Outer-rise Earthquakes
-Some Implications-

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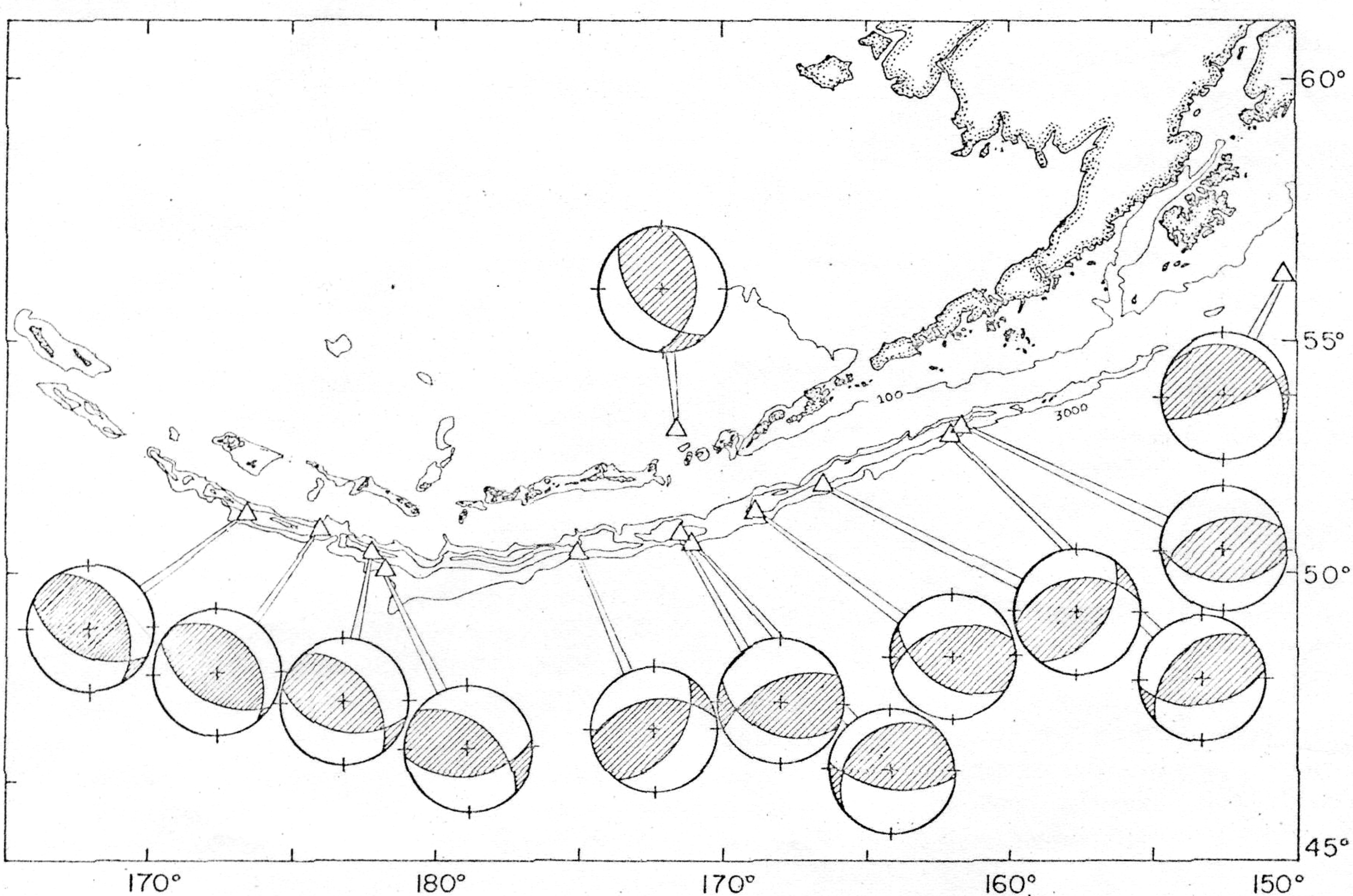
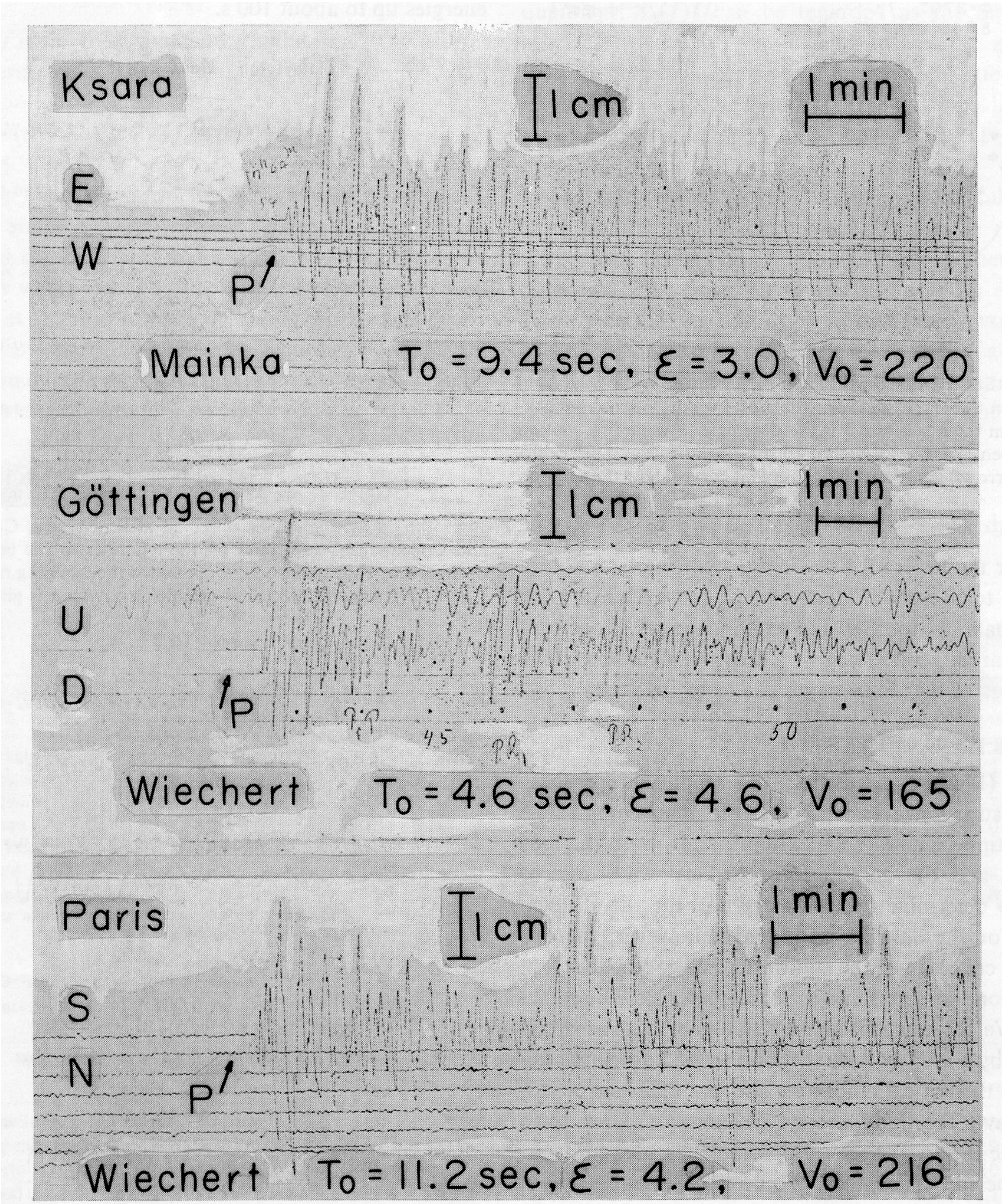
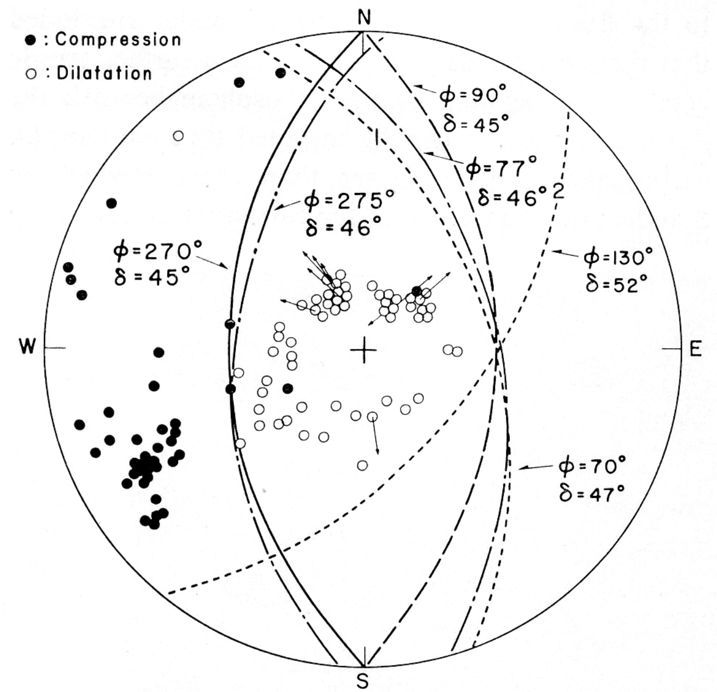
California Institute of Technology

Rat Is. earthquakes in 1965 (W. Stauder, JGR, 1968b)
(note: dilatational quadrants are shaded)



1933 Sanriku Earthquake (M_w=8.4)





Kanamori (1971)

Great ($M_w \geq 8$) Outer-rise Earthquakes

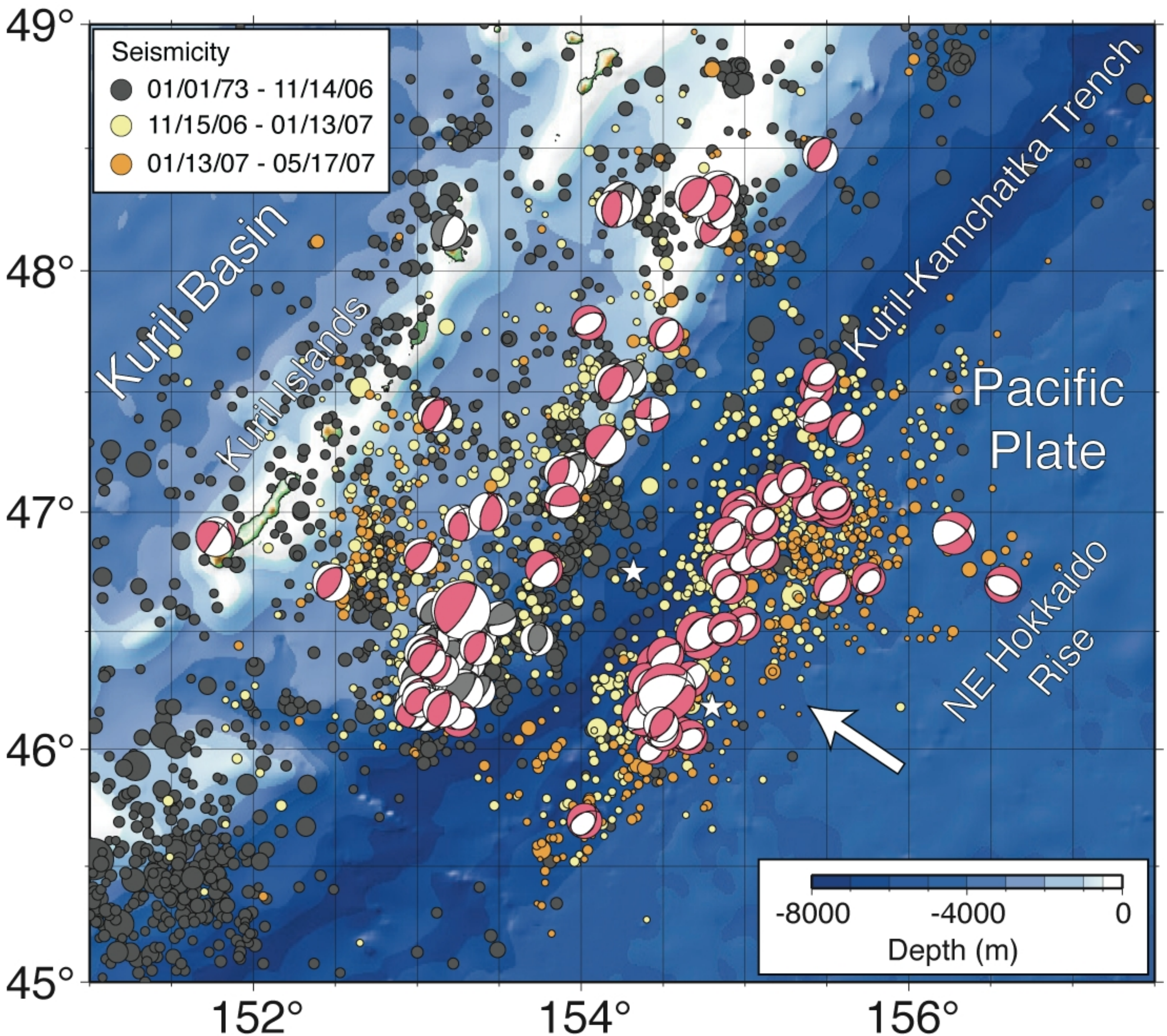
	Centroid Depth	Depth extent of rupture
1933 Sanriku (M_w=8.4)	?	"the entire thickness of the lithosphere" (Kanamori, 1971) (tsunami, aftershocks)
1977 Sumbawa (M_w=8.3)	23.3 km	30-50 km (Lynnes and Lay, 1988), 50-80 km (Zhang, 1988 thesis)
2007 Kuril (M_w=8.1)	12.0 km	?

