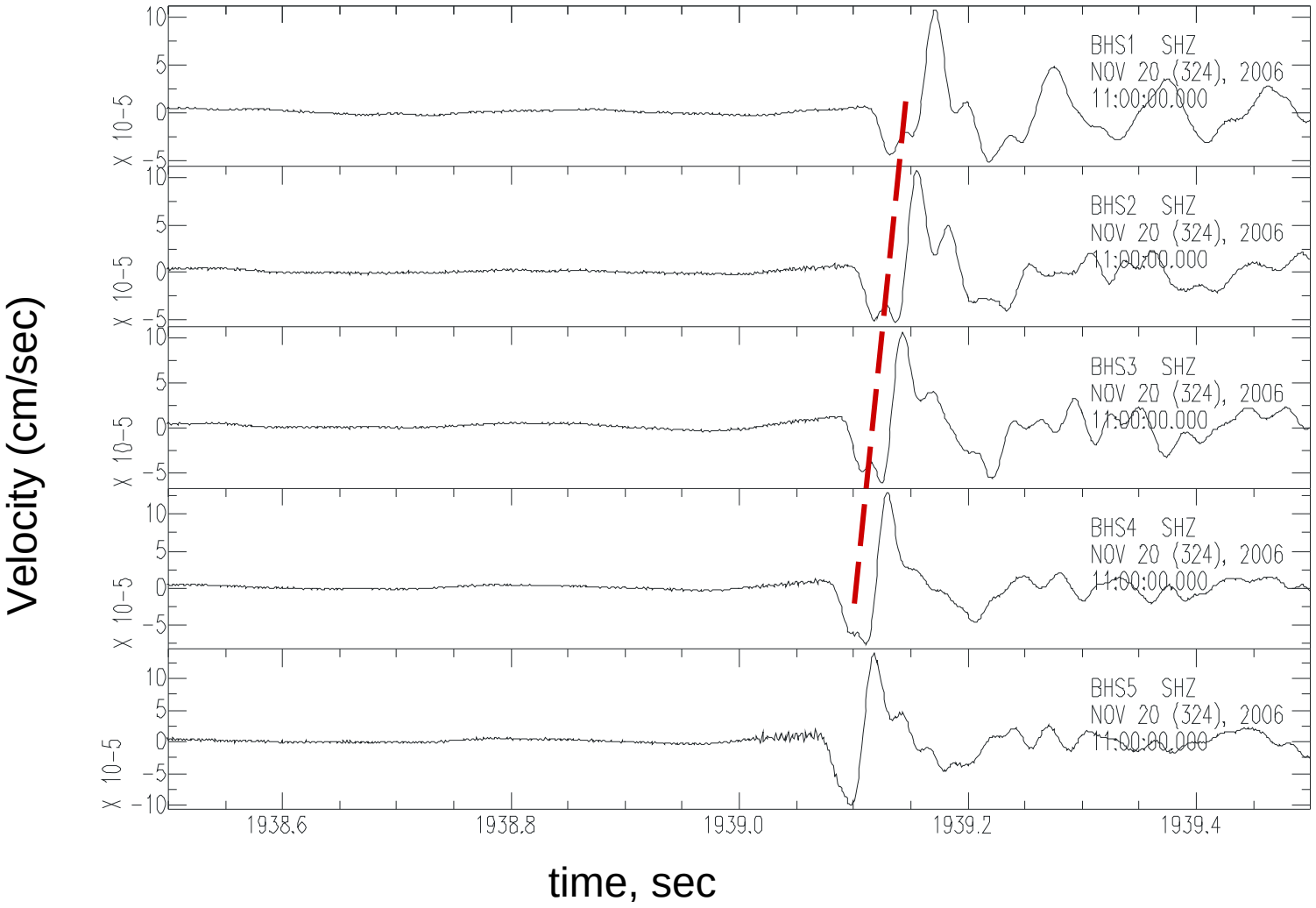
Downward first motion with small arrivals



2006/11/20 11:00 Z-Comp (1 sec record)

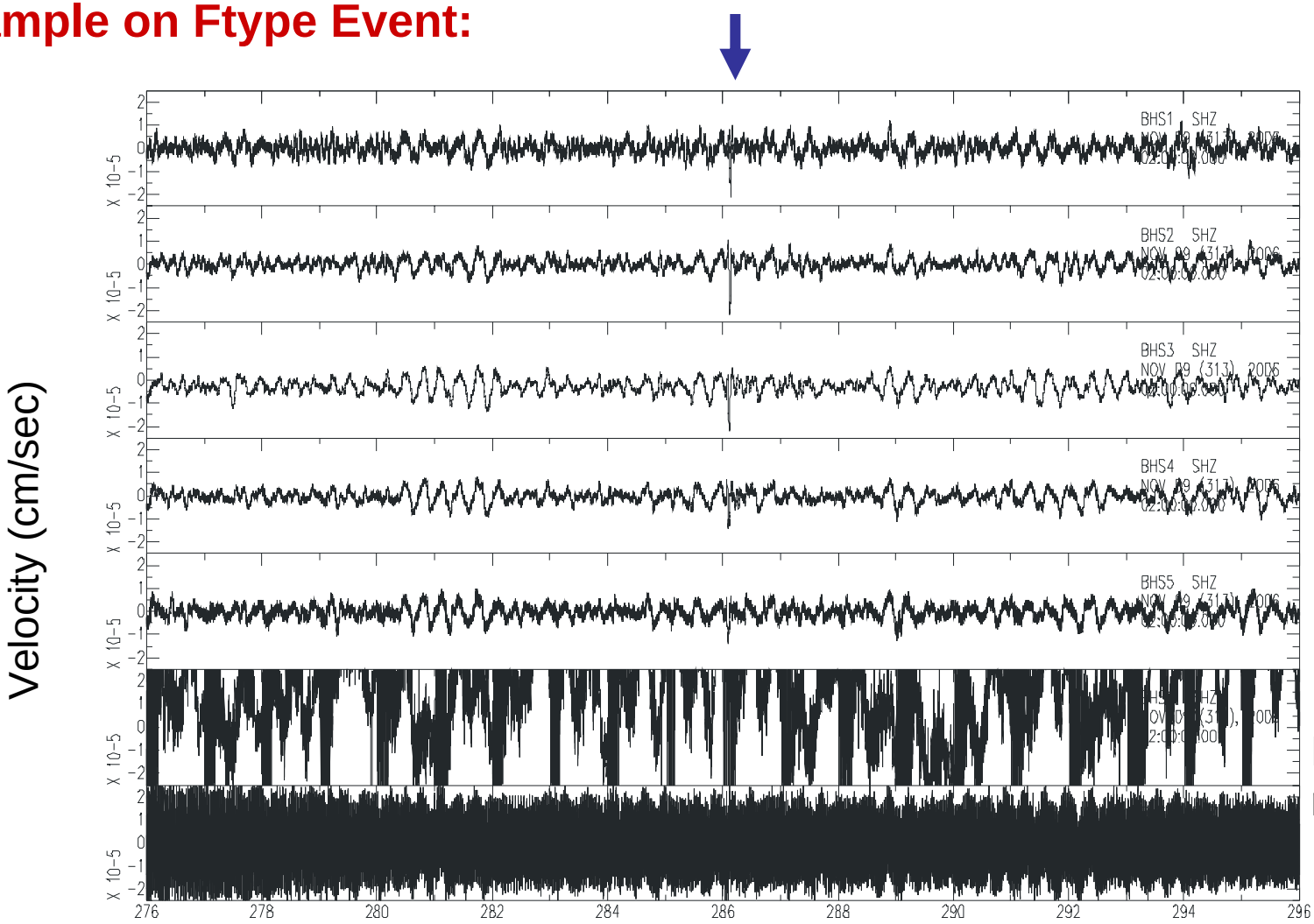
Downward first motion with LVZ head waves arrivals (?)

- Small arrivals for the BHS above fault zone (BHS 4,3,2,1)
- Most distinct for BHS3, and 2



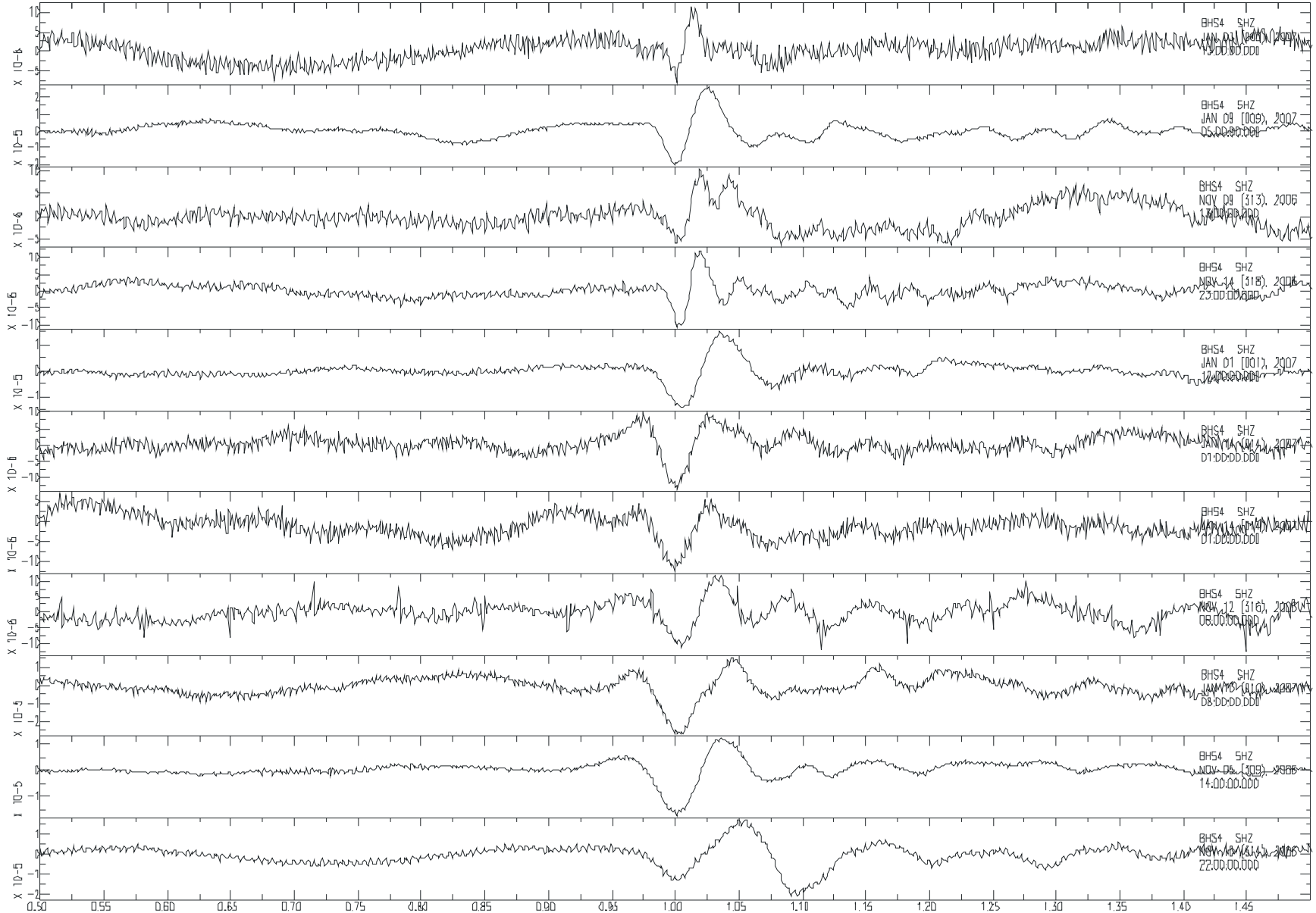
2006/11/09 02:00 Z-Comp (20 sec records)

Example on Ftype Event:



Function not properly

Downward phases at BHS4



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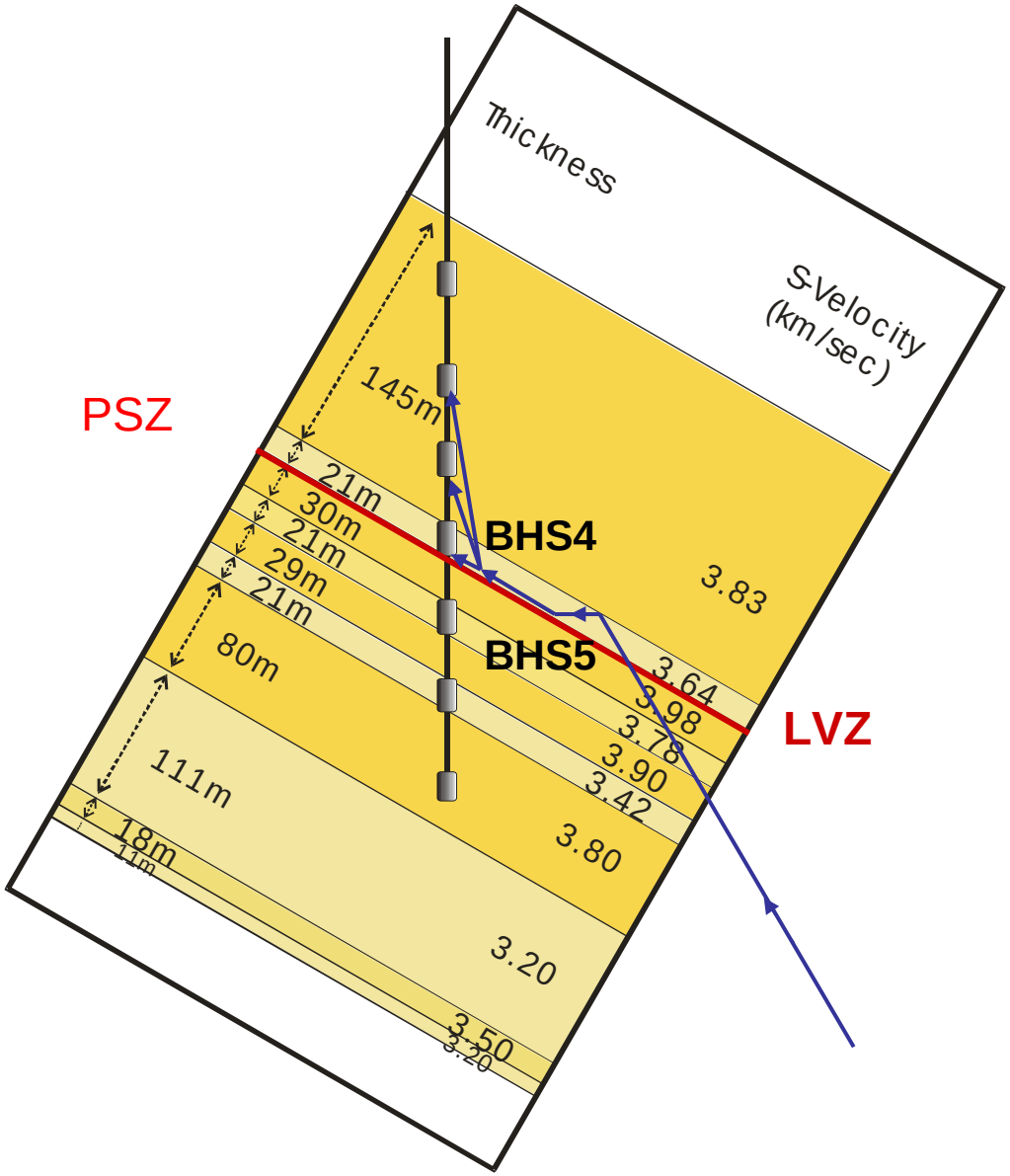
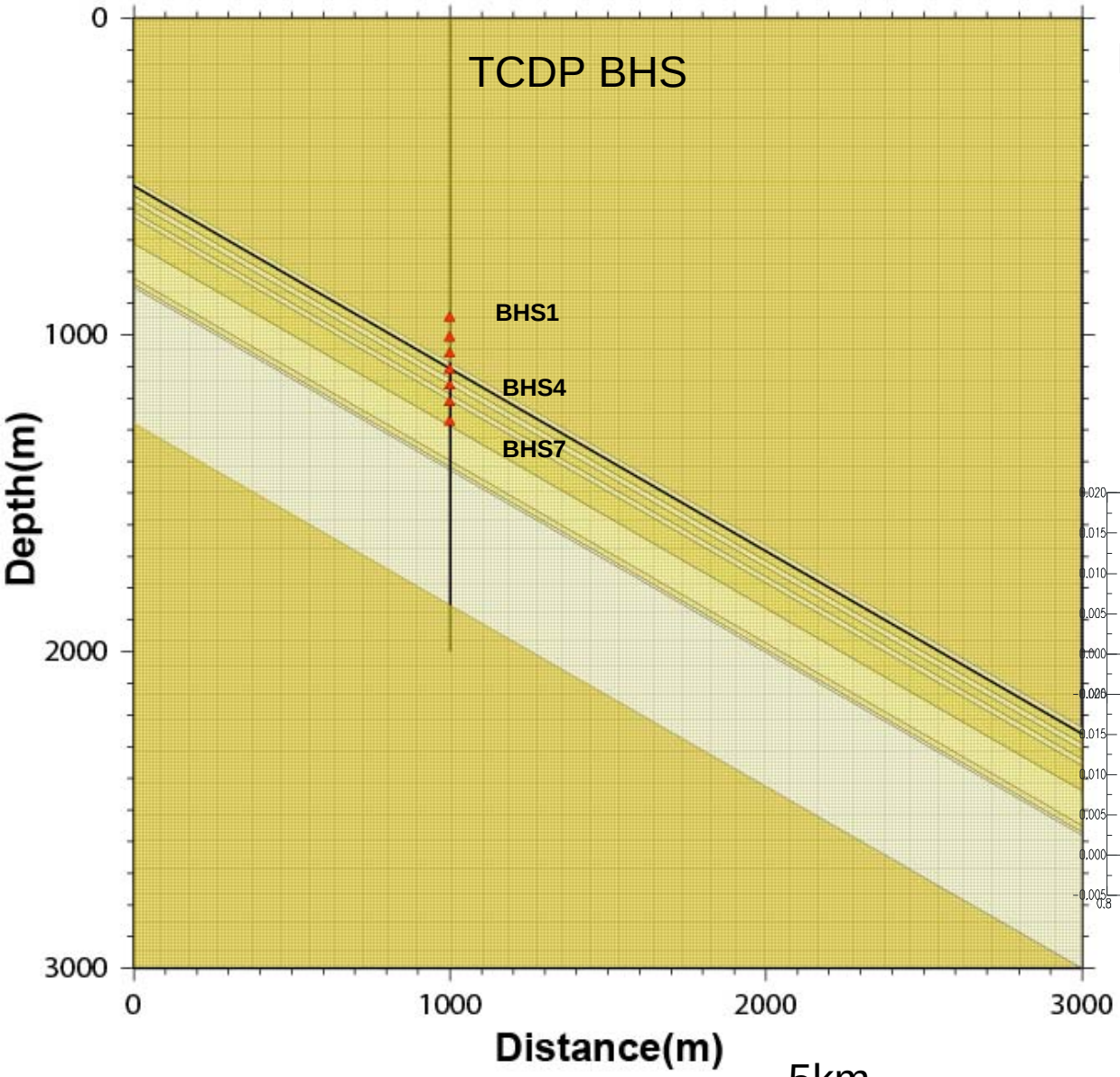


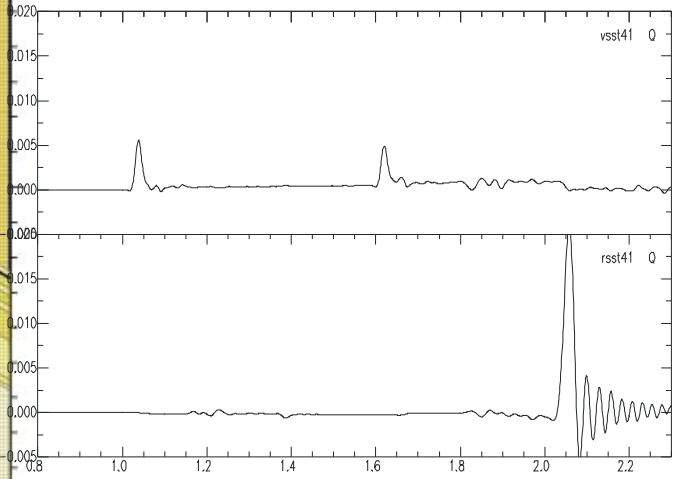
headwave phases (2 events) BHS4



Finite-Difference Modeling

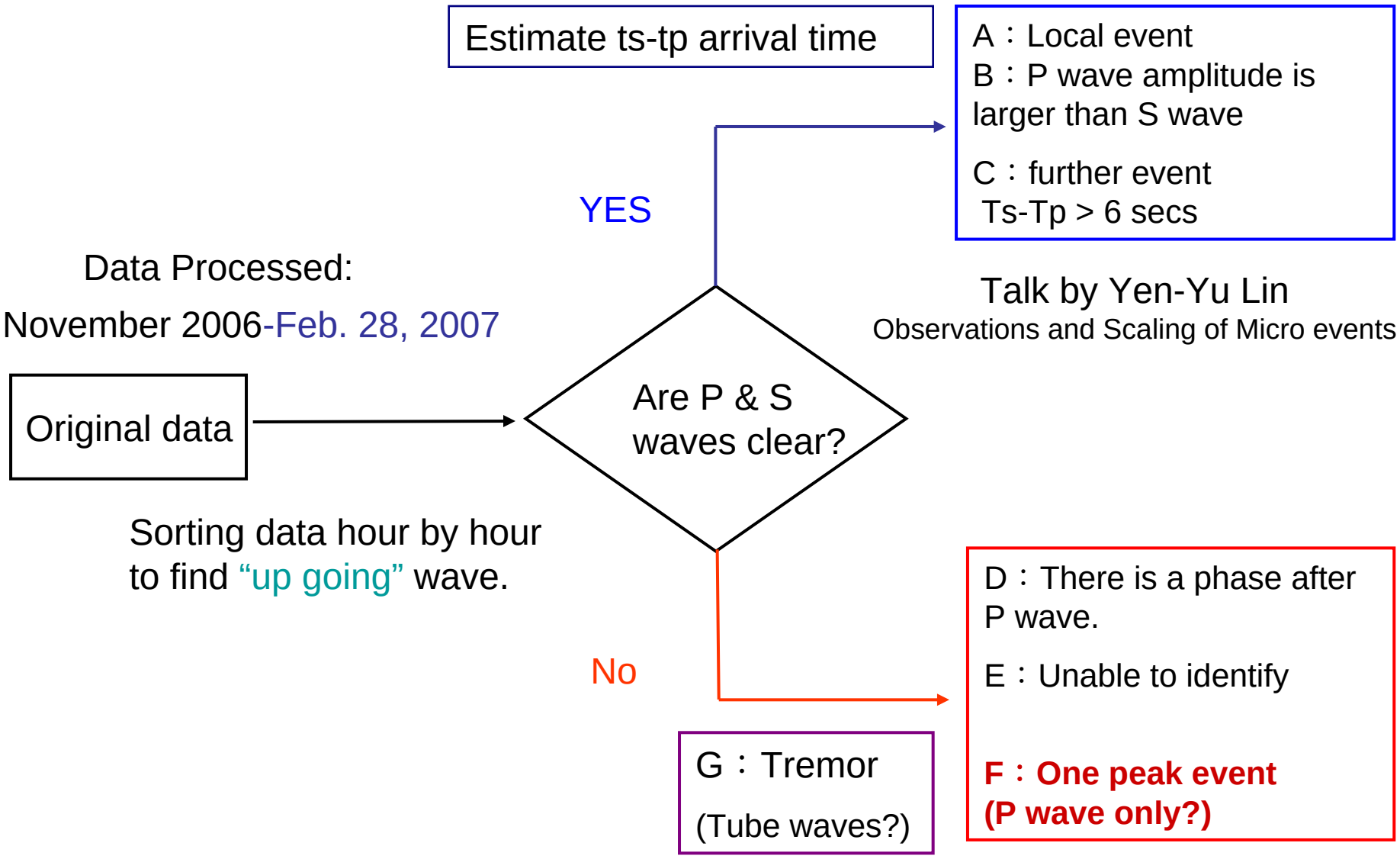
1km to the east to the TCDP
Depth 5km
Io at BHS4~(io at BHS4~