Kuril Island Earthquake M_w=8.1

January 13, 2007

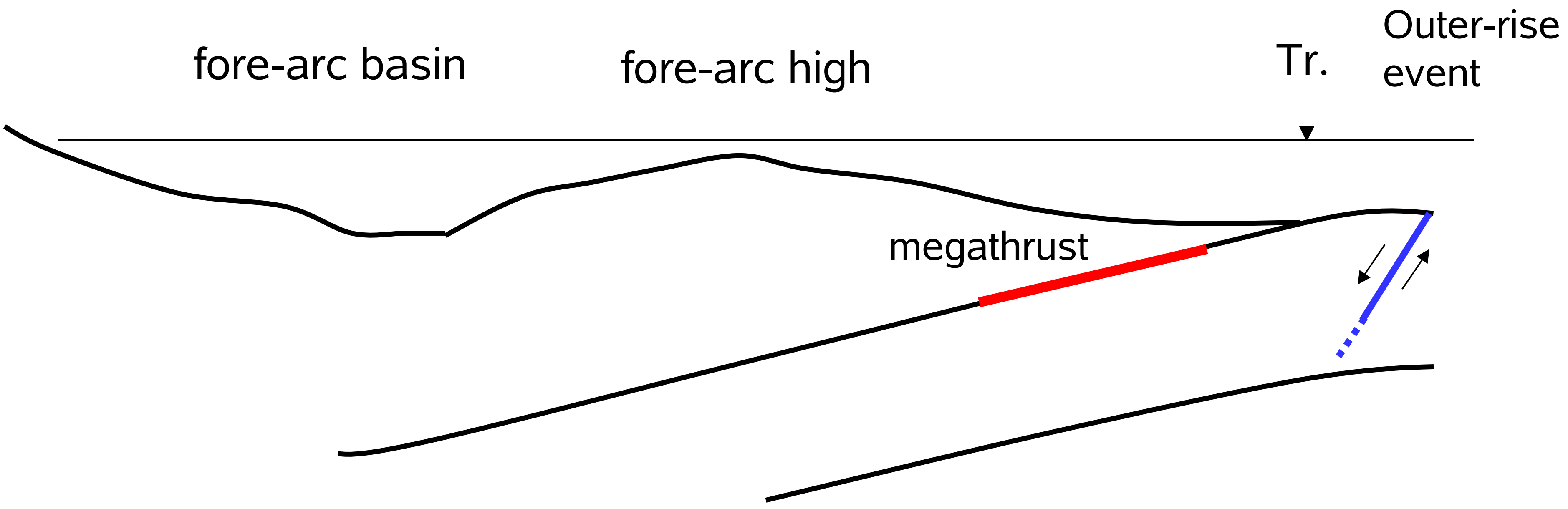
(Doublet: Nov. 15, 2006 Megathrust, M_w=8.3

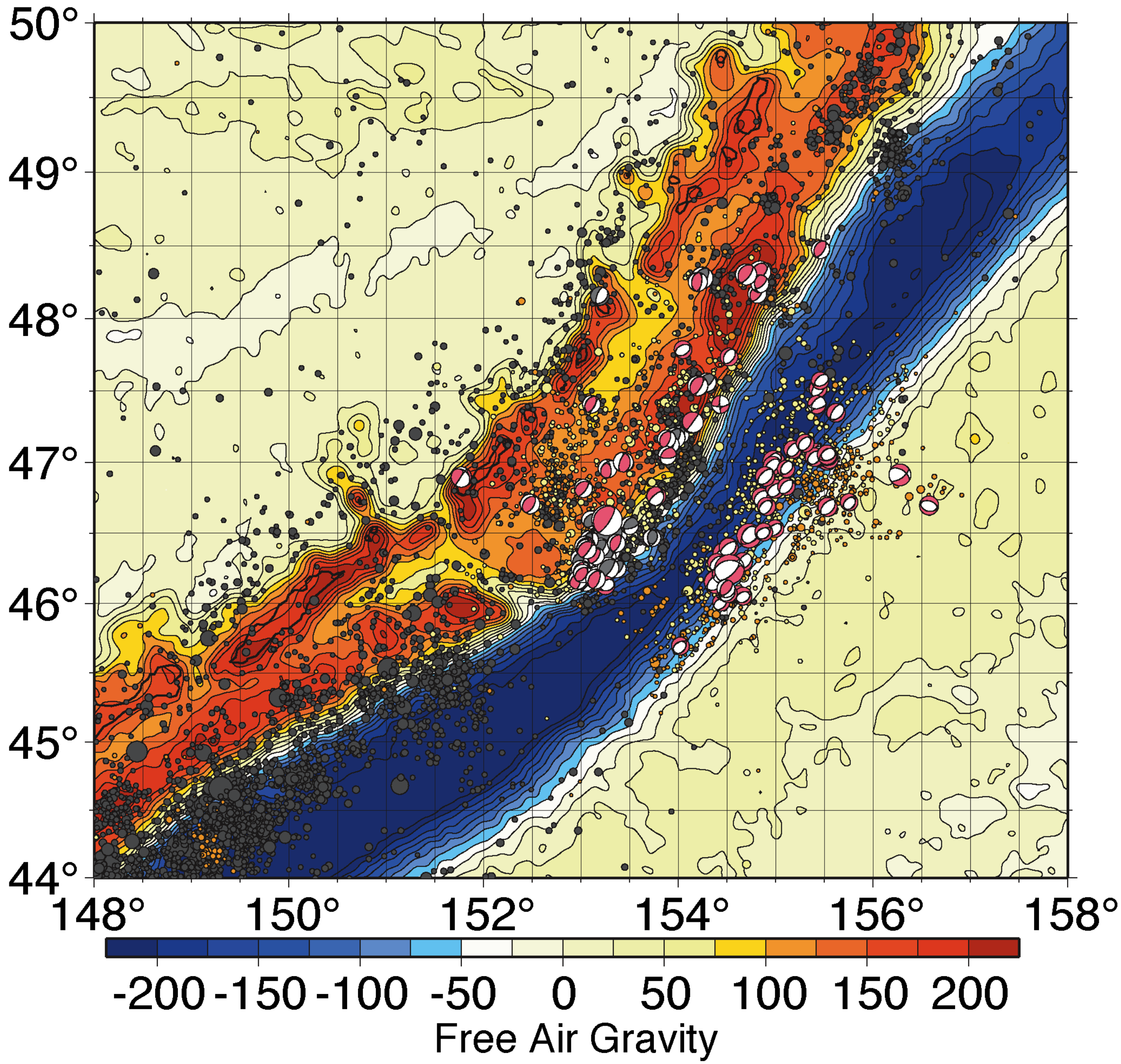
Jan. 13, 2007 Outer-rise, M_w=8.1)



Seismicity
01/01/73 - 11/14/06
11/15/06 - 01/13/07
01/13/07 - 05/17/07
Kuril Basin
Kuril Islands
Kuril-Kamchatka Trench
Pacific Plate
NE Hokkaido Rise
-8000
-4000
0
Depth (m)
49°
48°
47°
46°
45°
152°
154°
156°

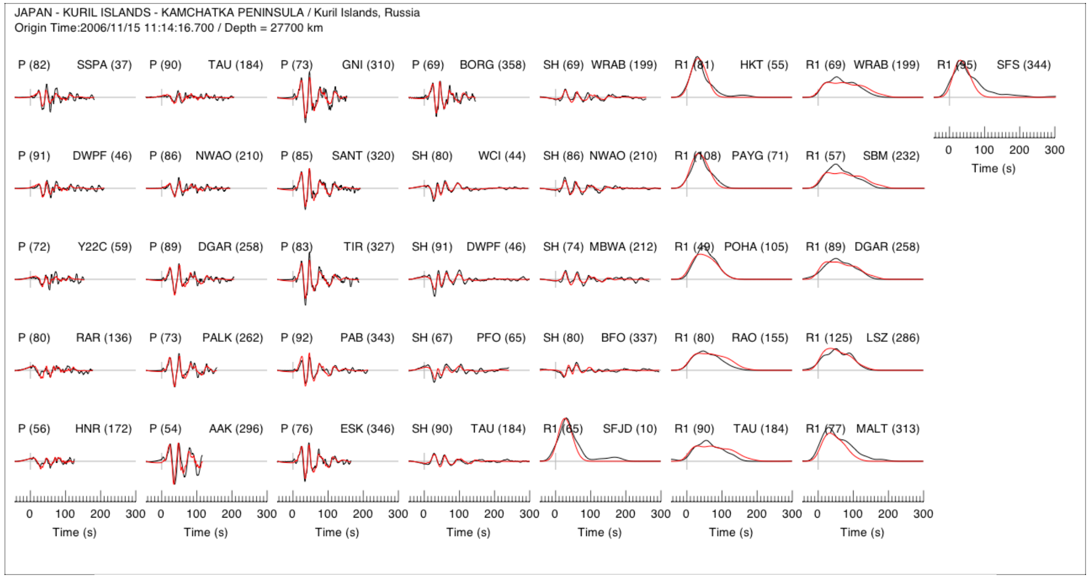
Outer-rise earthquake

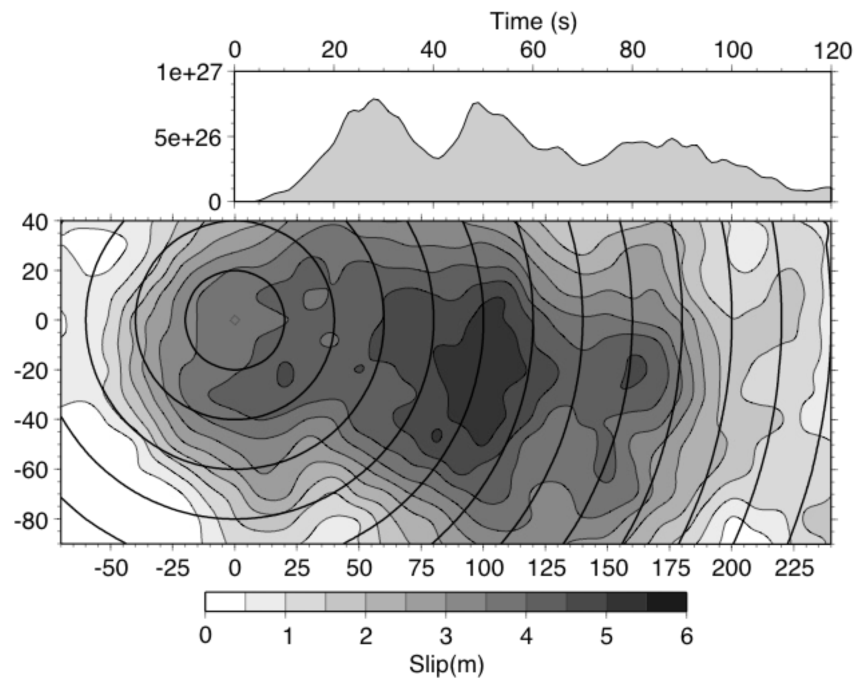




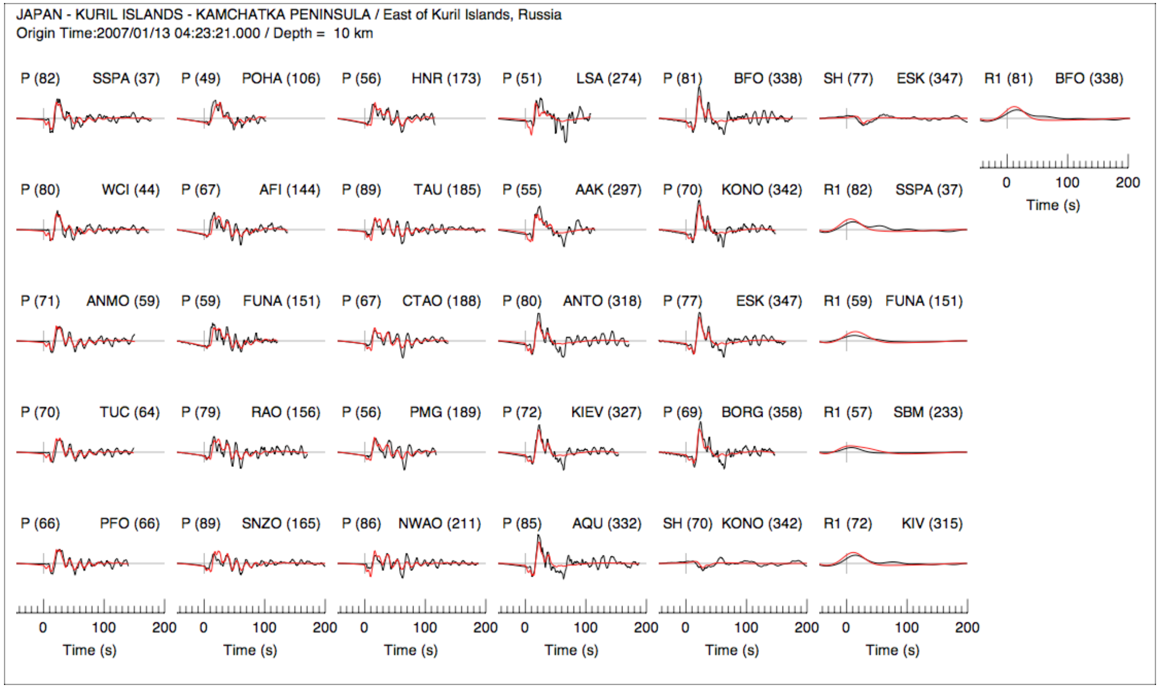
50°
49°
48°
47°
46°
45°
44°
148°
150°
152°
154°
156°
158°
-200 -150 -100 -50 0 50 100 150 200
Free Air Gravity

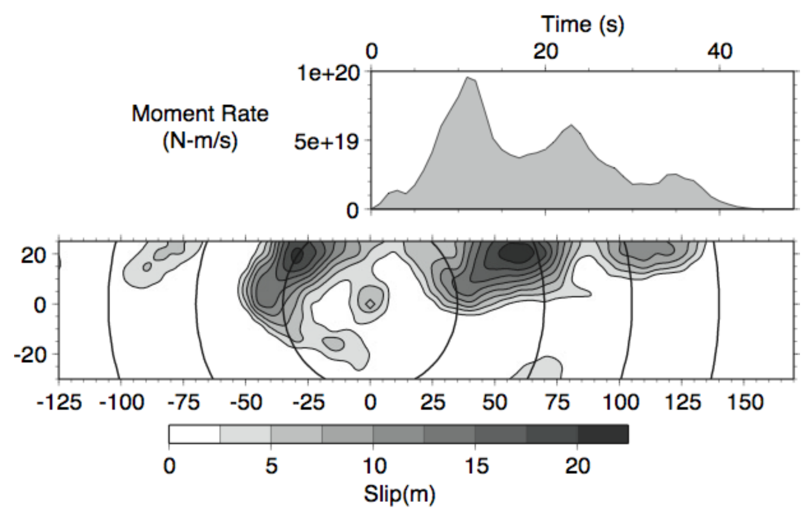
Nov. 15, 2006 Megathrust earthquake

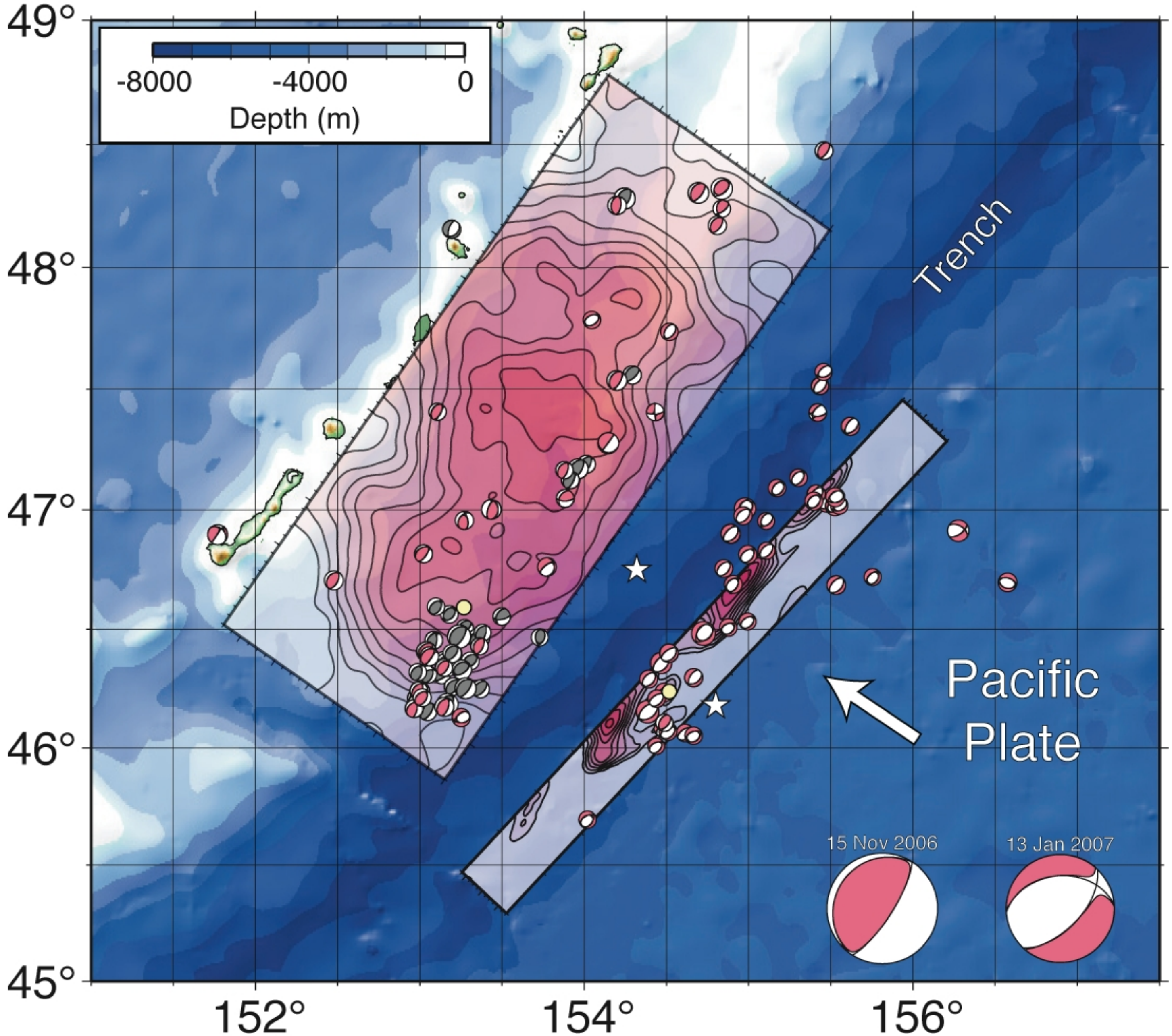




Jan. 13, 2007 Outer-rise earthquake





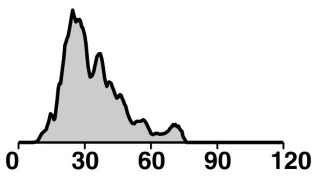


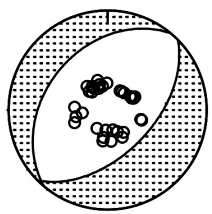
-8000
-4000
0
Depth (m)
49°
48°
47°
46°
45°
152°
154°
156°
Trench
Pacific
Plate
15 Nov 2006
13 Jan 2007

Kuril_20070113_yamanaka_mechanism_north-

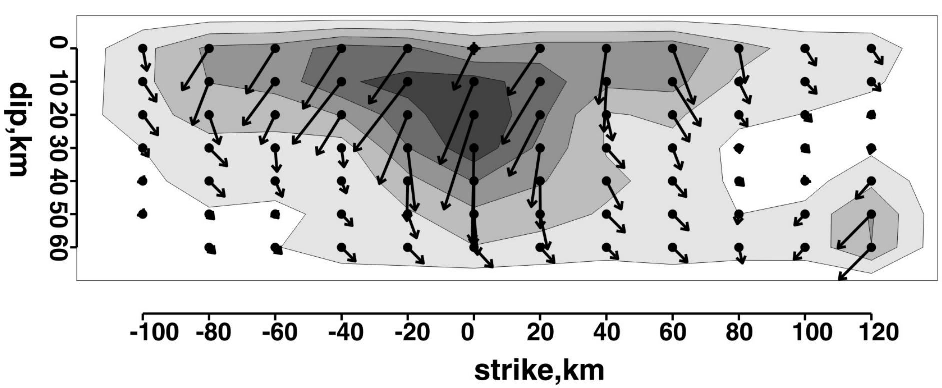
Mo = 0.230E+22 Nm Mw = 8.17

H = 7.0km T = s var. = 0.3382





(220.,37., -94.)



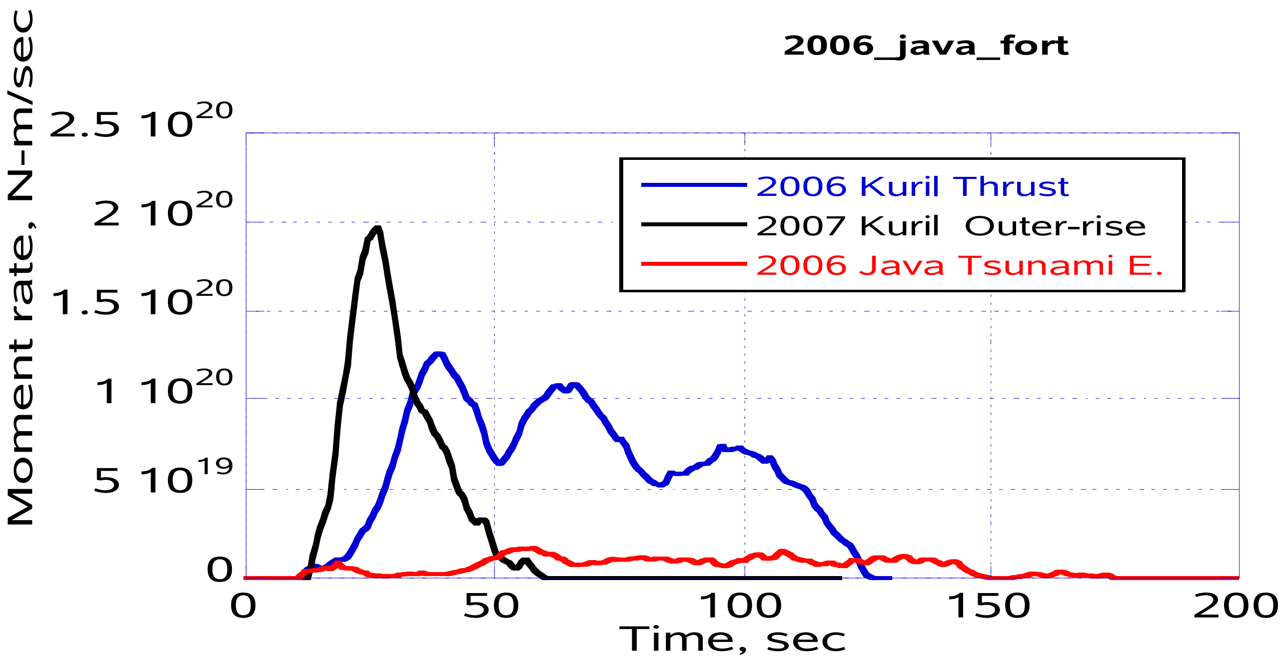
Yamanaka mechanism

North-dipping

V=2.5 km/s

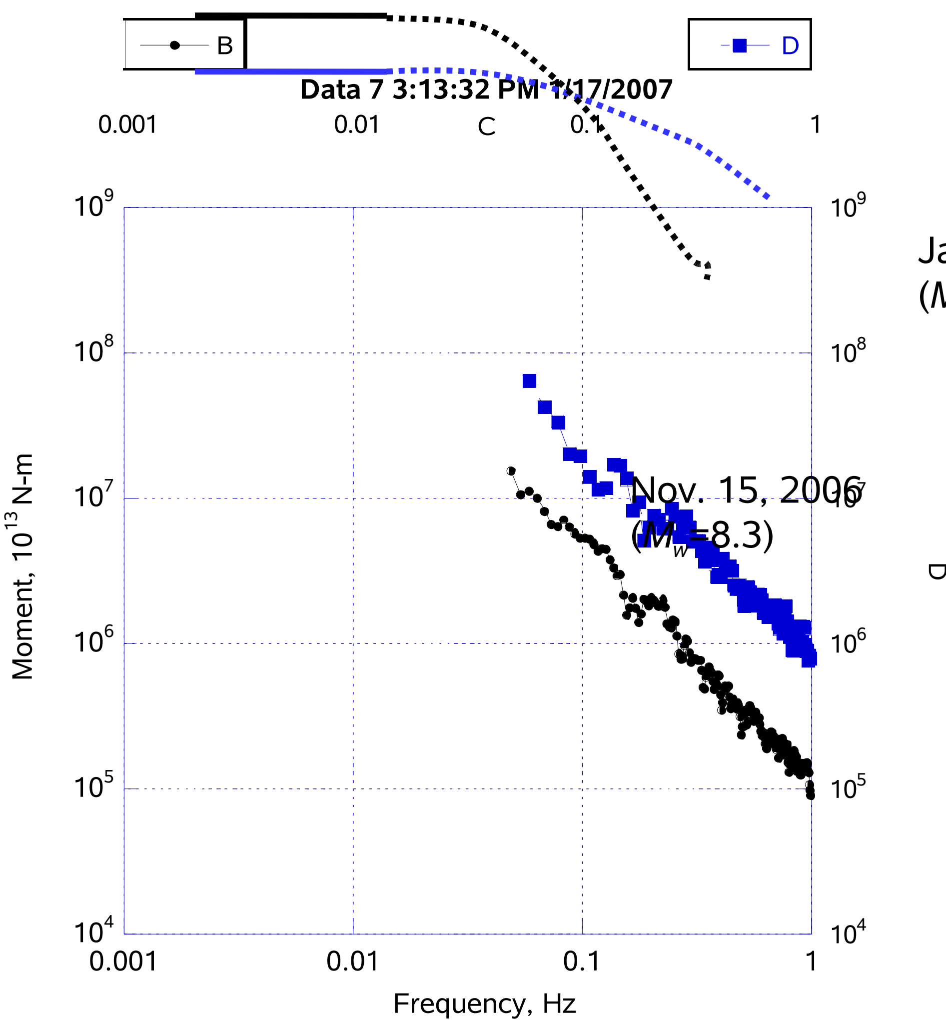
Ng=128, 2.-2.-8

Large fault



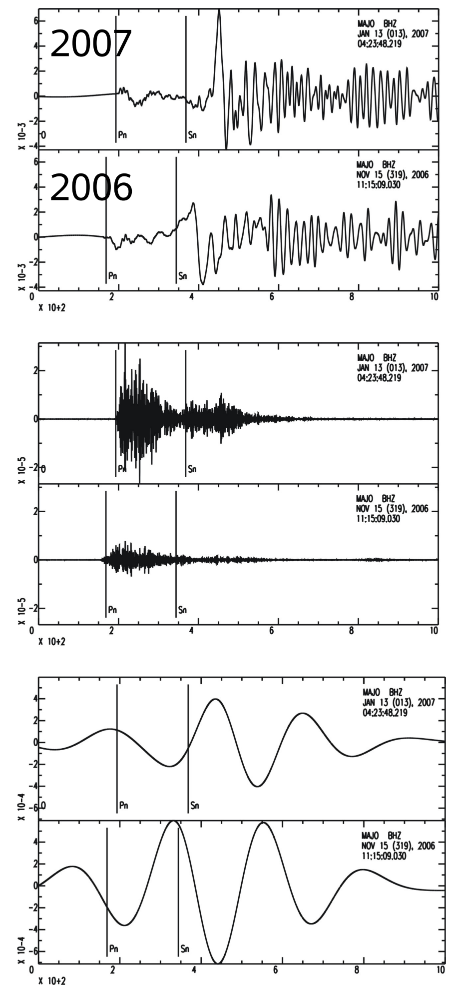
2006_java_fort
Moment rate, N-m/sec
2.5 10^20
2 10^20
1.5 10^20
1 10^20
5 10^19
0
2006 Kuril Thrust
2007 Kuril Outer-rise
2006 Java Tsunami E.
0
50
100
150
200
Time, sec