Strike0 dip30 rake 90



~ 5km

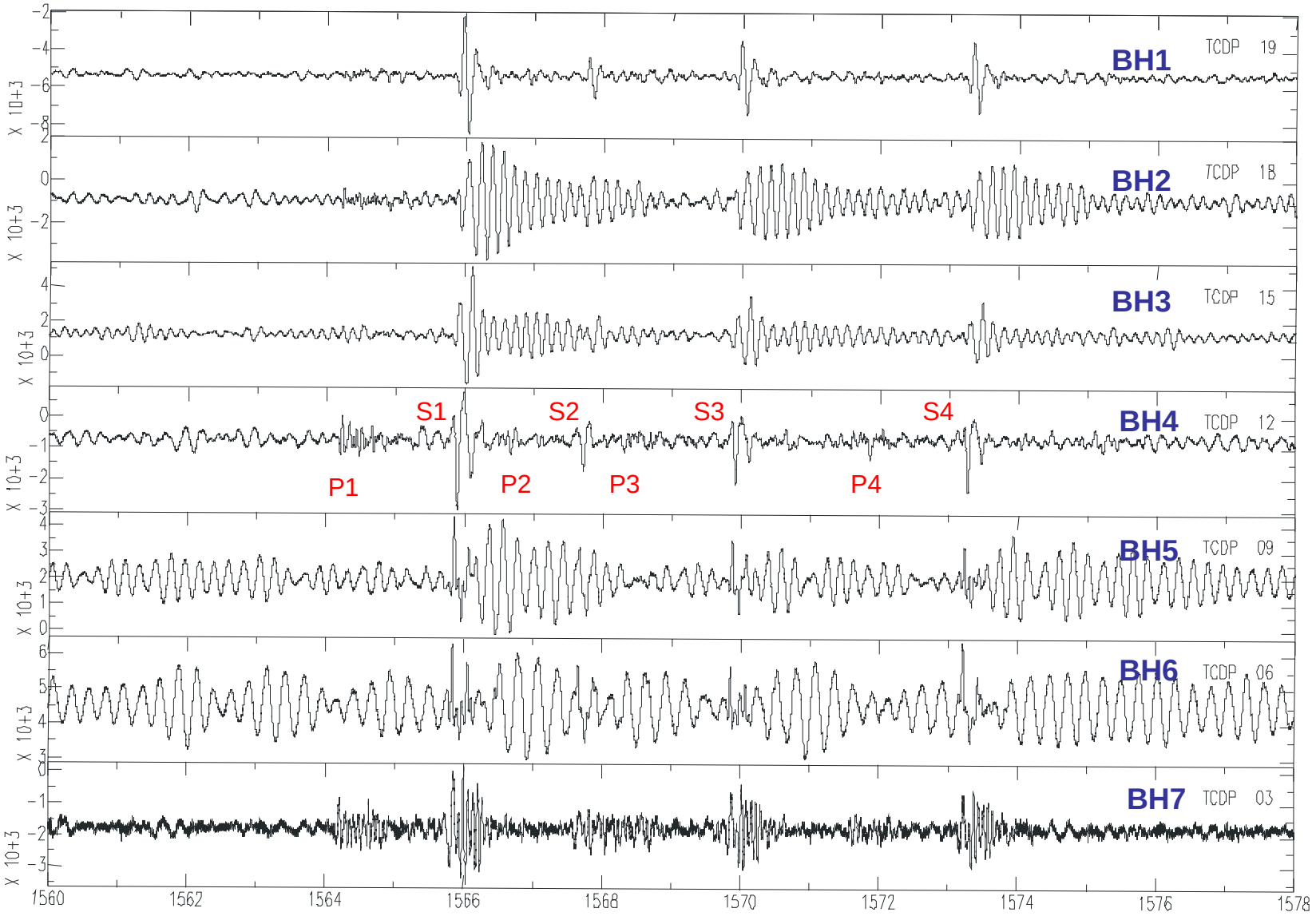
TCDP BHS Events Sorting



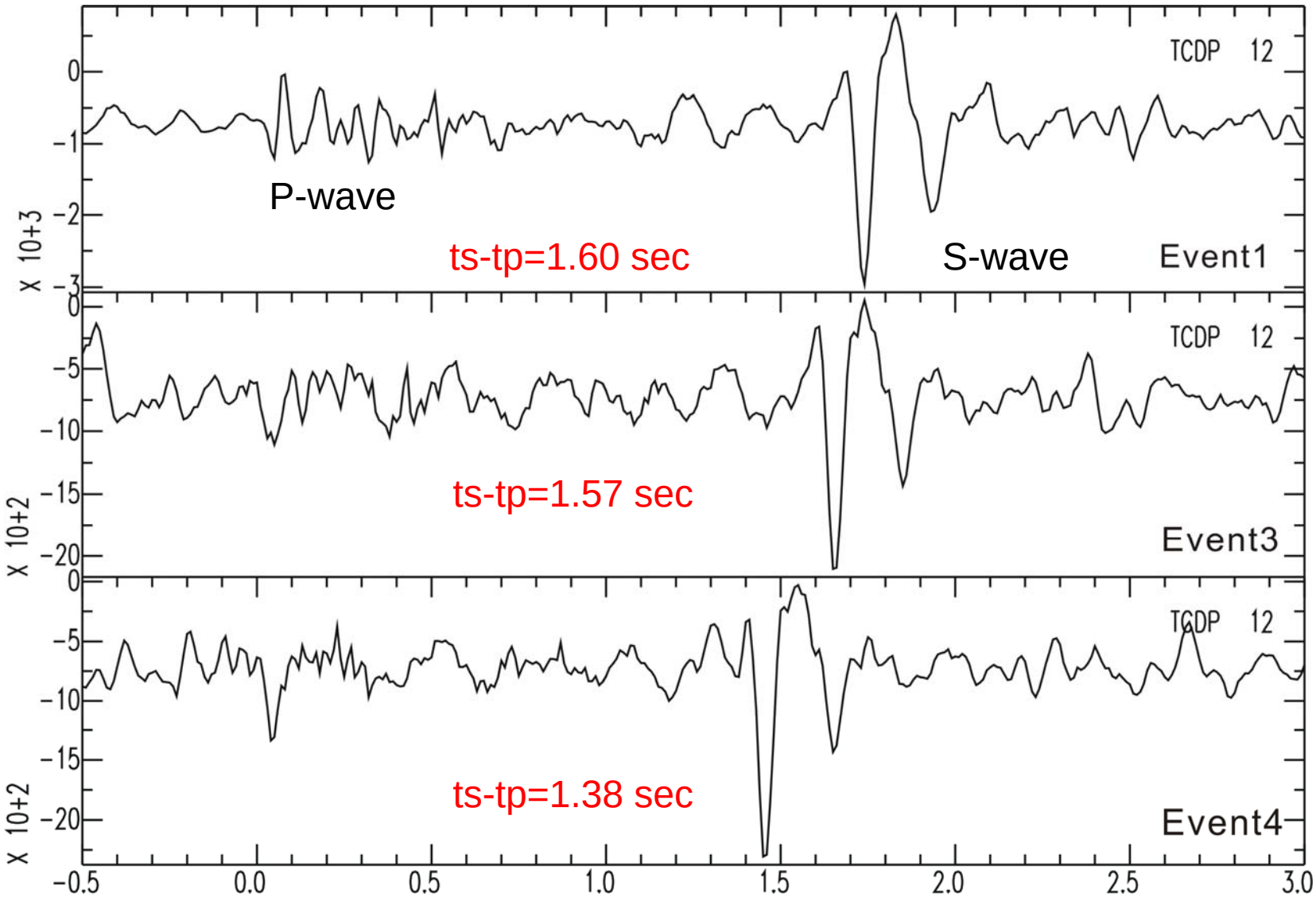
Observations of TCDP 7-level Borehole Seismometers (TCDP BHS)

- Various types of events
  - Regular earthquakes
  - Repeating events
  - Open Cracks Events