Difference in Moment-rate Spectrum



Jan. 13, 2007
(M_w=8.1)

MAJO Displacement



disp.

hp 0.5 Hz

lp 0.005 Hz

Scaled Energy: E_R/M_0

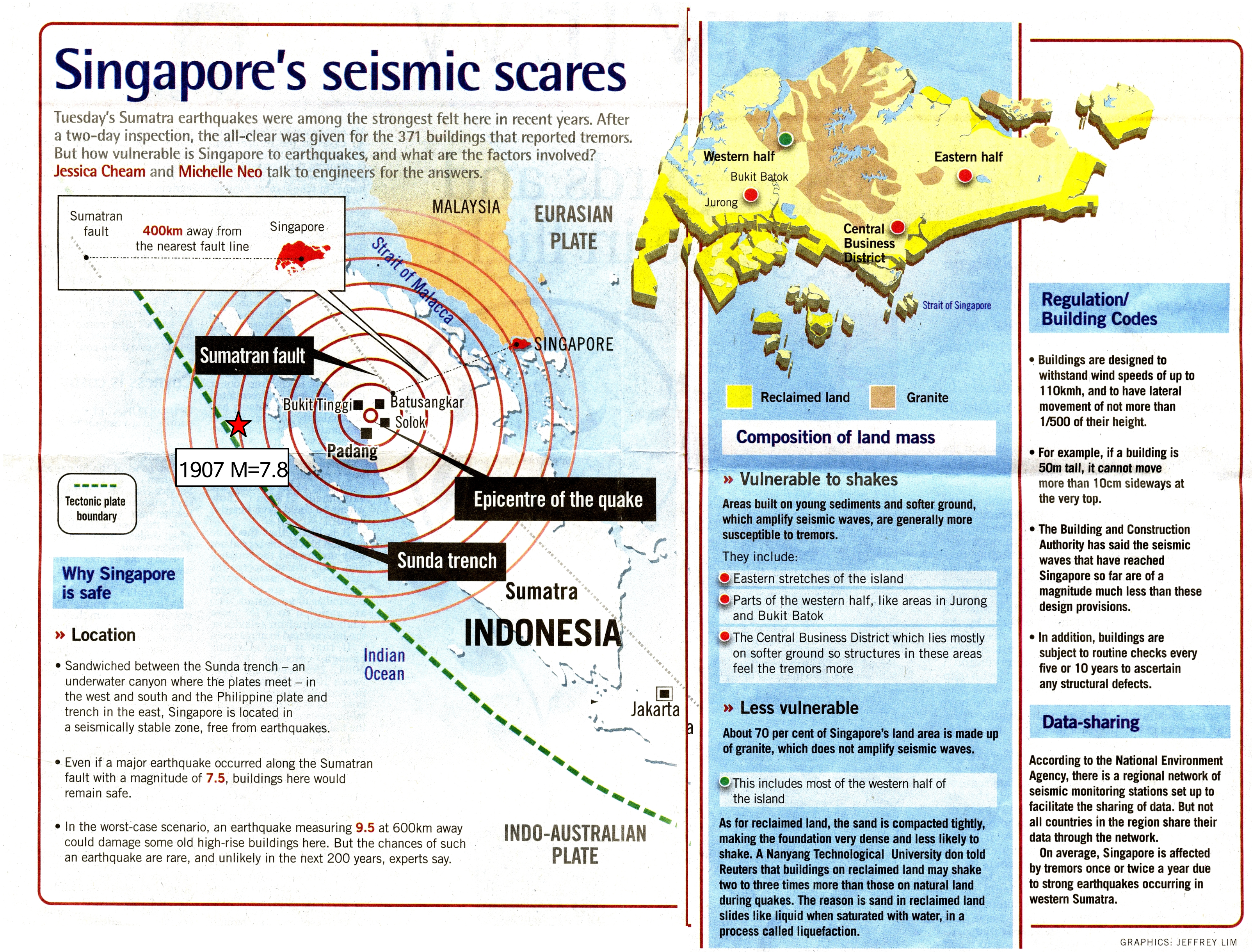
10^{-6}	slow tsunami earthquake
5×10^{-6} to 10^{-5}	mega-thrust earthquake
5×10^{-5} to 10^{-4}	outer-rise earthquake

$$\frac{E_R}{M_0} = \frac{1}{2\mu}(\eta\, g \Delta\sigma)$$

$$\eta = \text{radiation efficiency} \propto 1/G_c$$

$$\Delta\sigma = \text{stress drop}$$

Implication for seismic hazard: example



Singapore's seismic scares

Tuesday's Sumatra earthquakes were among the strongest felt here in recent years. After a two-day inspection, the all-clear was given for the 371 buildings that reported tremors. But how vulnerable is Singapore to earthquakes, and what are the factors involved? Jessica Cheam and Michelle Neo talk to engineers for the answers.

Why Singapore is safe

» Location

- Sandwiched between the Sunda trench – an underwater canyon where the plates meet – in the west and south and the Philippine plate and trench in the east, Singapore is located in a seismically stable zone, free from earthquakes.
- Even if a major earthquake occurred along the Sumatran fault with a magnitude of 7.5, buildings here would remain safe.
- In the worst-case scenario, an earthquake measuring 9.5 at 600km away could damage some old high-rise buildings here. But the chances of such an earthquake are rare, and unlikely in the next 200 years, experts say.

Composition of land mass

» Vulnerable to shakes

Areas built on young sediments and softer ground, which amplify seismic waves, are generally more susceptible to tremors.

They include:

- Eastern stretches of the island
- Parts of the western half, like areas in Jurong and Bukit Batok
- The Central Business District which lies mostly on softer ground so structures in these areas feel the tremors more

» Less vulnerable

About 70 per cent of Singapore's land area is made up of granite, which does not amplify seismic waves.

- This includes most of the western half of the island

As for reclaimed land, the sand is compacted tightly, making the foundation very dense and less likely to shake. A Nanyang Technological University don told Reuters that buildings on reclaimed land may shake two to three times more than those on natural land during quakes. The reason is sand in reclaimed land slides like liquid when saturated with water, in a process called liquefaction.

Regulation/ Building Codes

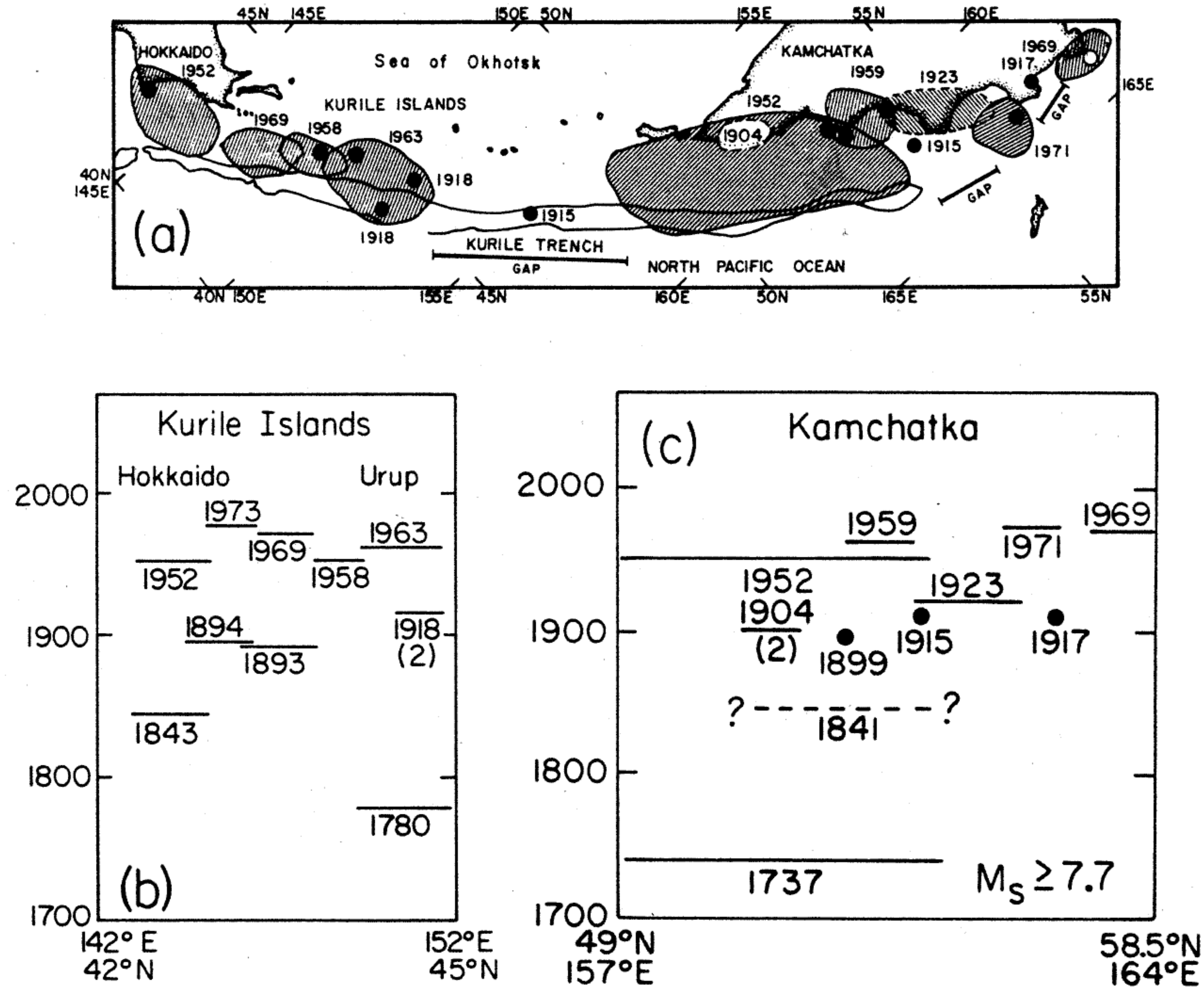
- Buildings are designed to withstand wind speeds of up to 110kmh, and to have lateral movement of not more than 1/500 of their height.
- For example, if a building is 50m tall, it cannot move more than 10cm sideways at the very top.
- The Building and Construction Authority has said the seismic waves that have reached Singapore so far are of a magnitude much less than these design provisions.
- In addition, buildings are subject to routine checks every five or 10 years to ascertain any structural defects.

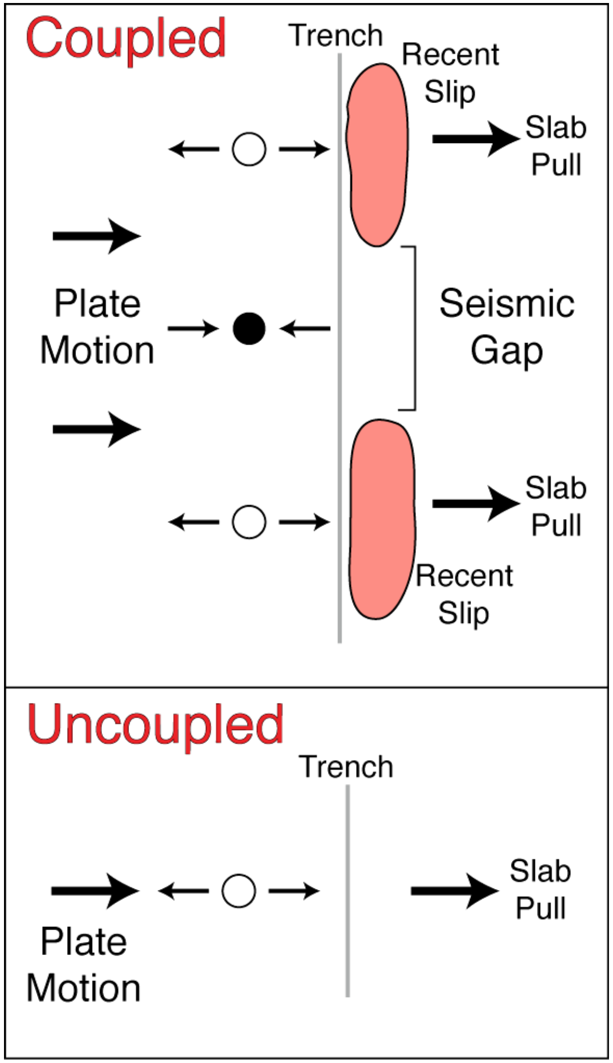
Data-sharing

According to the National Environment Agency, there is a regional network of seismic monitoring stations set up to facilitate the sharing of data. But not all countries in the region share their data through the network.