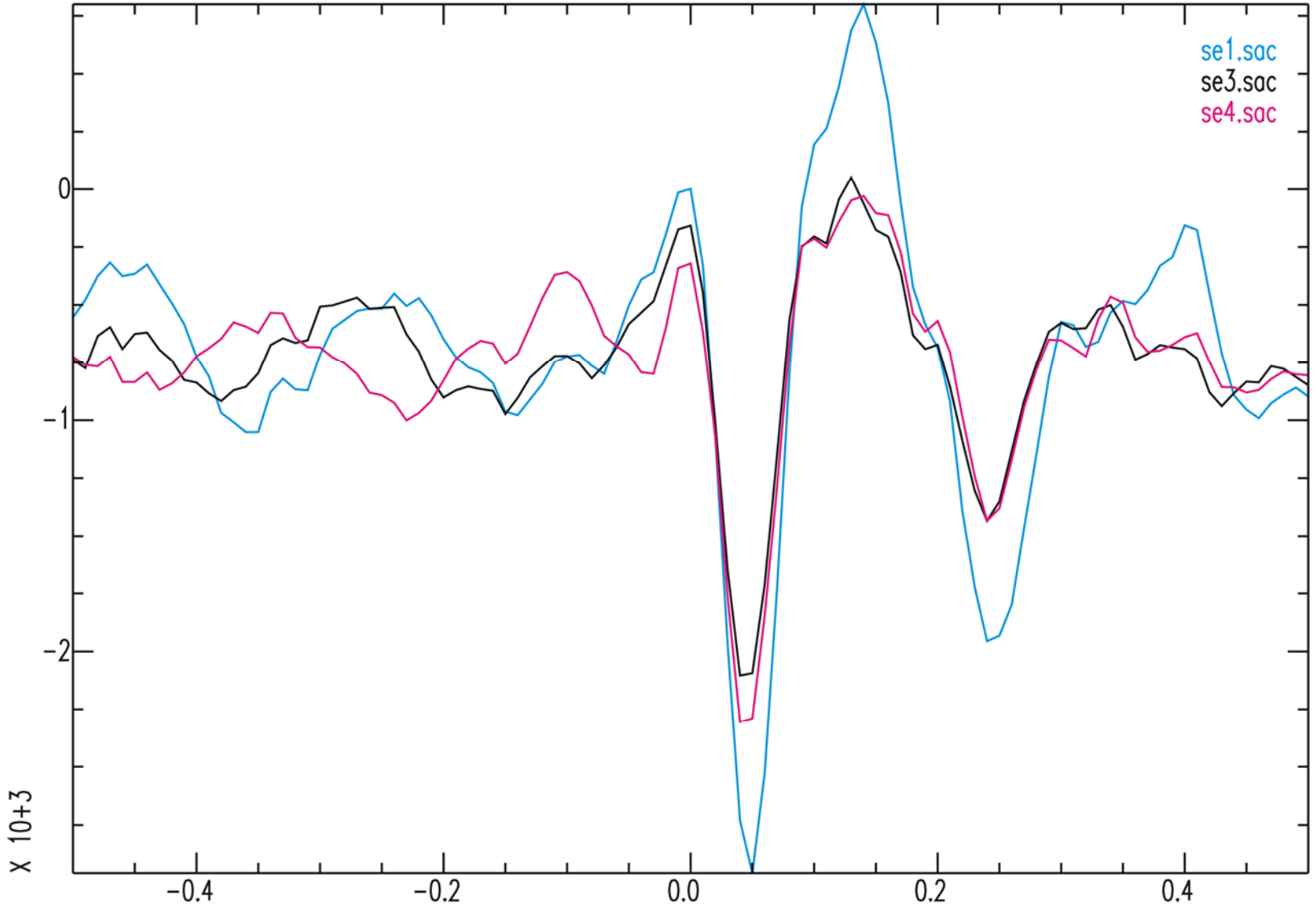
repeating events: events 1, 3 & 4



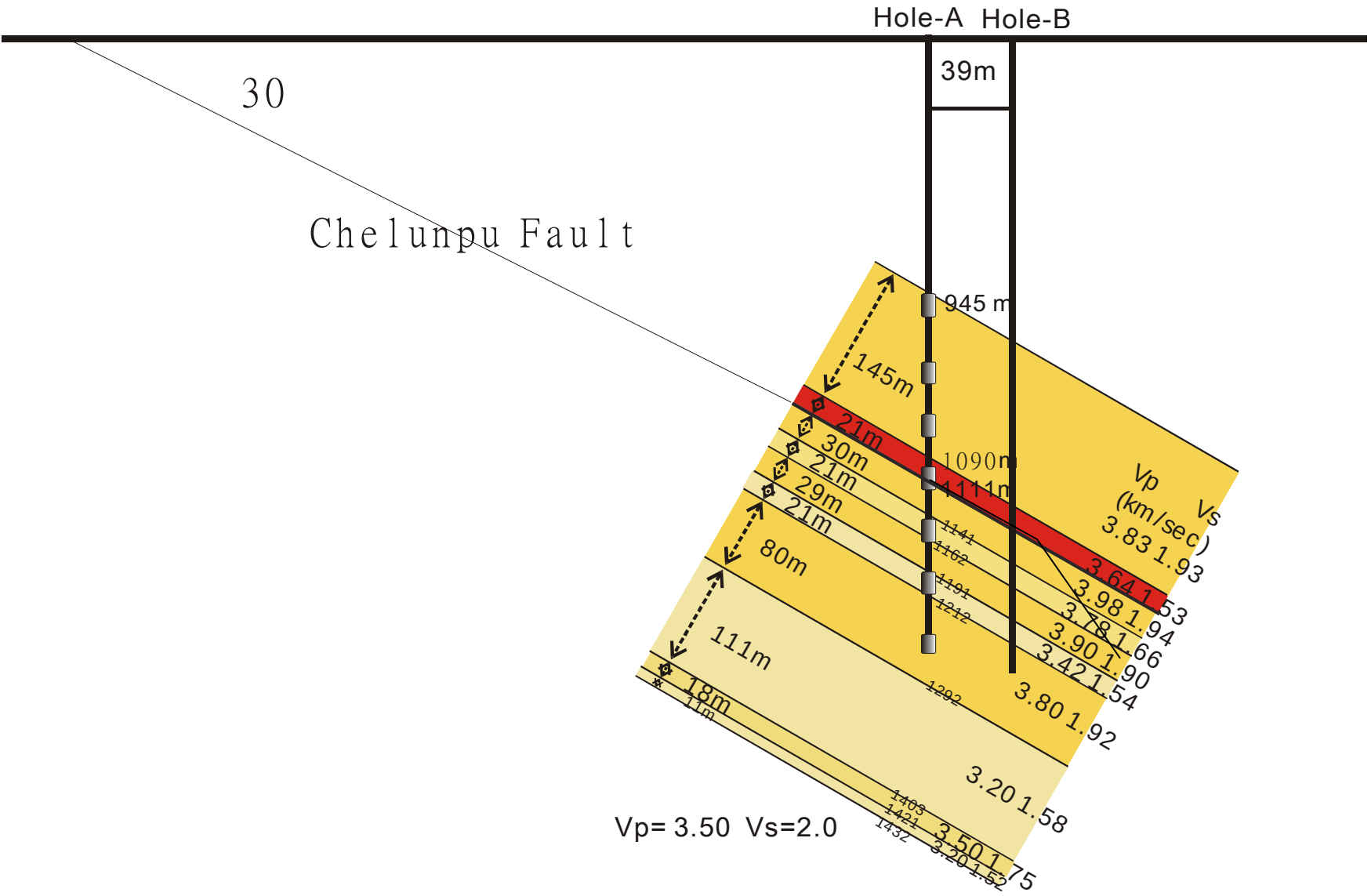
TCDP BHS 4 for events 1, 3 & 4



TCDP BHS 4: S-waves of events 1,3 &4



Fault Zone Velocity Structure from Loggings

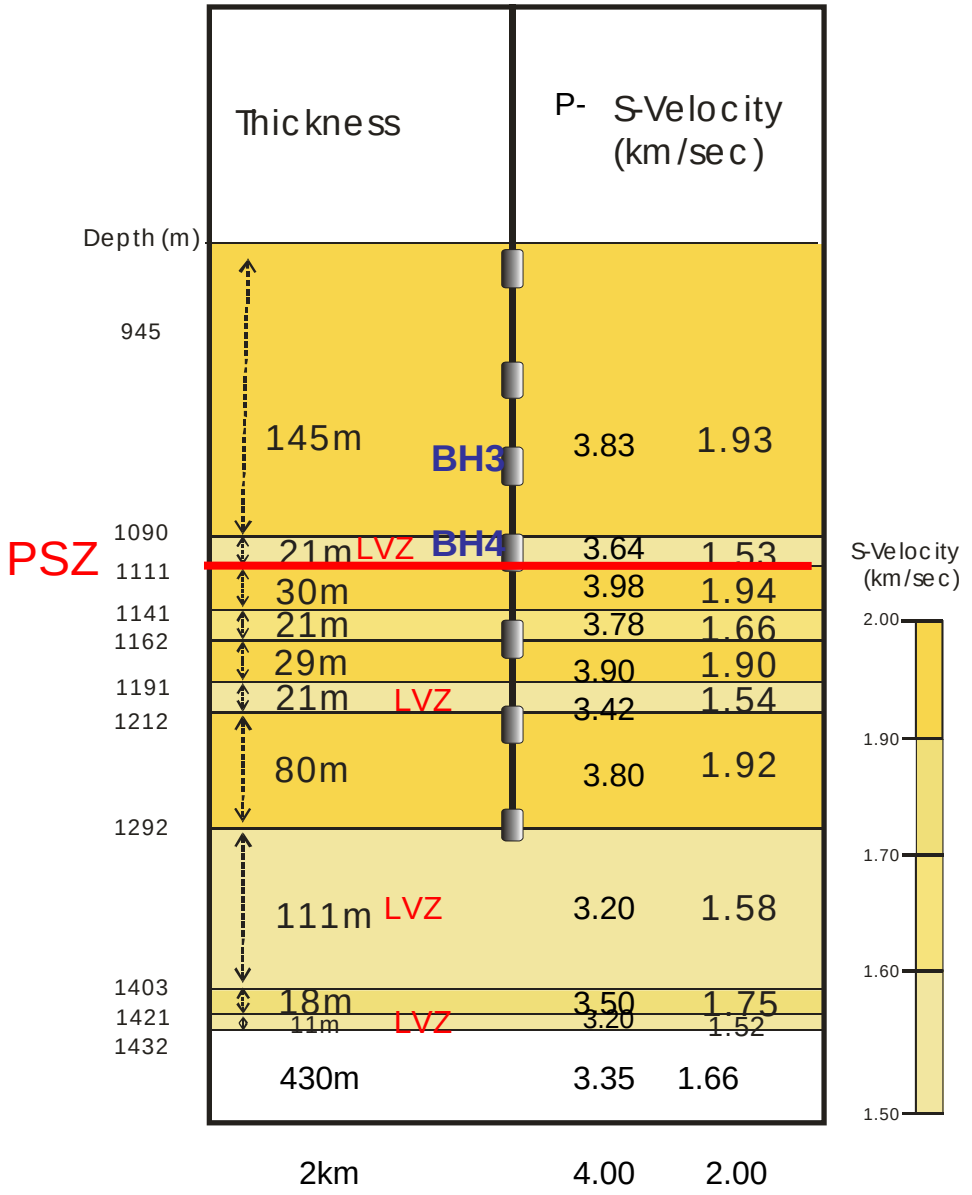


Velocity Structure in the Fault Zone

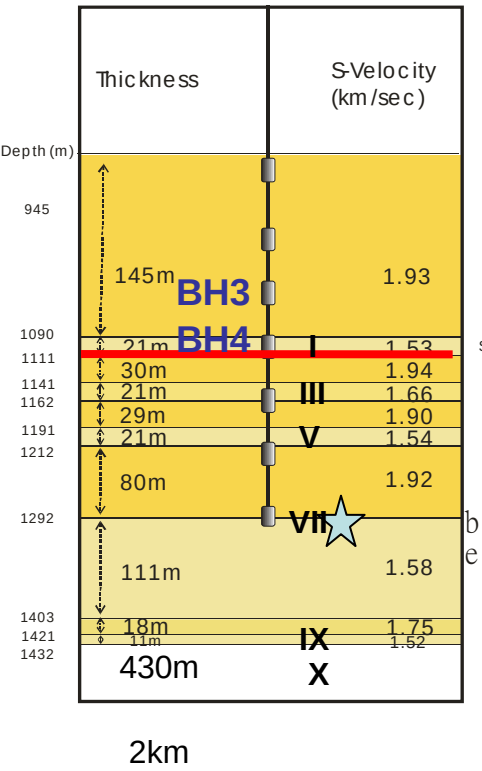
Low Velocity Zone,
Vp~3.20-3.40 km/sec
Vs~1.50-1.60 km/sec

Transition zone
Vp~3.50-3.70km/sec
Vs~1.66-1.75 km/sec

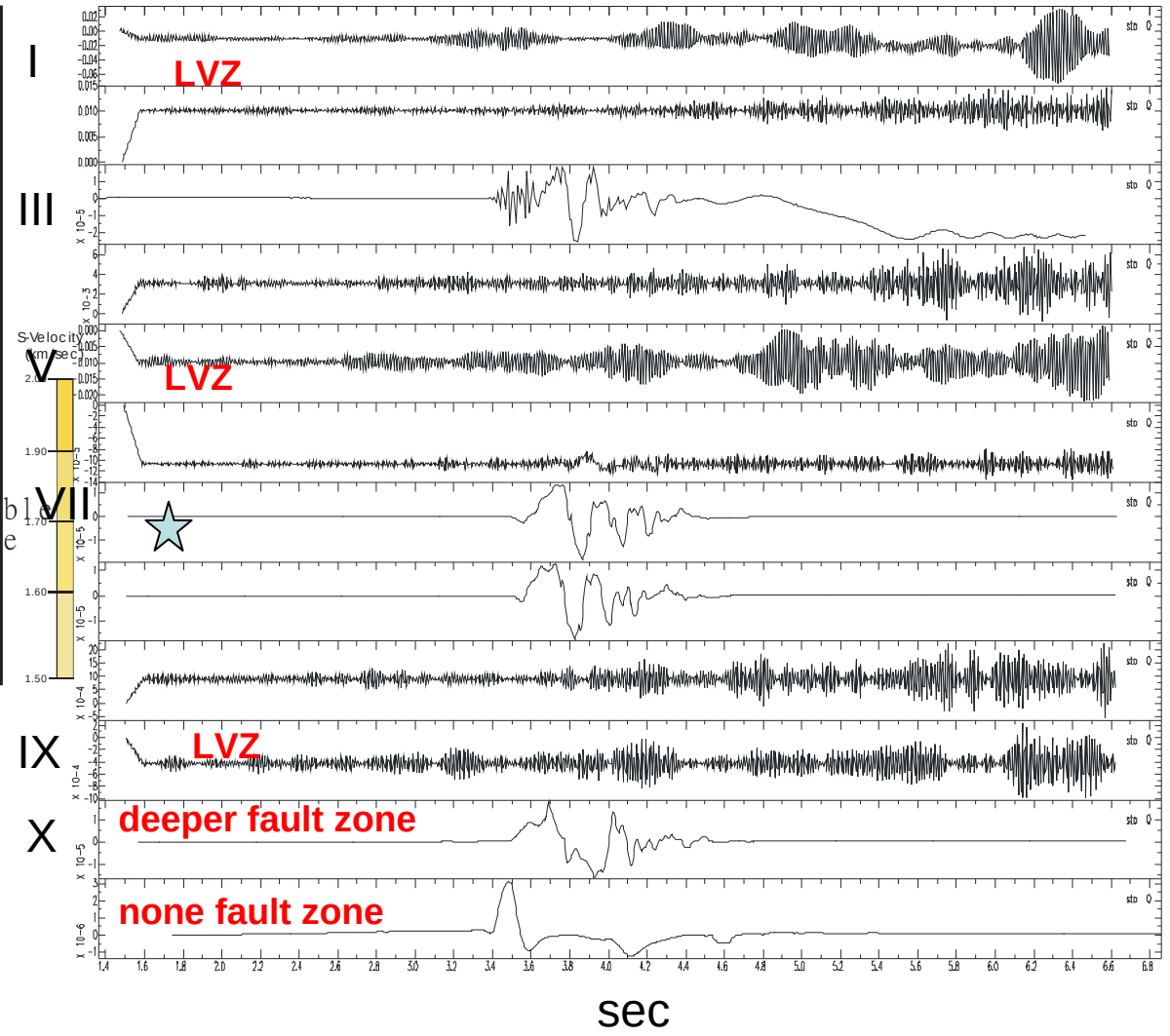
Host Rock
Vp~3.80-4.0 km/sec
Vs~1.90-2.00 km/sec



FK Synthetics (5.12 sec time series)