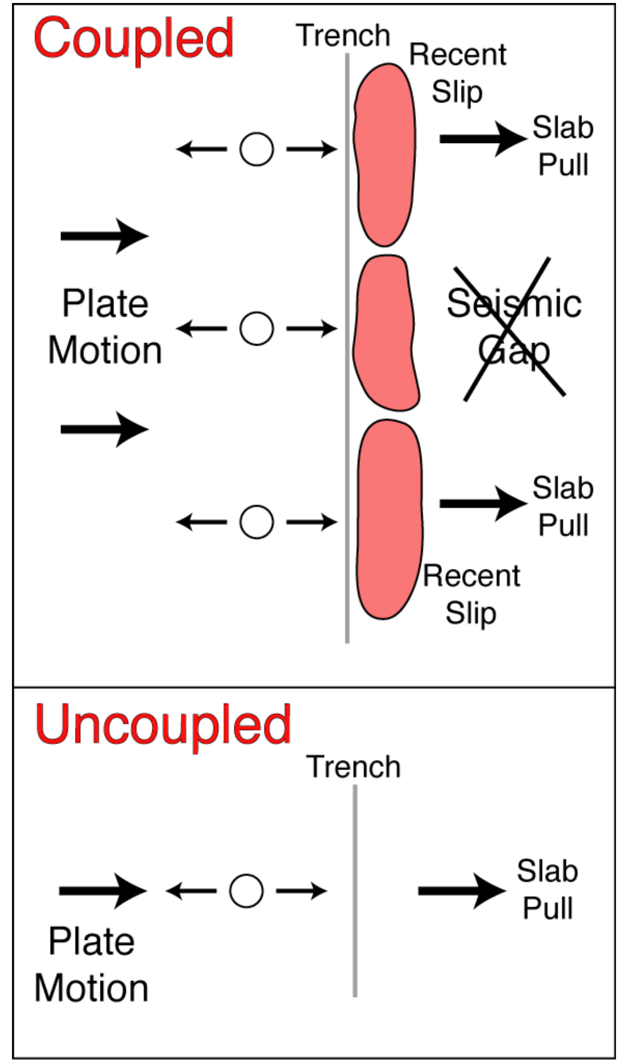
On average, Singapore is affected by tremors once or twice a year due to strong earthquakes occurring in western Sumatra.

GRAPHICS: JEFFREY LIM

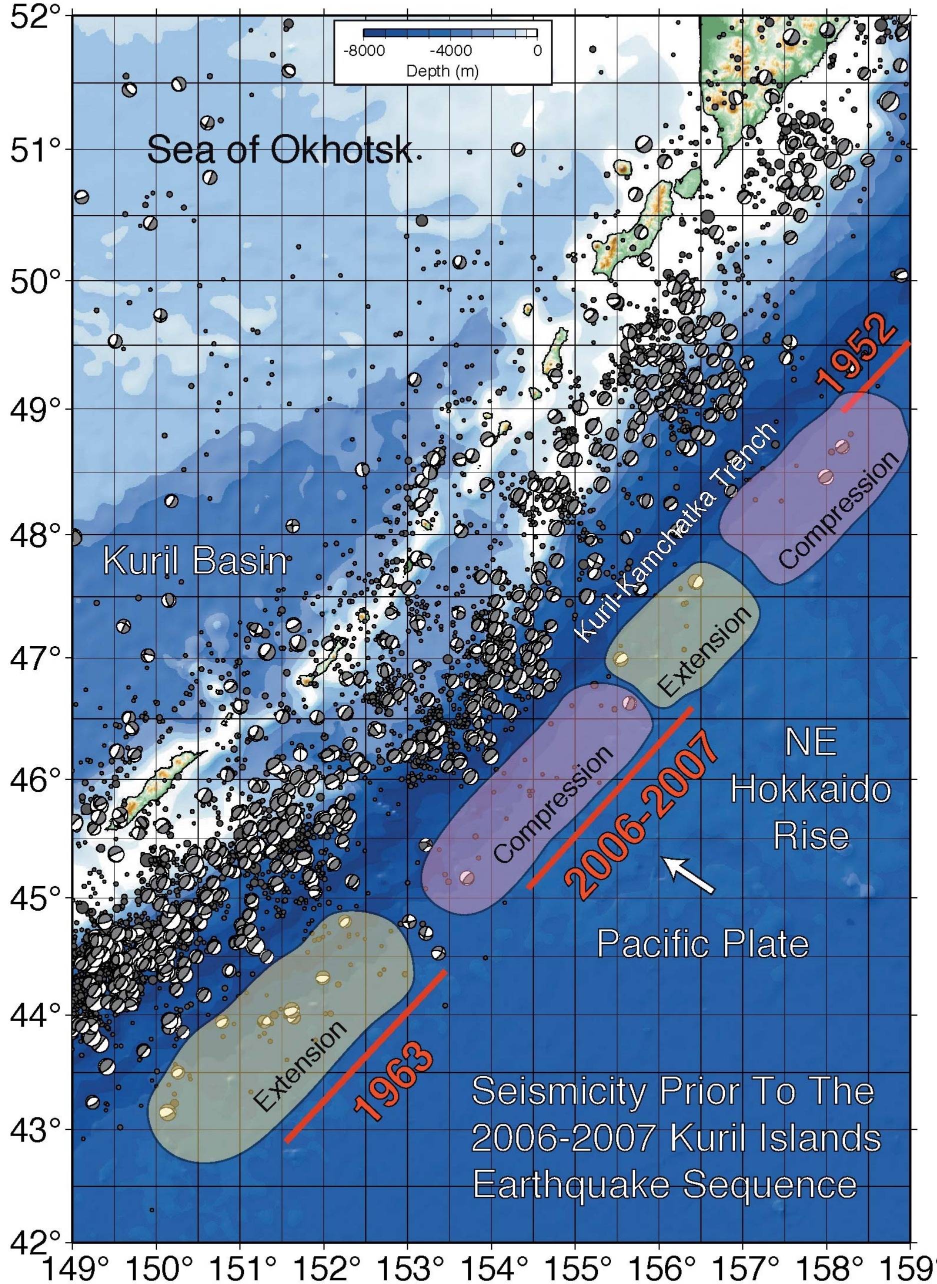

45N 145E
150E 50N
155E
55N
160E
165E
40N 145E
40N 150E
155E 45N
160E
50N
165E
55N
HOKKAIDO
1952
Sea of Okhotsk
KURILE ISLANDS
1969
1958
1963
1918
1918
1915
(a)
KURILE TRENCH
GAP
NORTH PACIFIC OCEAN
KAMCHATKA
1952
1904
1959
1923
1969
1917
1915
1971
GAP
GAP
Kurile Islands
Hokkaido
Urup
2000
1900
1800
1700
1973
1969
1963
1952
1958
1894
1893
1918
(2)
1843
1780
(b)
142° E
42° N
152° E
45° N
(c)
Kamchatka
2000
1900
1800
1700
1959
1969
1971
1952
1904
(2)
1923
1899
1915
1917
? 1841 ?
1737
$M_S \geq 7.7$
49° N
157° E
58.5° N
164° E



After Christensen and Ruff, 1988



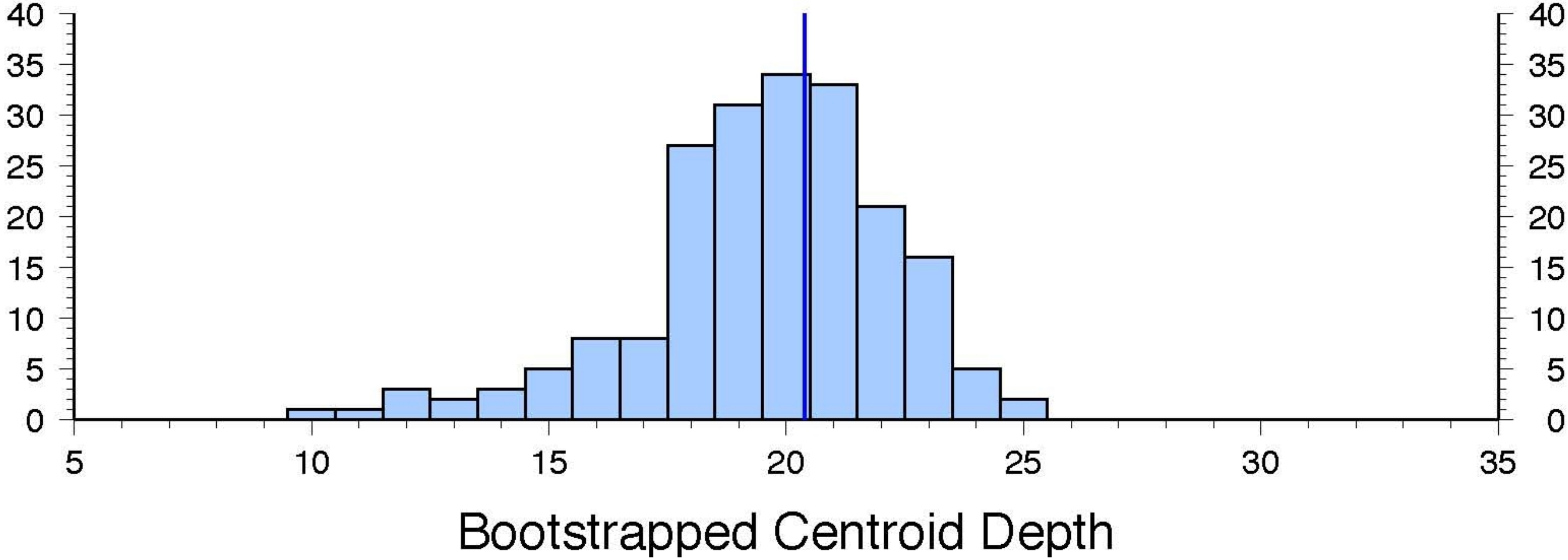
After Christensen and Ruff, 1988



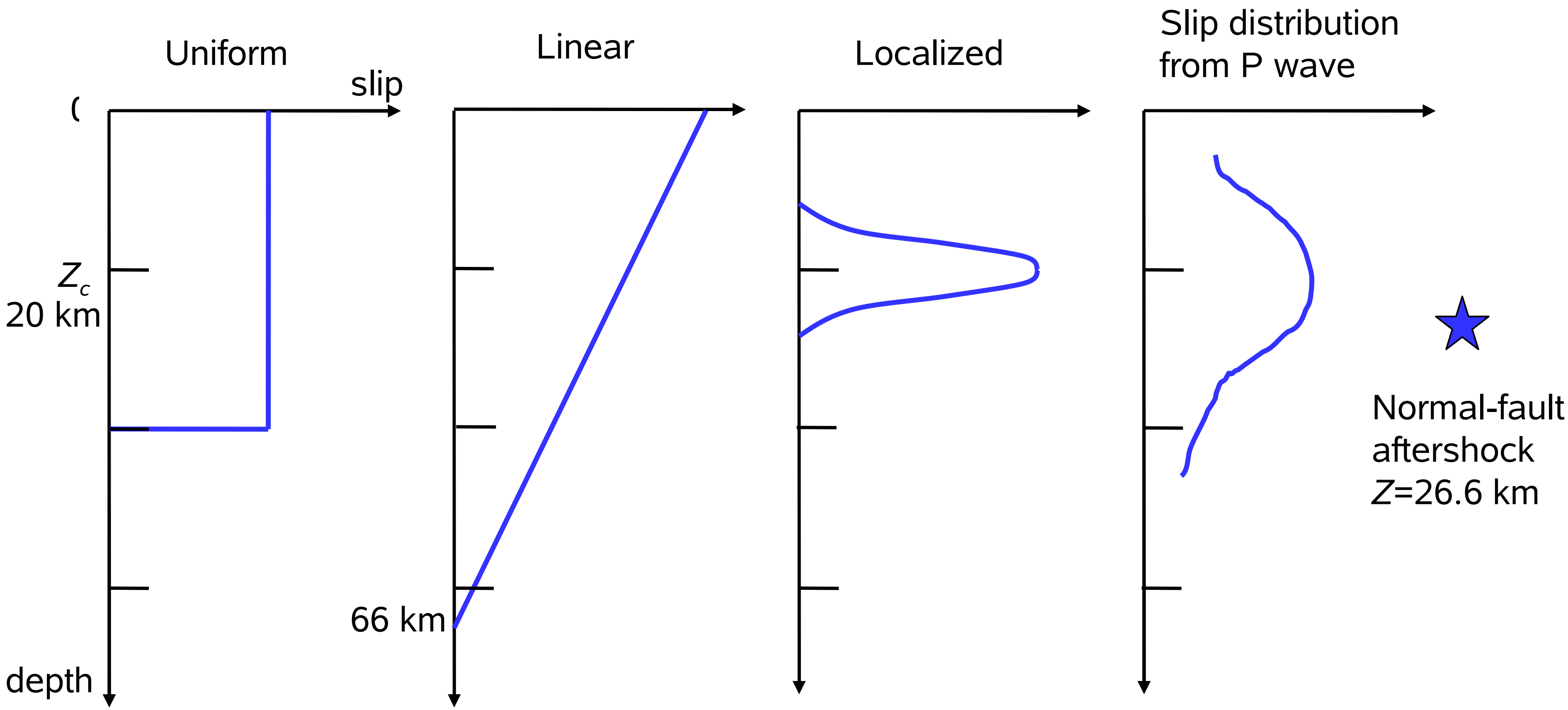
-8000 -4000 0
Depth (m)
Sea of Okhotsk
Kuril Basin
Kuril-Kamchatka Trench
1952
Compression
Extension
Compression
2006-2007
NE
Hokkaido
Rise
Pacific Plate
Extension
1963
Seismicity Prior To The
2006-2007 Kuril Islands
Earthquake Sequence
52°
51°
50°
49°
48°
47°
46°
45°
44°
43°
42°
149°
150°
151°
152°
153°
154°
155°
156°
157°
158°
159°

Centroid Depth of the Jan. 13 Kuril Is. Earthquake (Mw=8.1)

(J. Polet, written communication, 2007)