Source

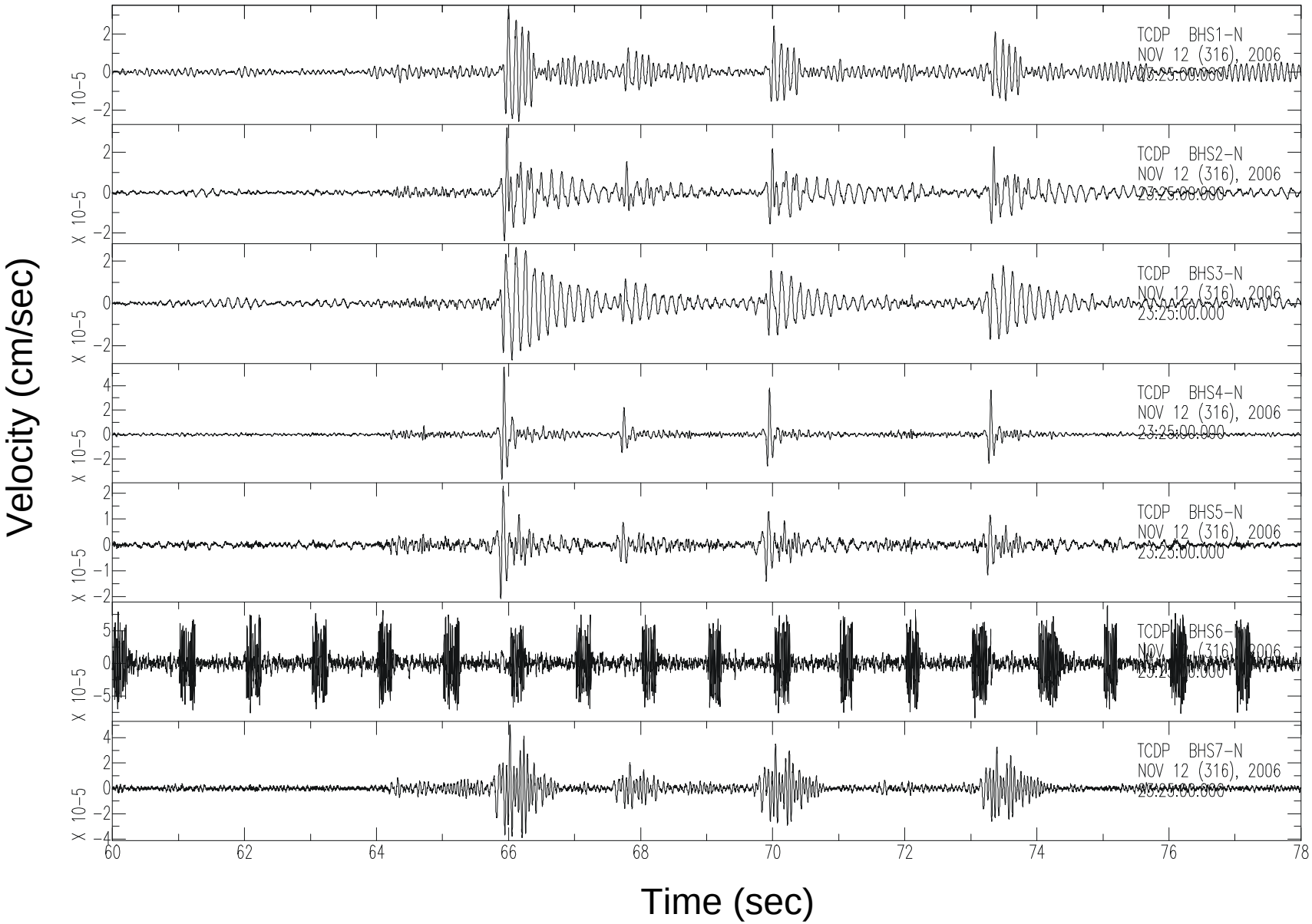


depth (km) from BH3

0.04
0.066
0.091
0.117
0.141
0.192
0.235
0.287
0.352
0.368
0.645
2.0

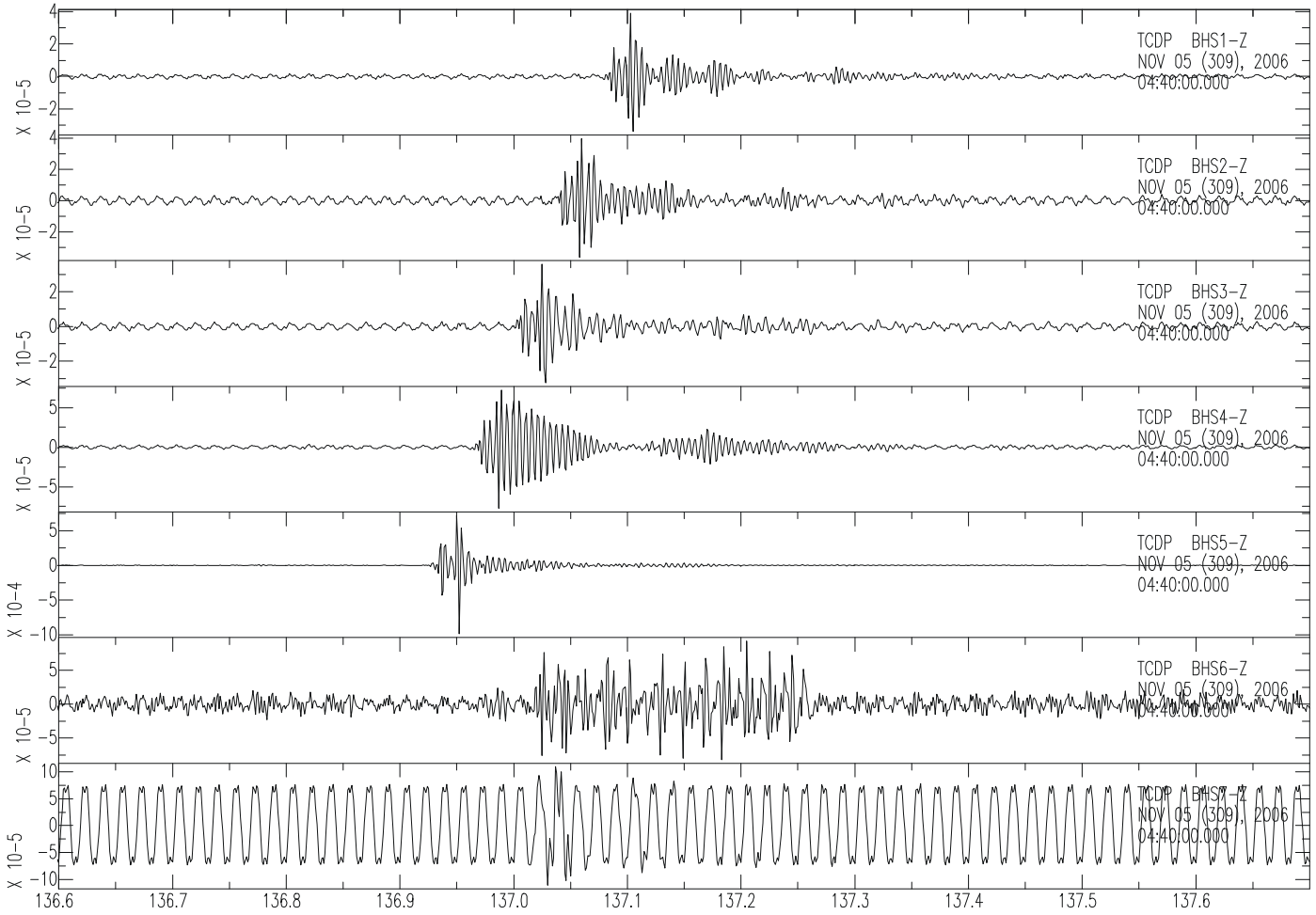
2006/11/12 23:25 N-Comp Bp 10 100

Repeating events from Fault Zone

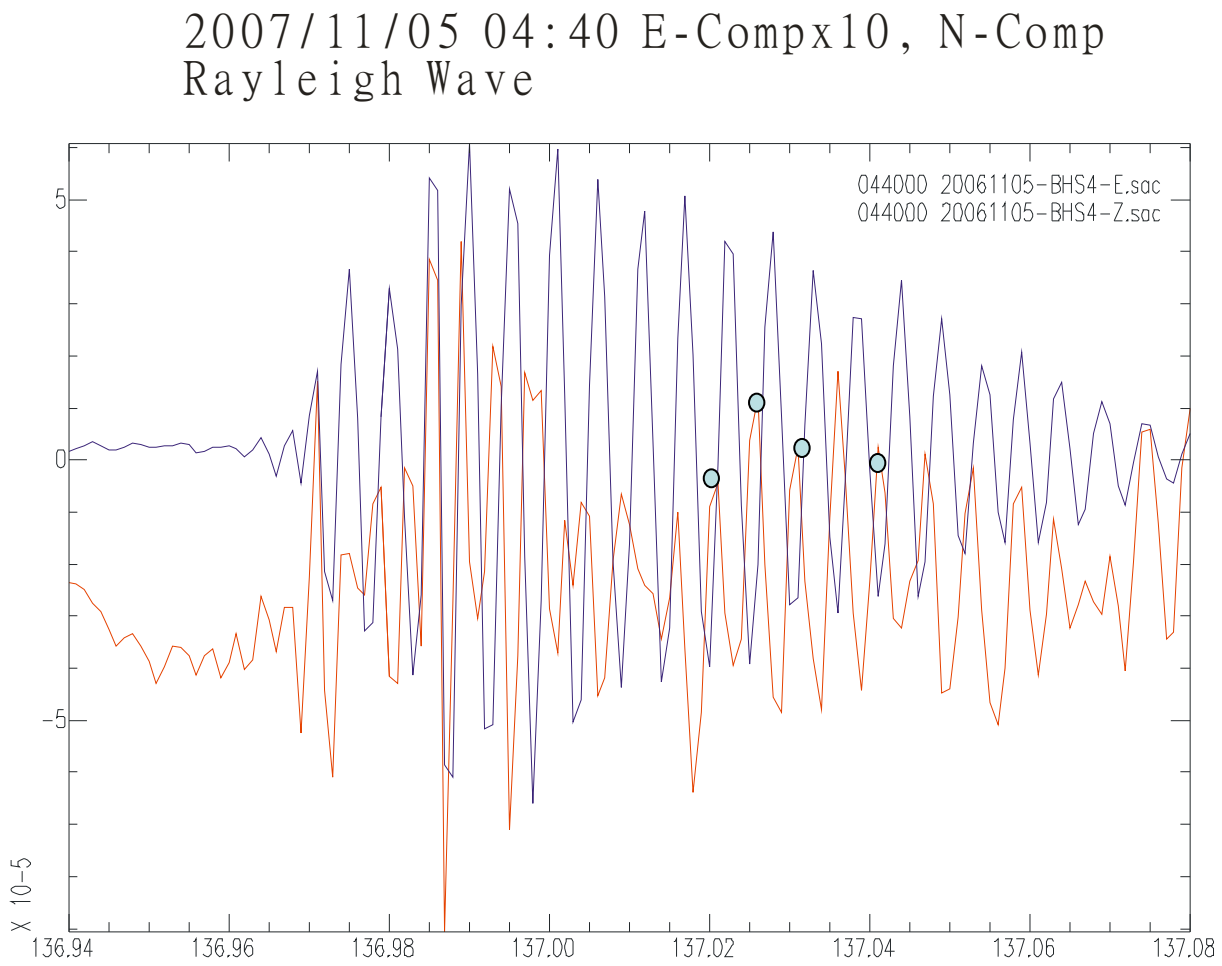