Centroid Depth (Z_c) and Slip Distribution



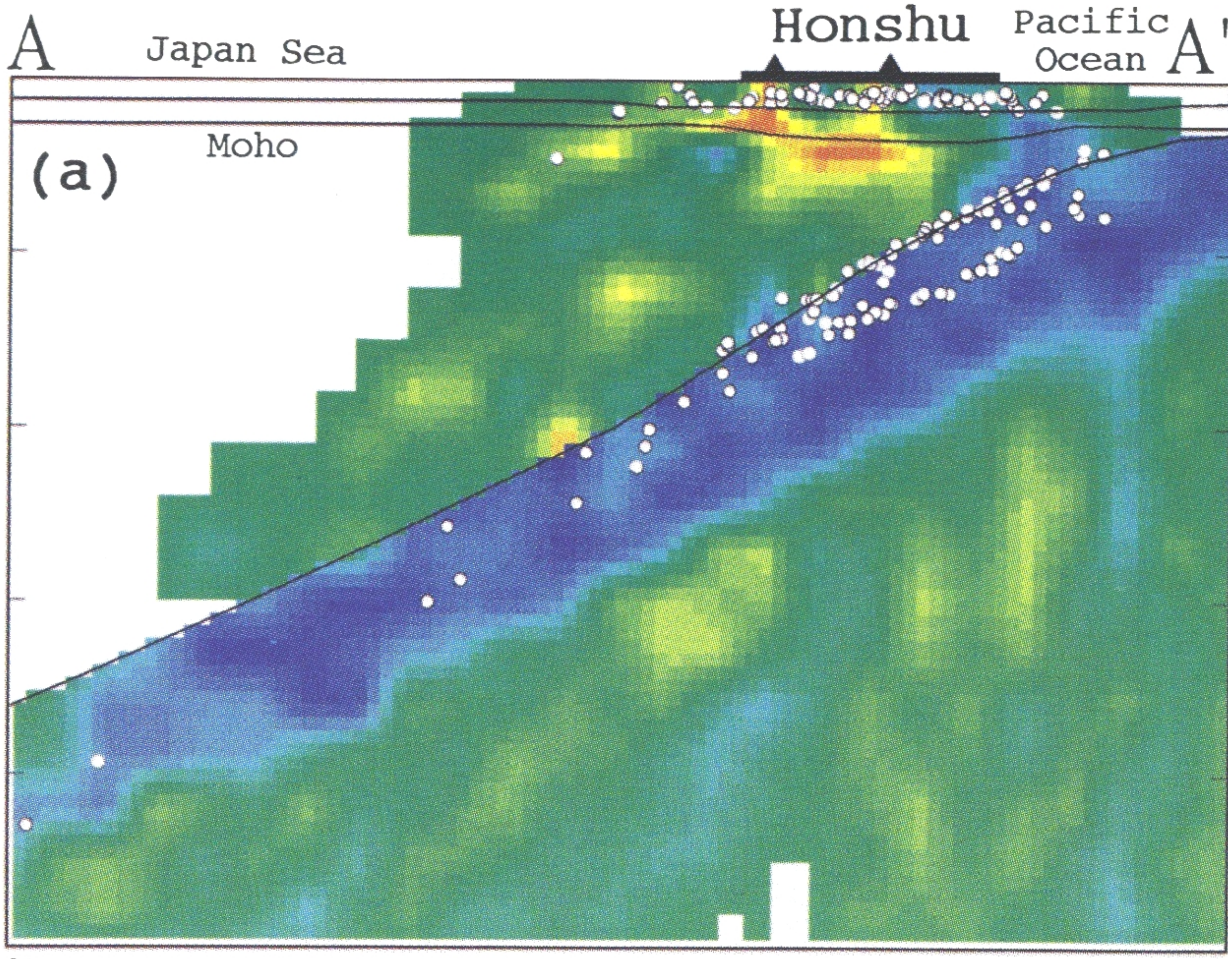
Slab Structure Beneath Japan

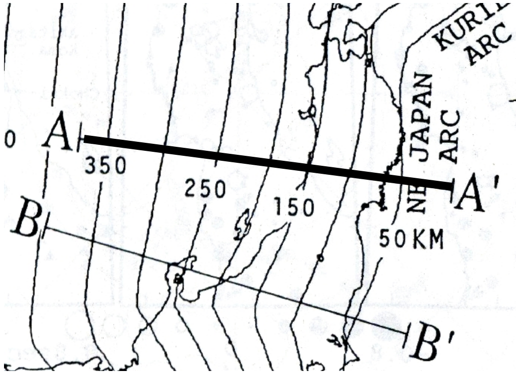
and Intra-slab Structure

Tohoku (Japan) Cross Section

(local+regional+teleseismic)

[Zhao, Hasegawa, and Kanamori, 1994]

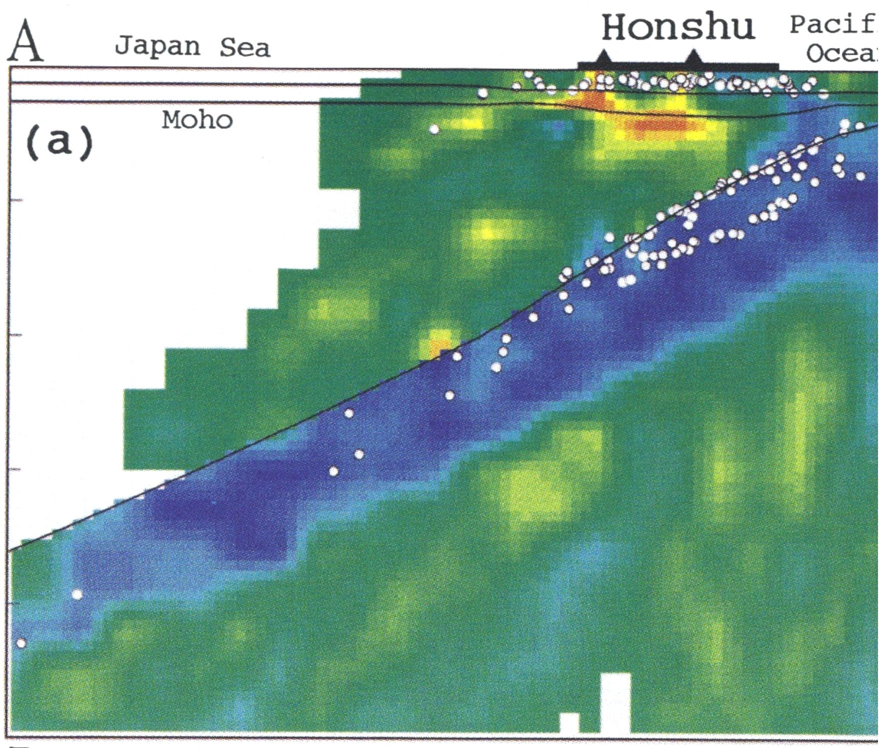


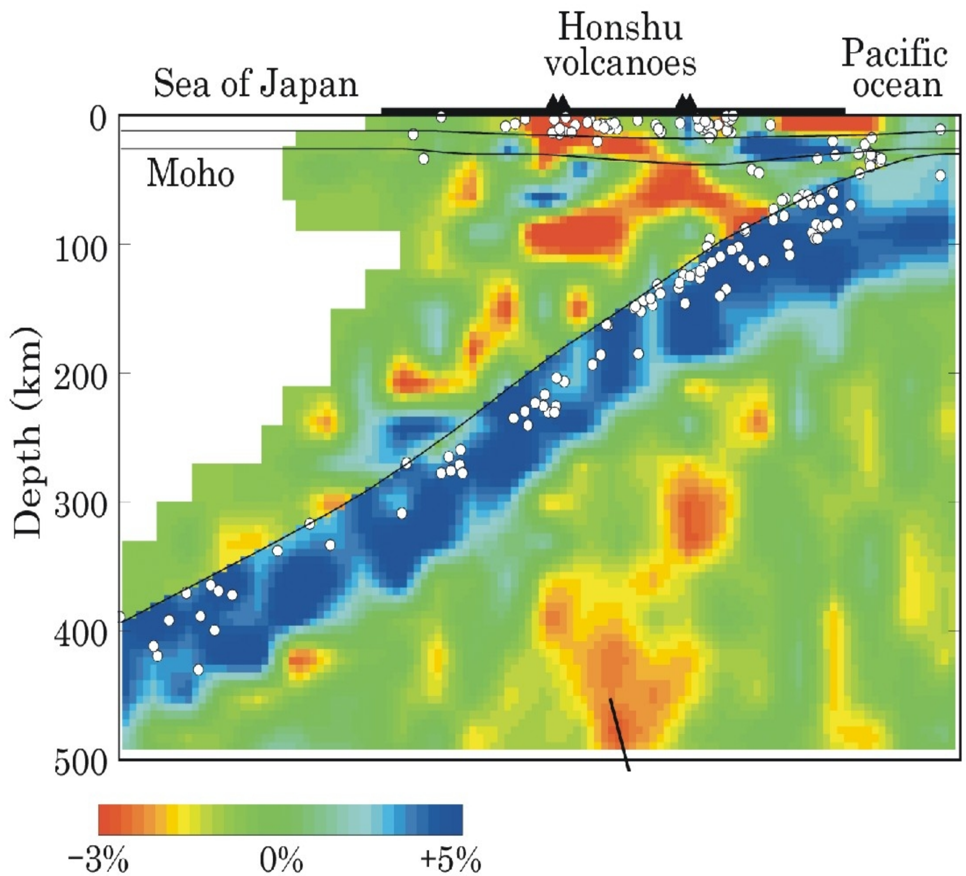


0

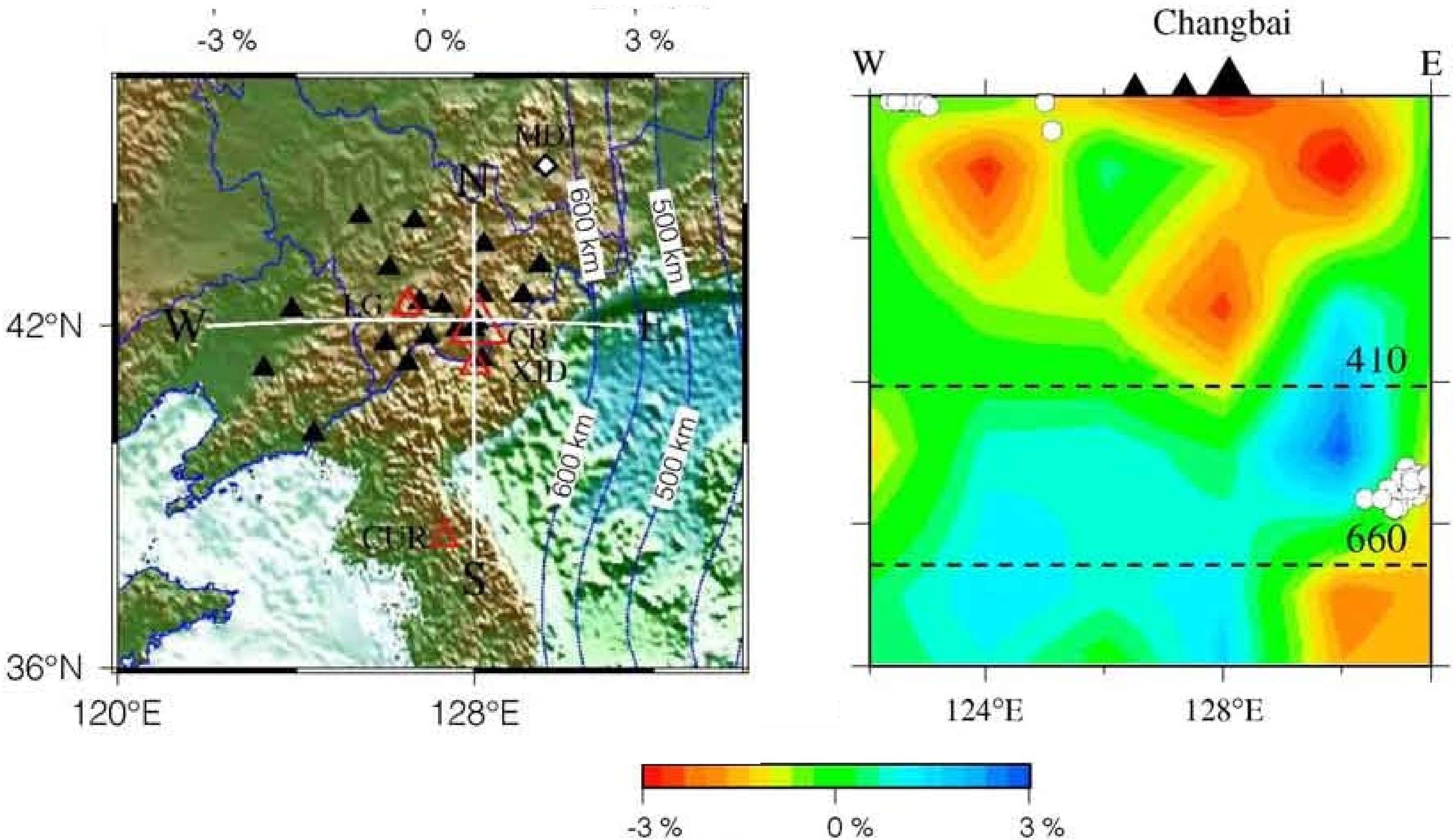
400 km

More Recent Structure, Zhao [2003]





Tomographic image of LV structure beneath Changbai volcano



Lei and Zhao (Tectonophysics, 2005)

Source of water?

2. Oceanic crust (sediments, hydrous minerals
e.g. lawsonite, phengite etc)

(e.g. Kirby et al., 1996; Peacock and Wang, 1999)

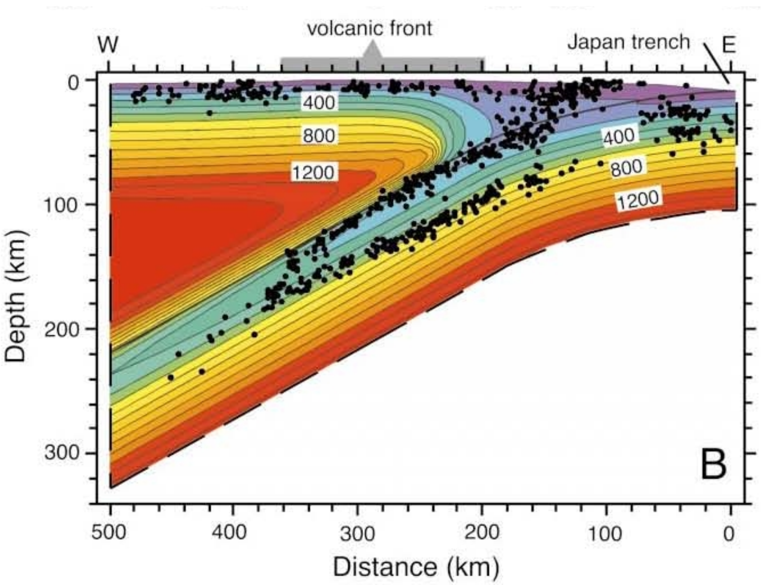
2. Slab interior

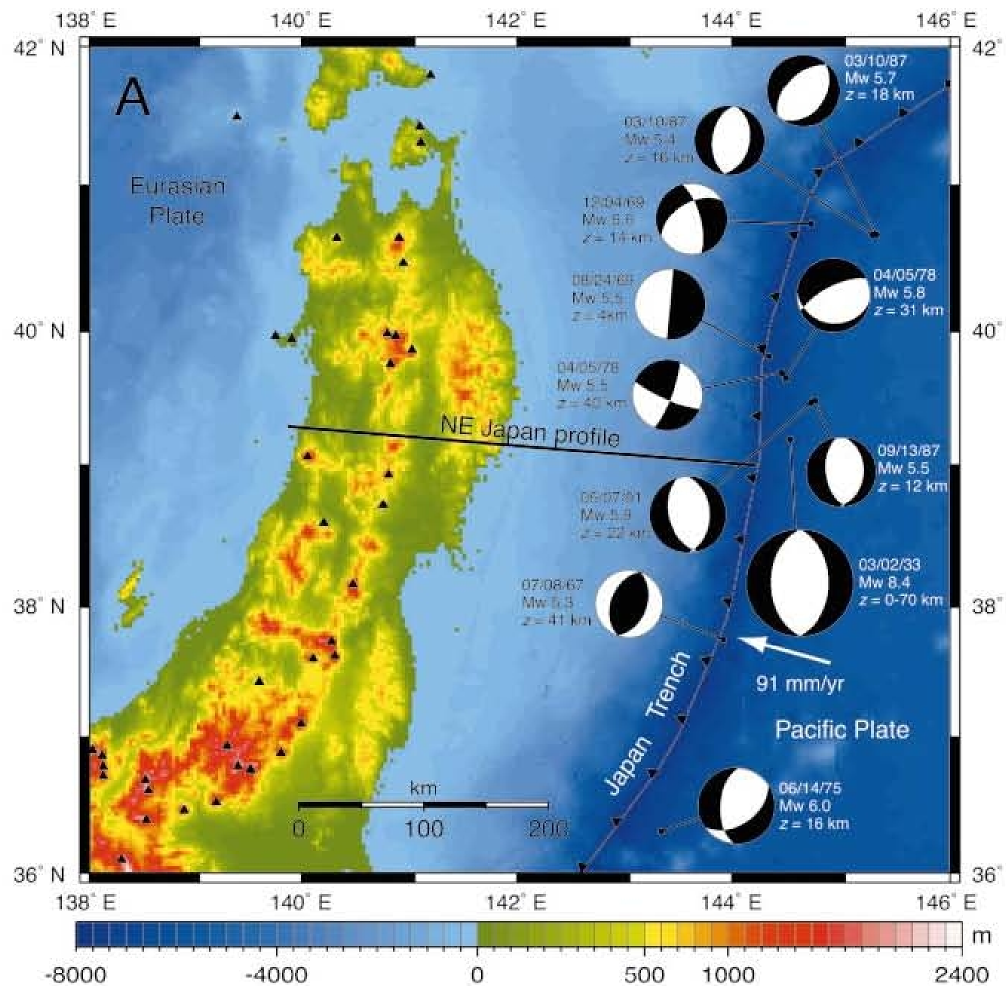
(e.g. Mead and Jeanloz, 1991; Seno and Yamanaka, 1996; Peacock, 2001,)

Outer-rise (hydrous minerals, serpentinite, talc etc)

Oceanic plate (sandwiched gabbro)

Double Seismic Zone and Outer-rise Earthquakes

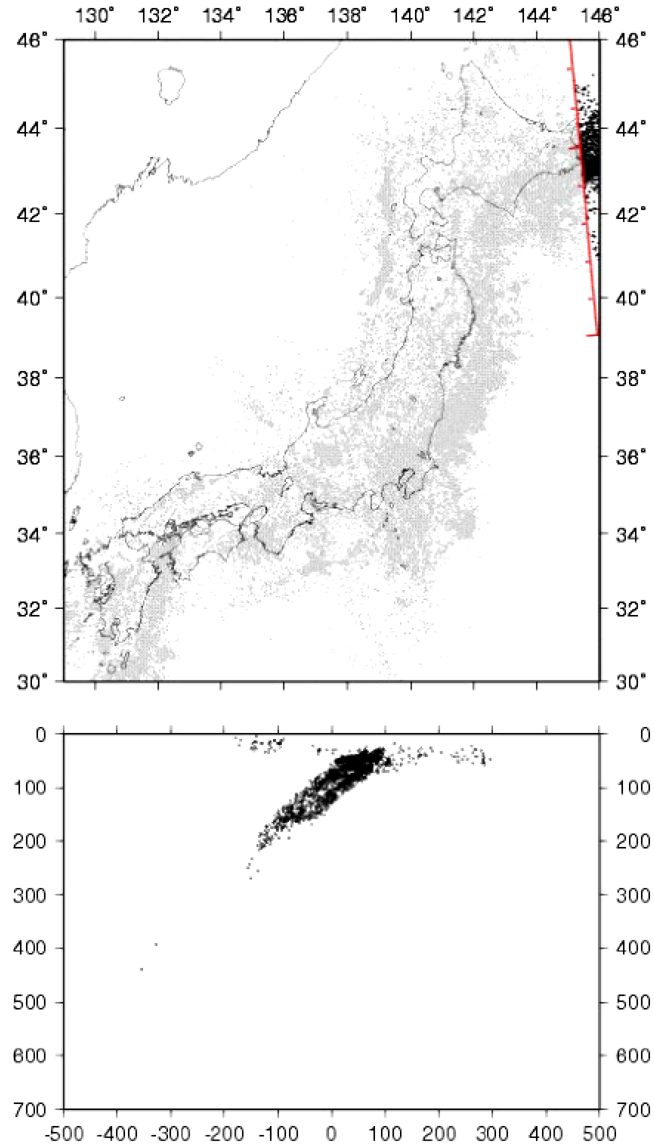




(taken from Peacock, Geology, 2001)

Double seismic zone

Hasegawa, Umino, and Takagi (1978)

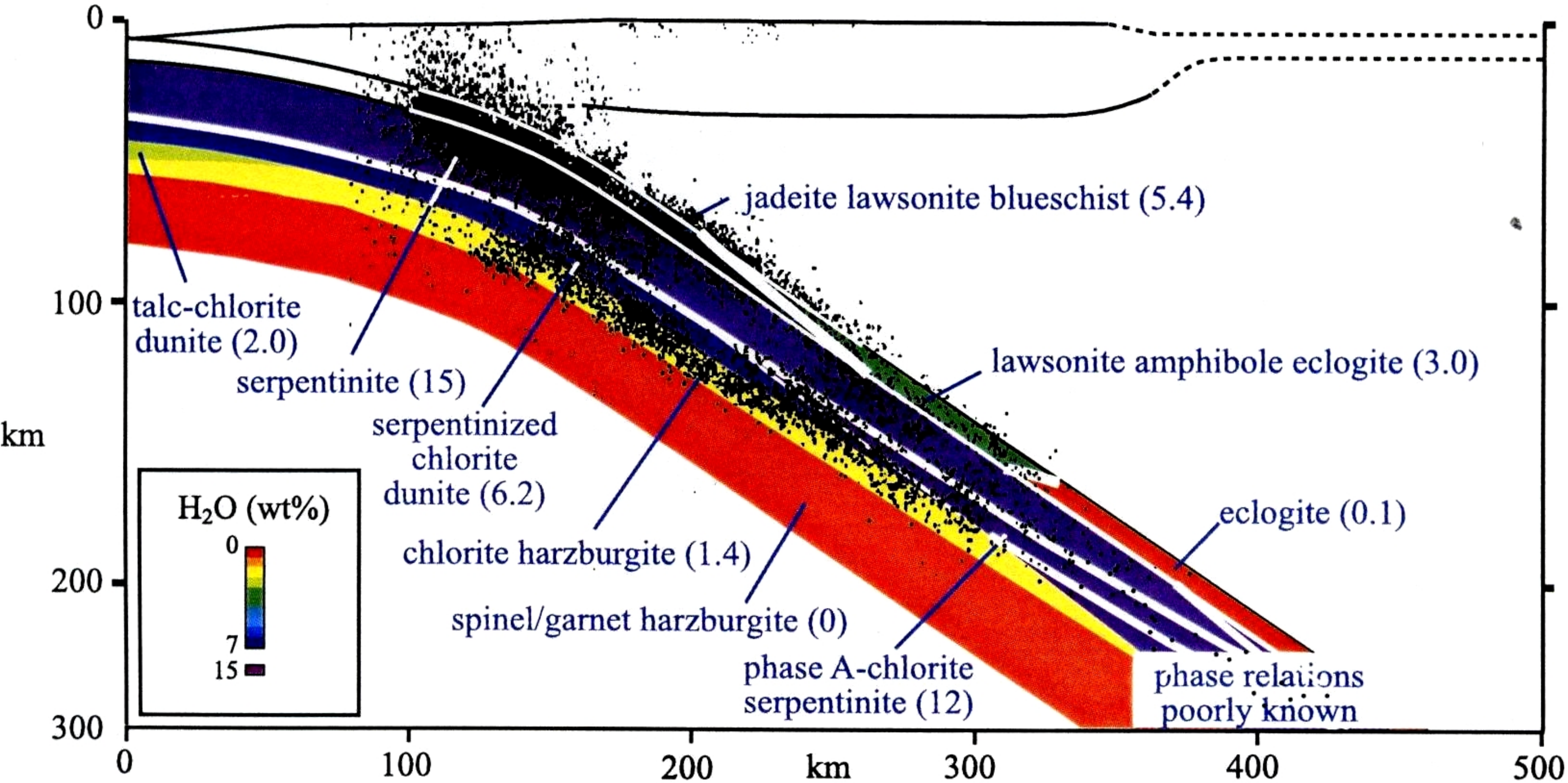


Movie:

Courtesy of NIED

Slab structure of the Tohoku (NE Japan) subduction zone

(Hacker et al., 2003)



Seismological Questions

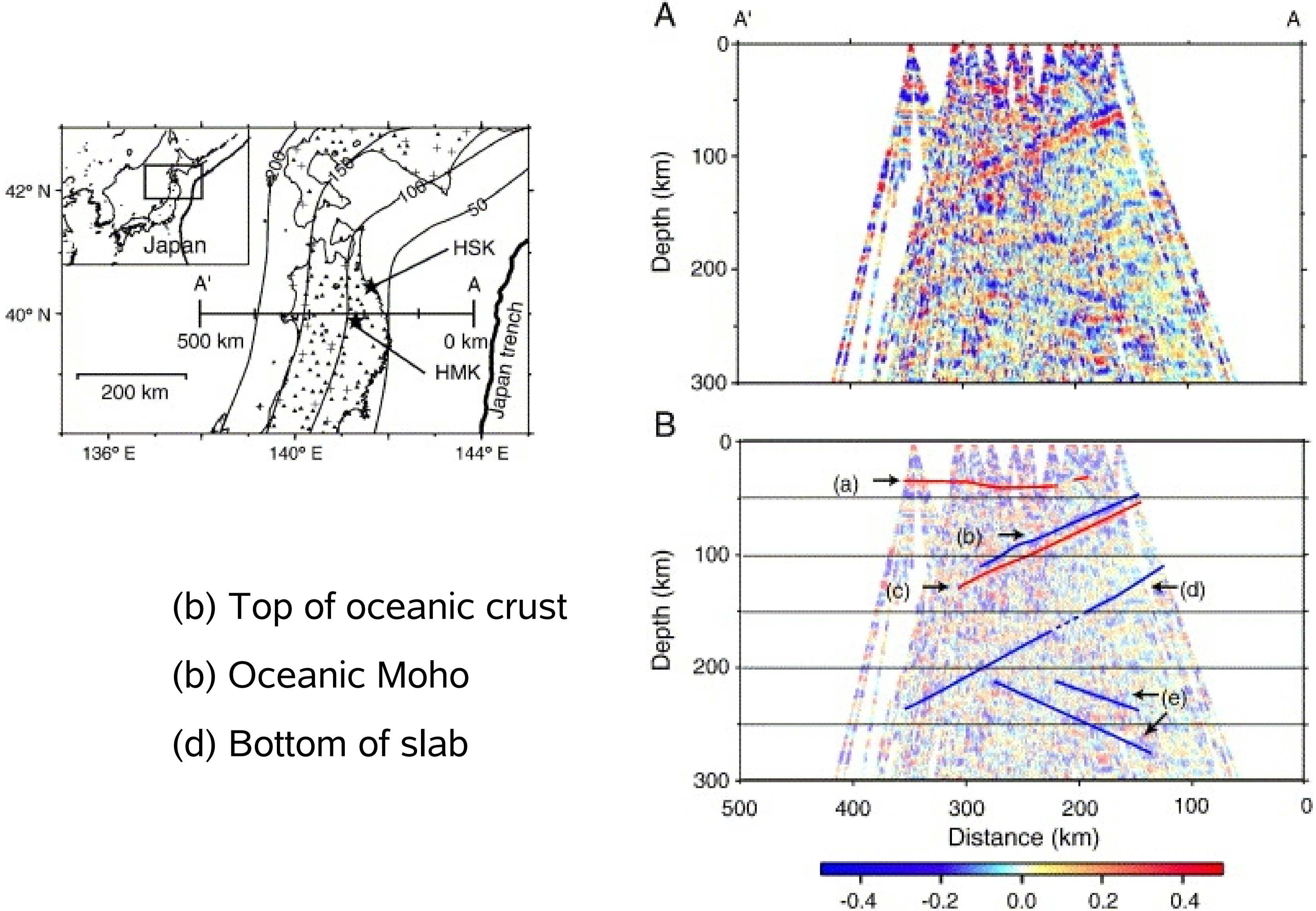
3. Evidence for an Intra-slab low-velocity structure

    existence of hydrous minerals?