2006/11/05 04:40:00 Z-Comp/ Hp 100 Hz

First Arrival at BHS5

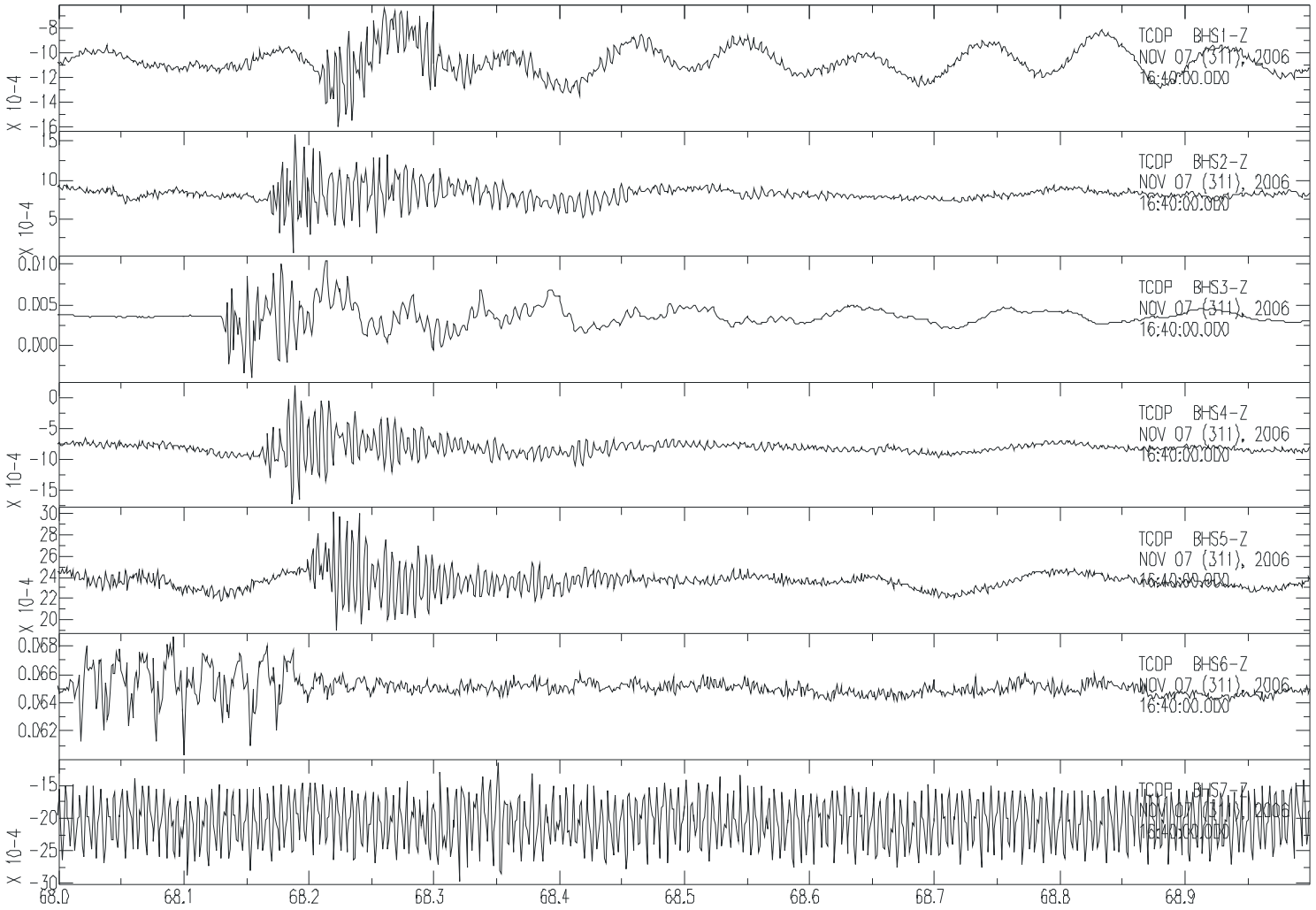


90 degree phase shift: Rayleigh Wave V_R~0.92β



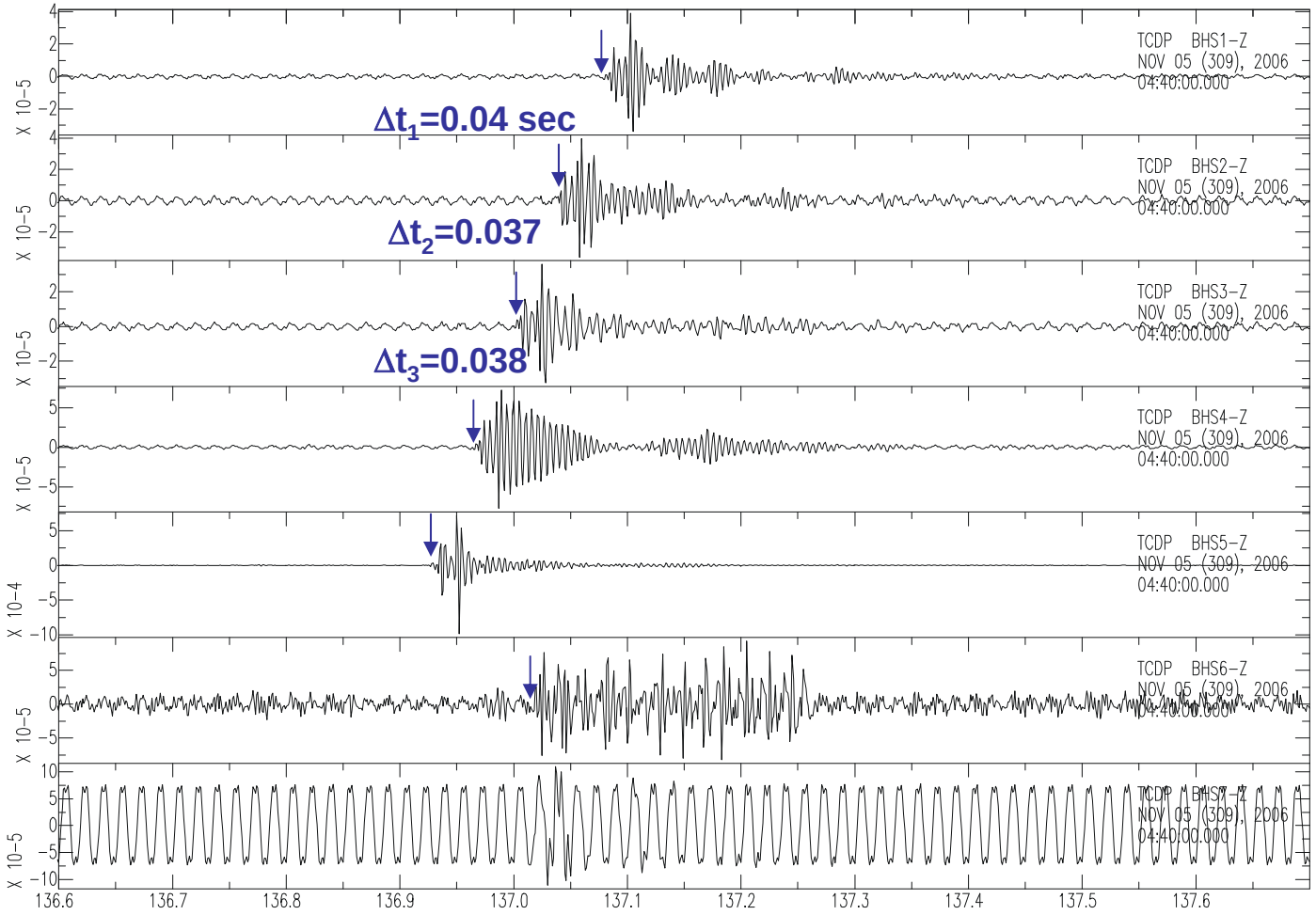
2006/11/07 16:40:00 Z-Comp

First Arrival at BHS3

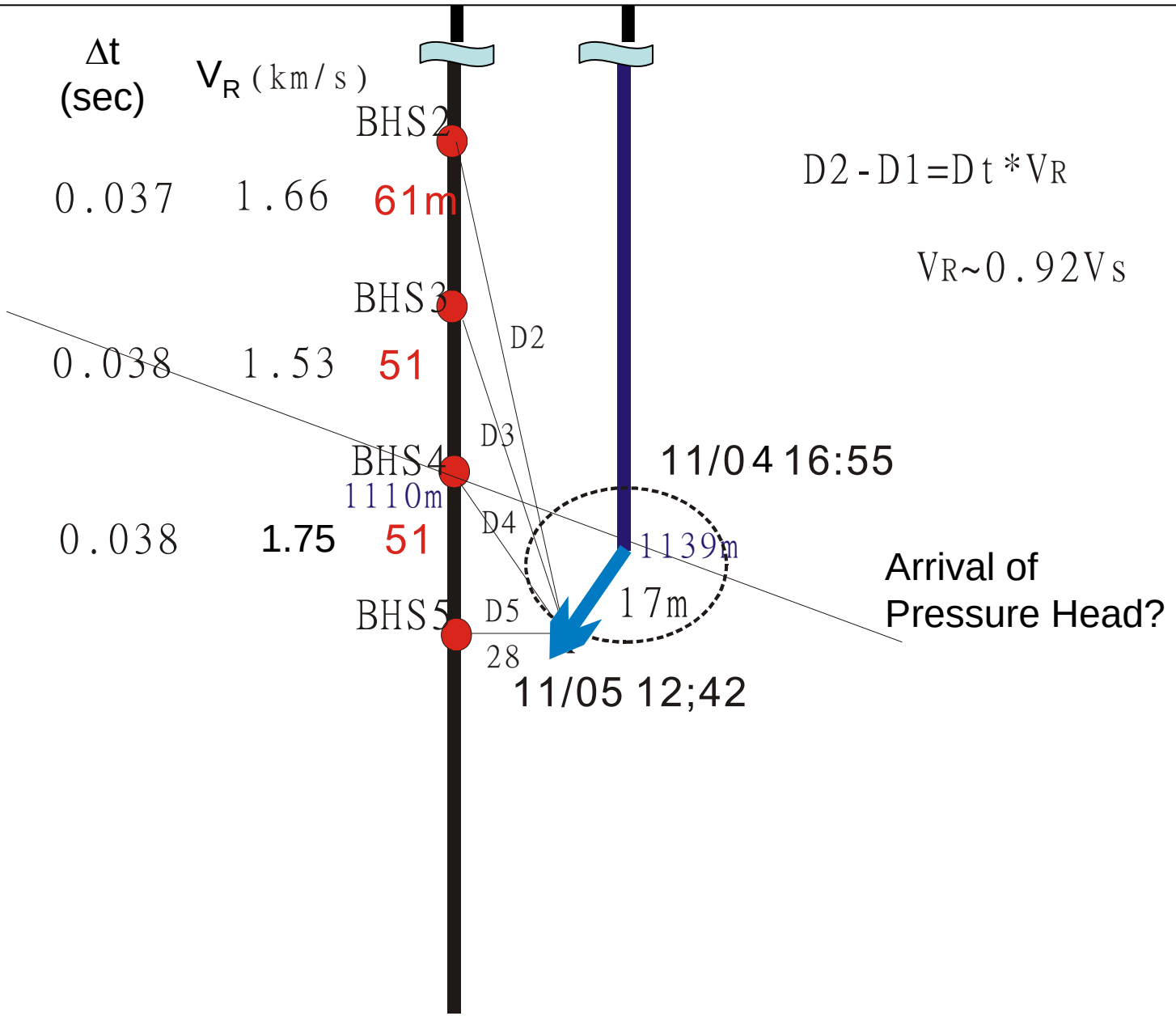


2006/11/05 04:40:00 Z-Comp/ Hp 100 Hz

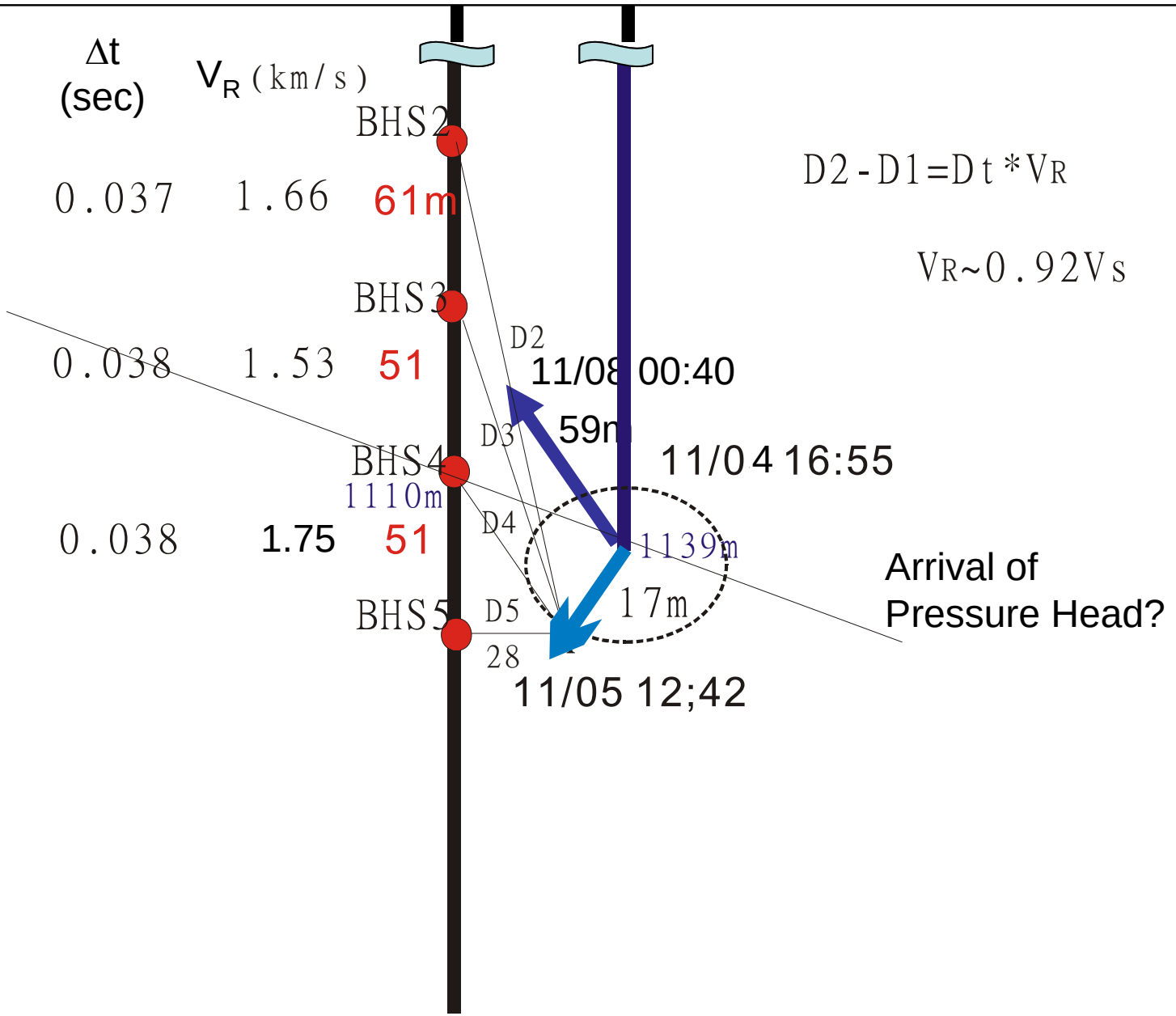
First Arrival at BHS5



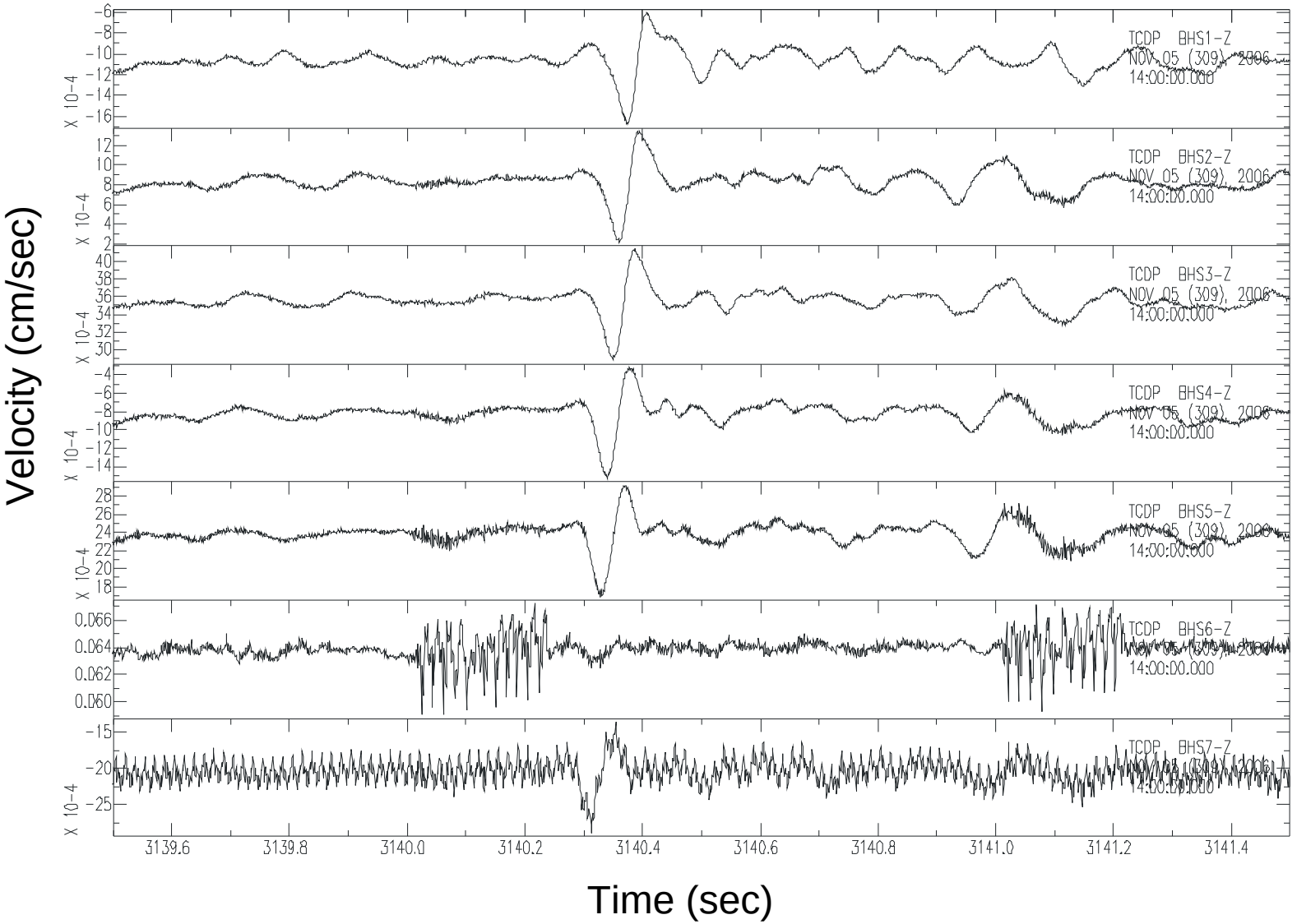
Configuration



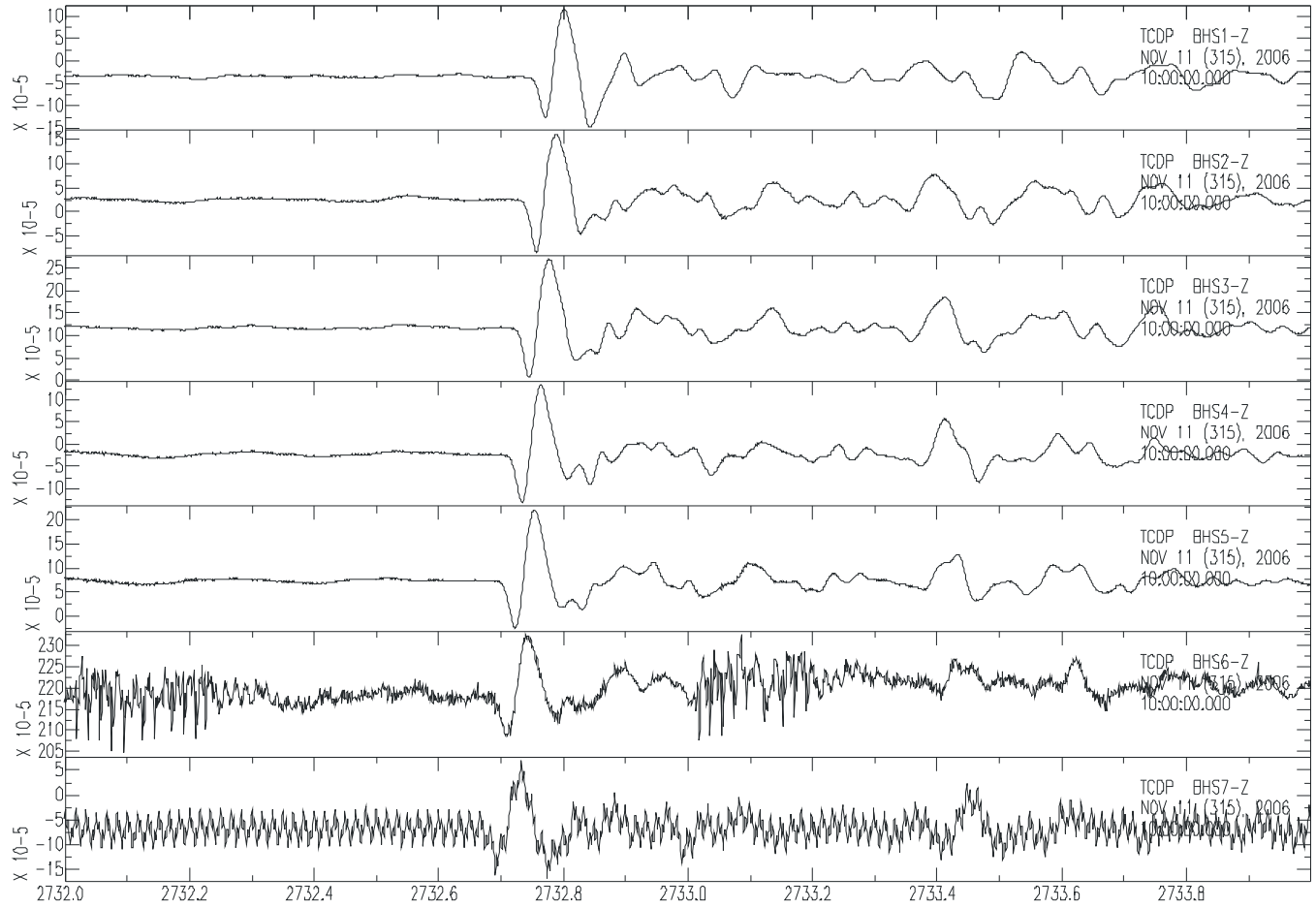
Configuration



New Open Cracks from FIT?

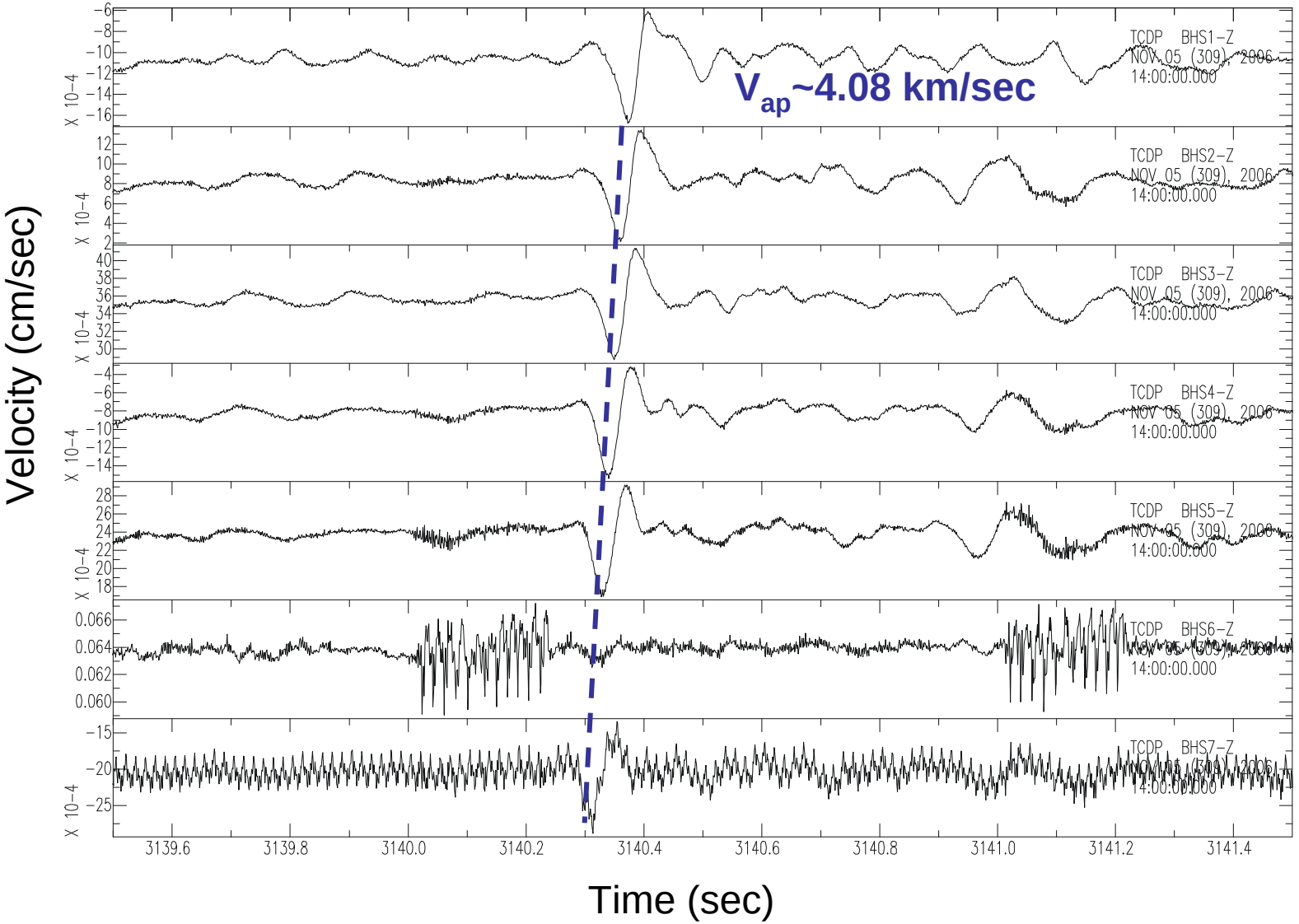


2007/11/11 1000 Z-Comp Ftype

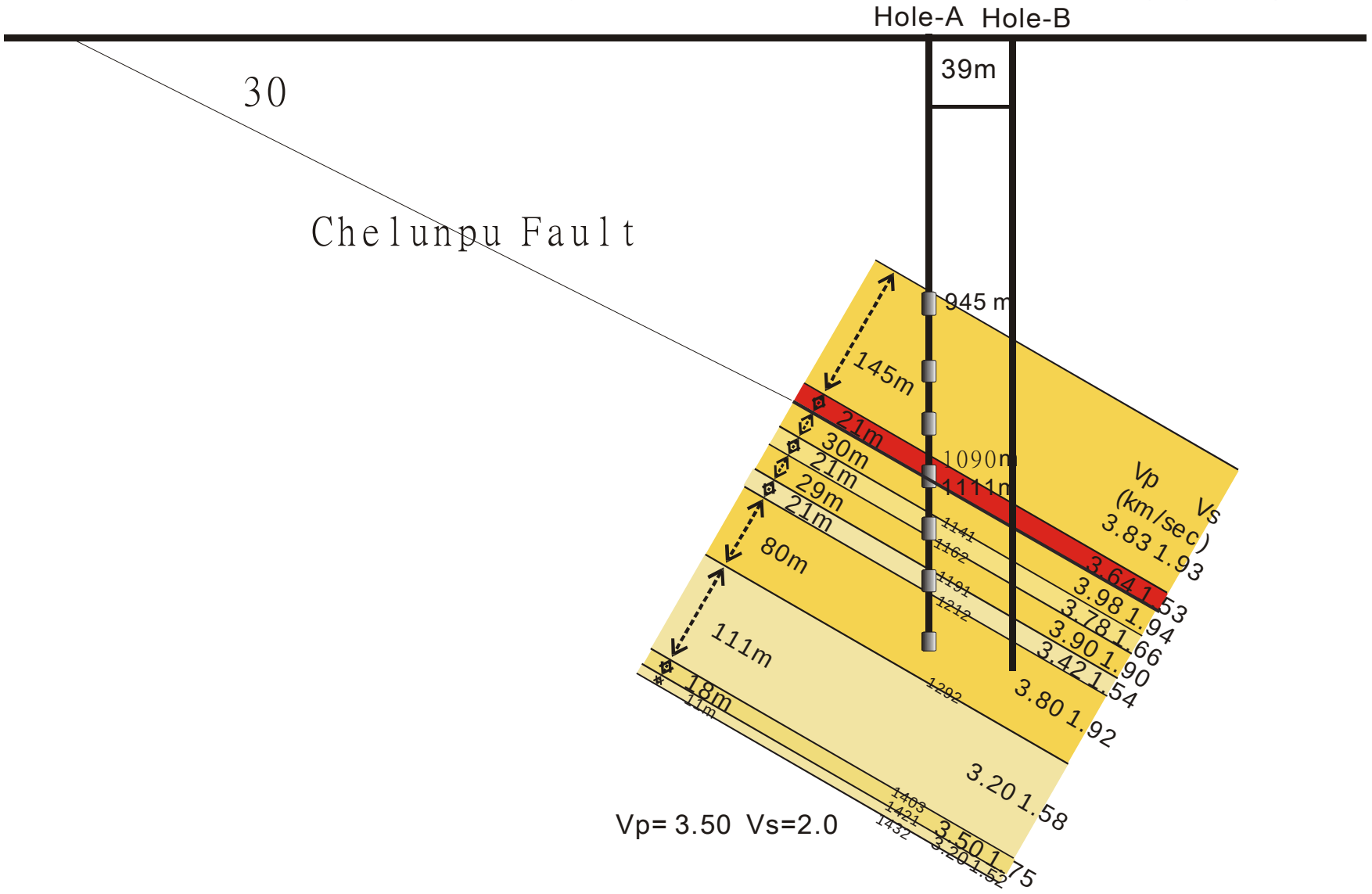


New Open Cracks from FIT?

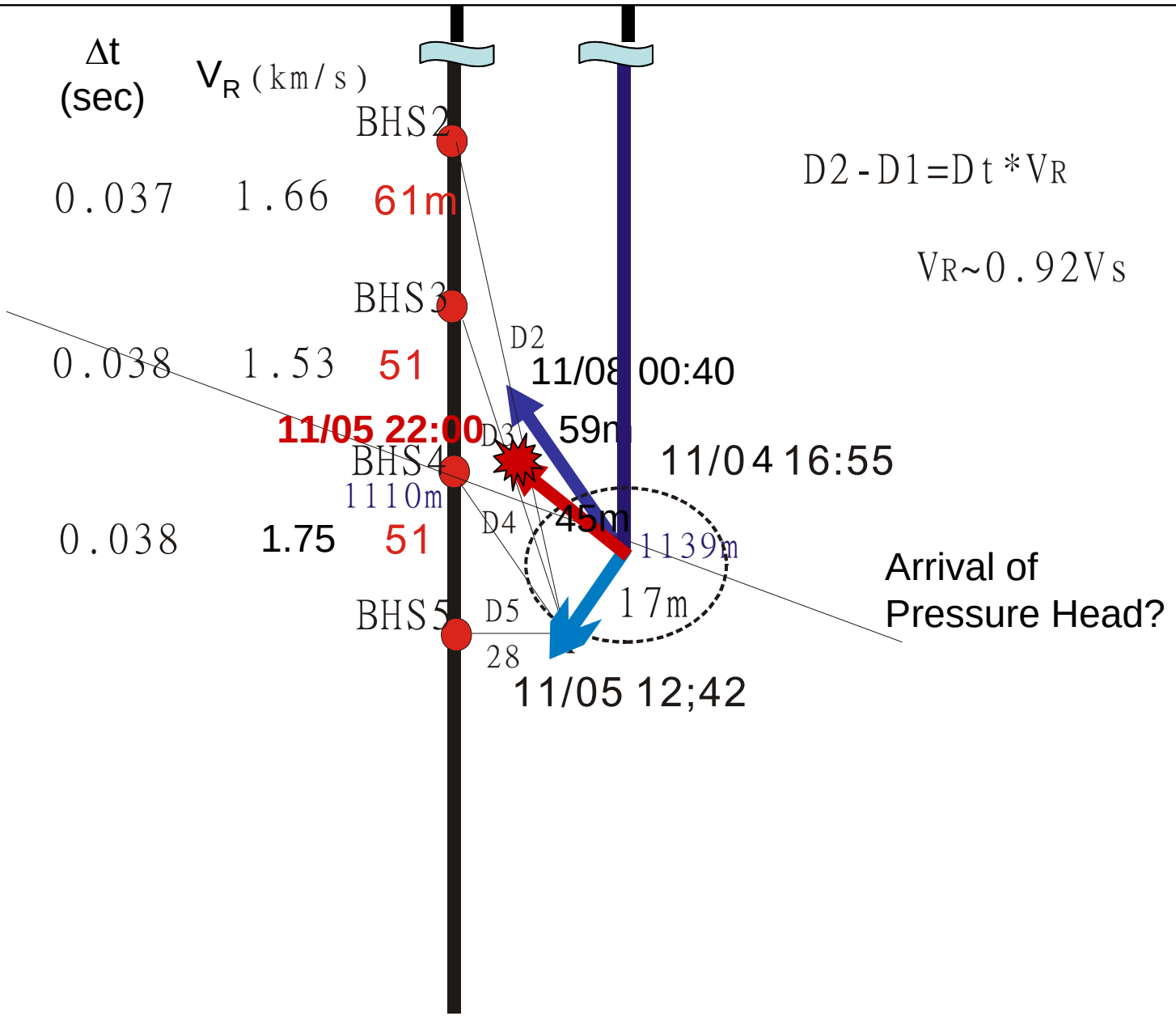
2006/11/05 3140sec Z-Comp Ftype



Fault Zone Velocity Structure from Loggings



Configuration



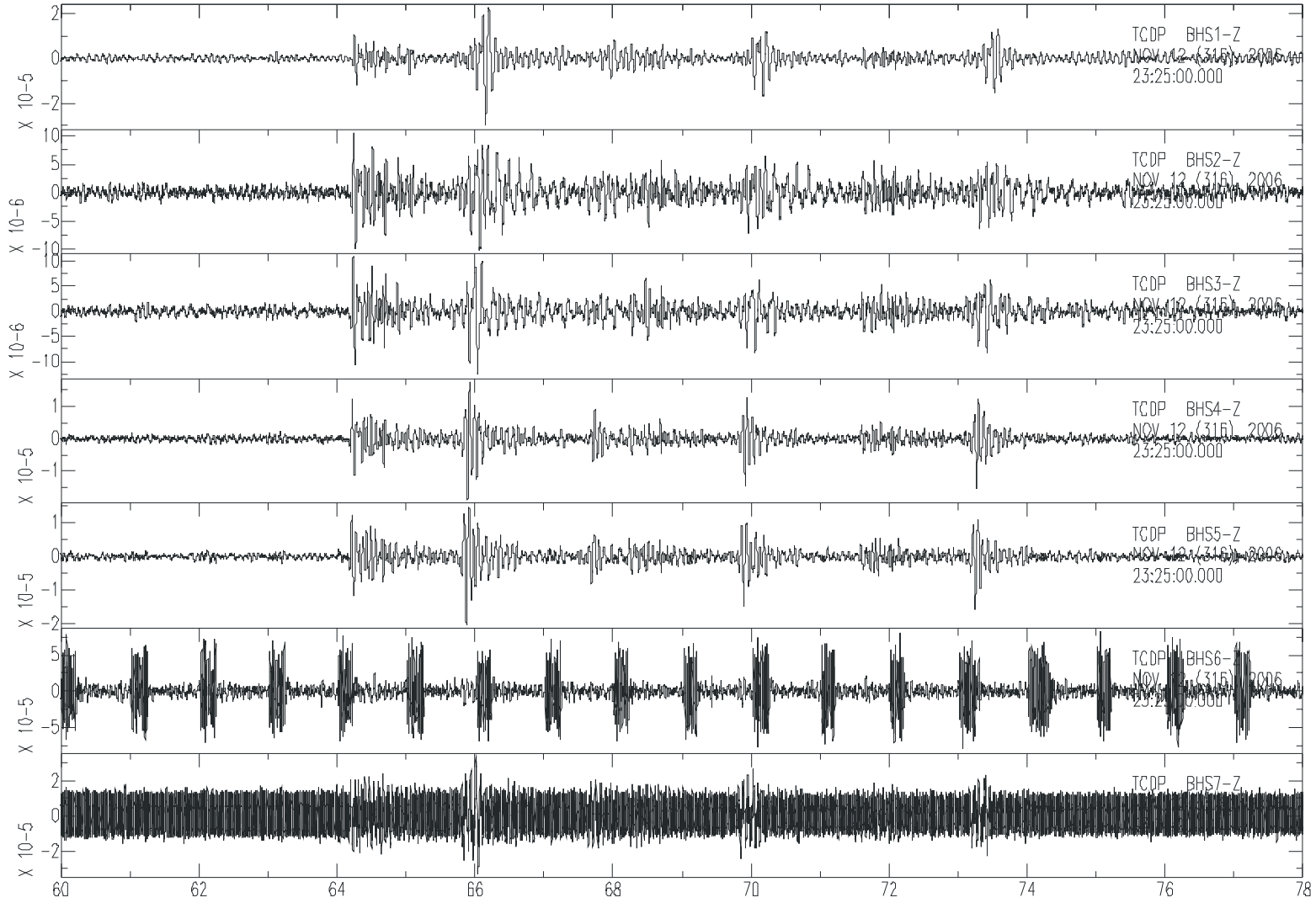
Conclusions

- Repeating events from fault zone were observed showing similar waveforms

  (delay in time, propagating cracks?)
- Possible FIT related fault zone tremors were identified as surface waves. It might triggered by the passage of the pressure head from FIT
- New open cracks were formed during FIT. Only P-wave was formed without S wave. Understanding of earthquake nucleation.
- The relationship of the locations of the micro tremors and open cracks to the FIT will be examined along with gas/chemical and pressure observation of FIT for understanding of in-situ fault zone hydraulic property.

- Thank You for your attention

2006/11/12 23:25 Z-Comp. Bp 10 100



wrong

2006/11/05 2000 1760sec Ftype Z-Comp