4. Depth extent of outer-rise earthquakes

    a pathway for water infiltration?

Receiver Function Profile Across Tohoku Japan



(b) Top of oceanic crust

(b) Oceanic Moho

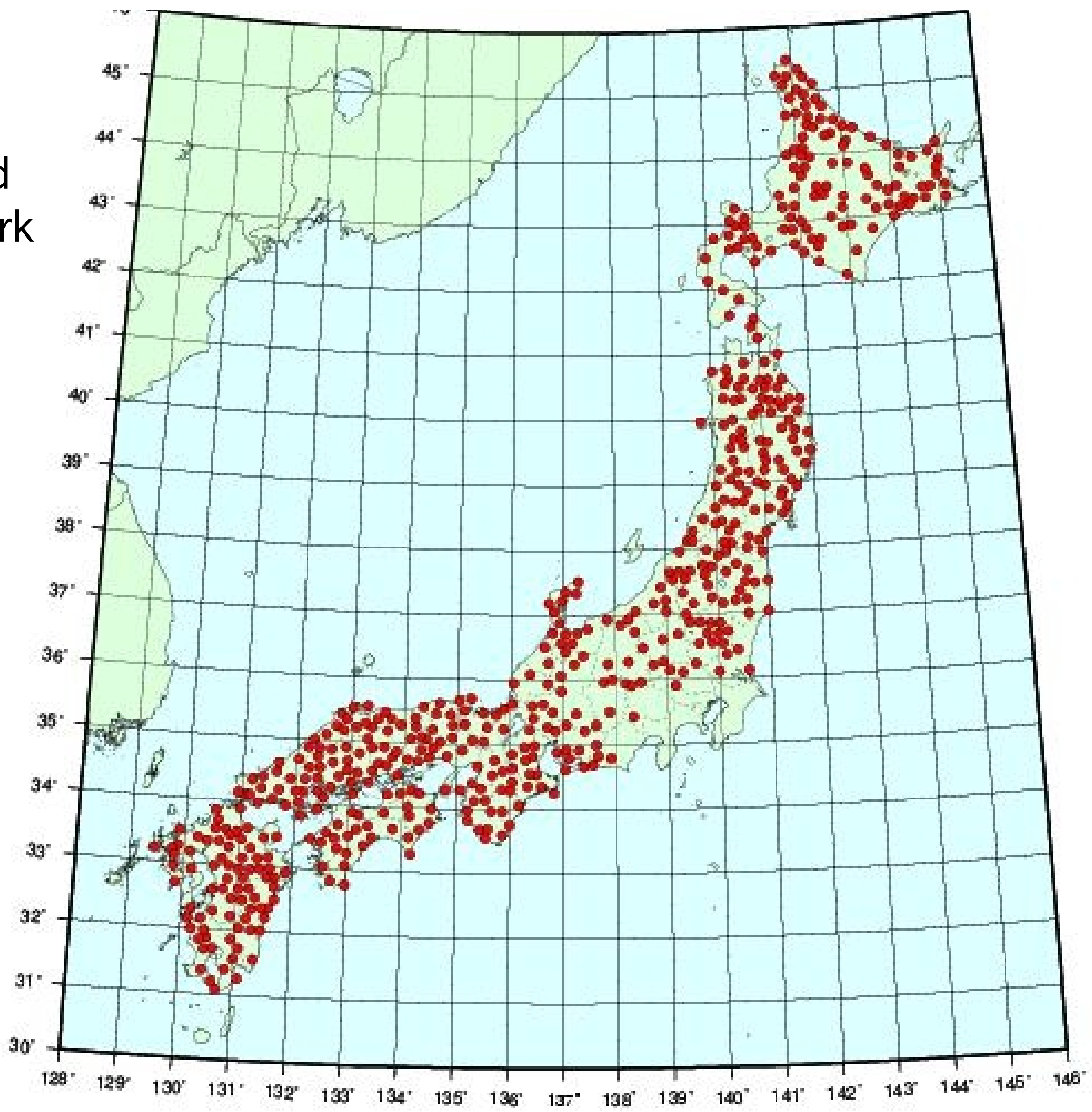
(d) Bottom of slab

T. Tonegawa, K. Hirahara, T. Shibutani, and N. Fujii (EPSL, 2006)

Examination of Hi-net Displacement Records from a Deep Earthquake

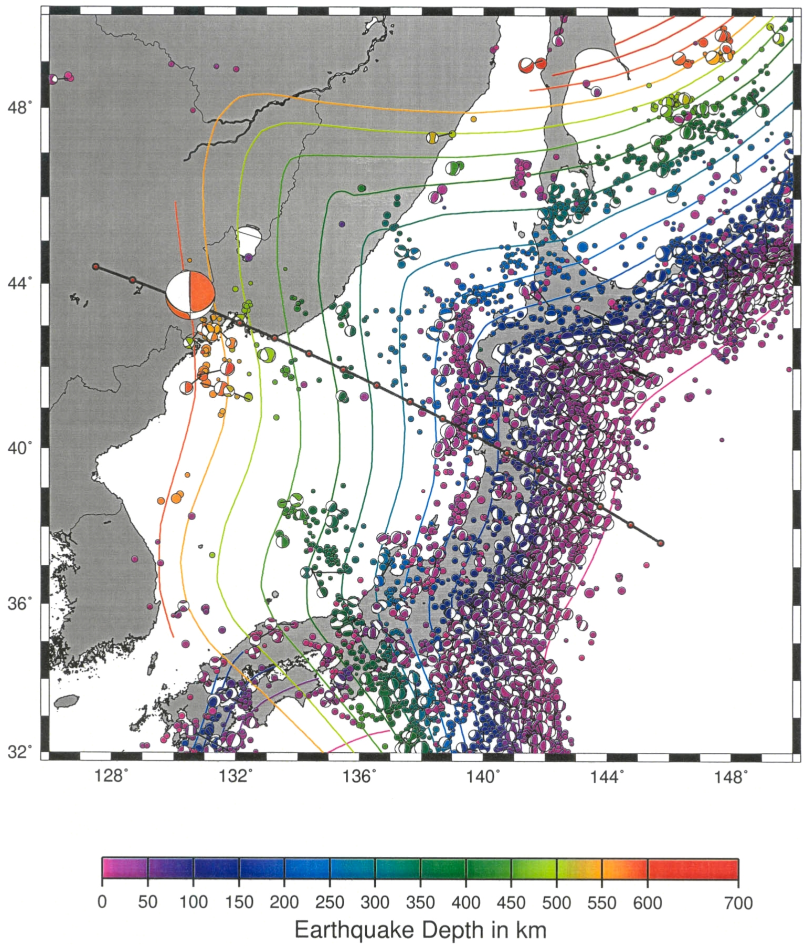
Hi-Net

500+ Station Short-Period Downhole (100 m) Network

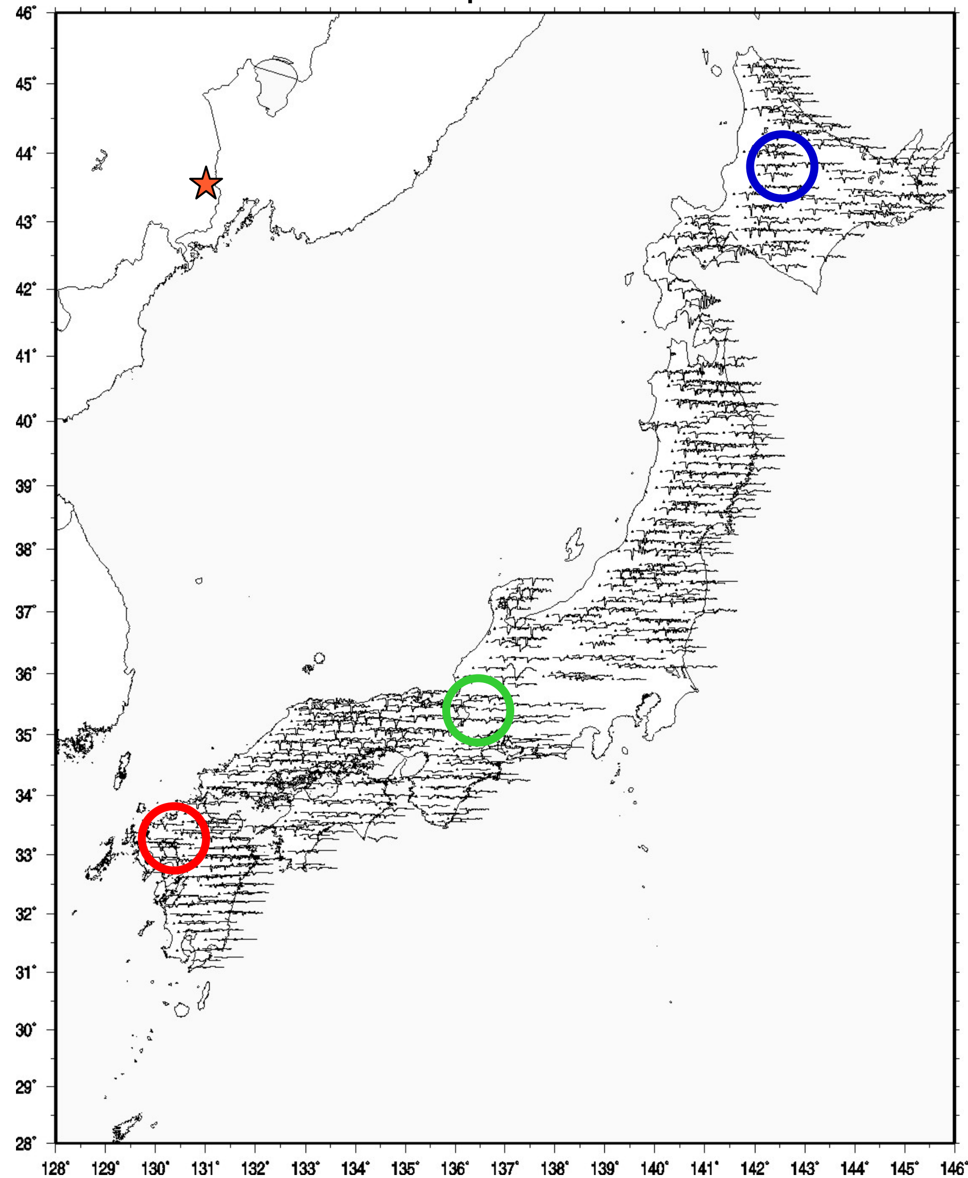


Spatially Unaliased Wave-Form

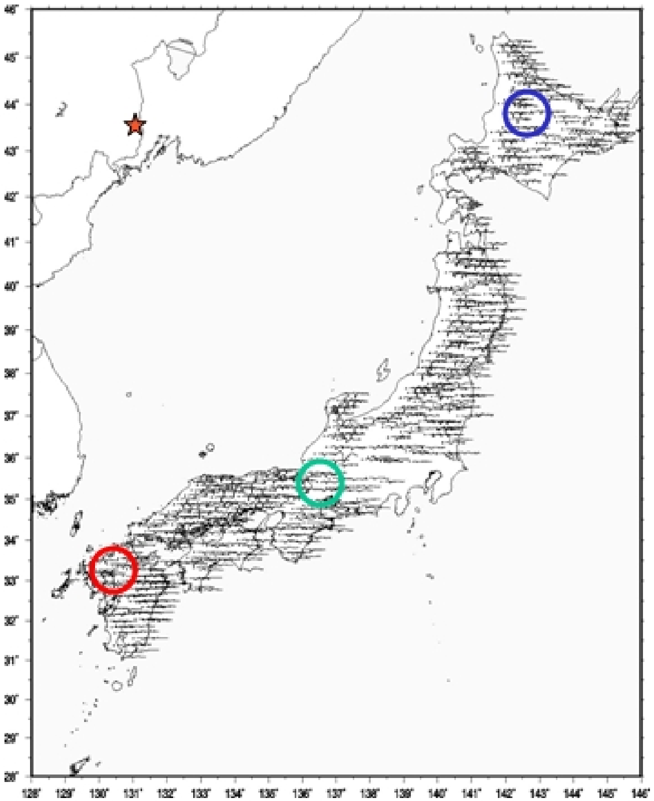
Hi-net Displacement Waveforms of 20020915 Earthquake

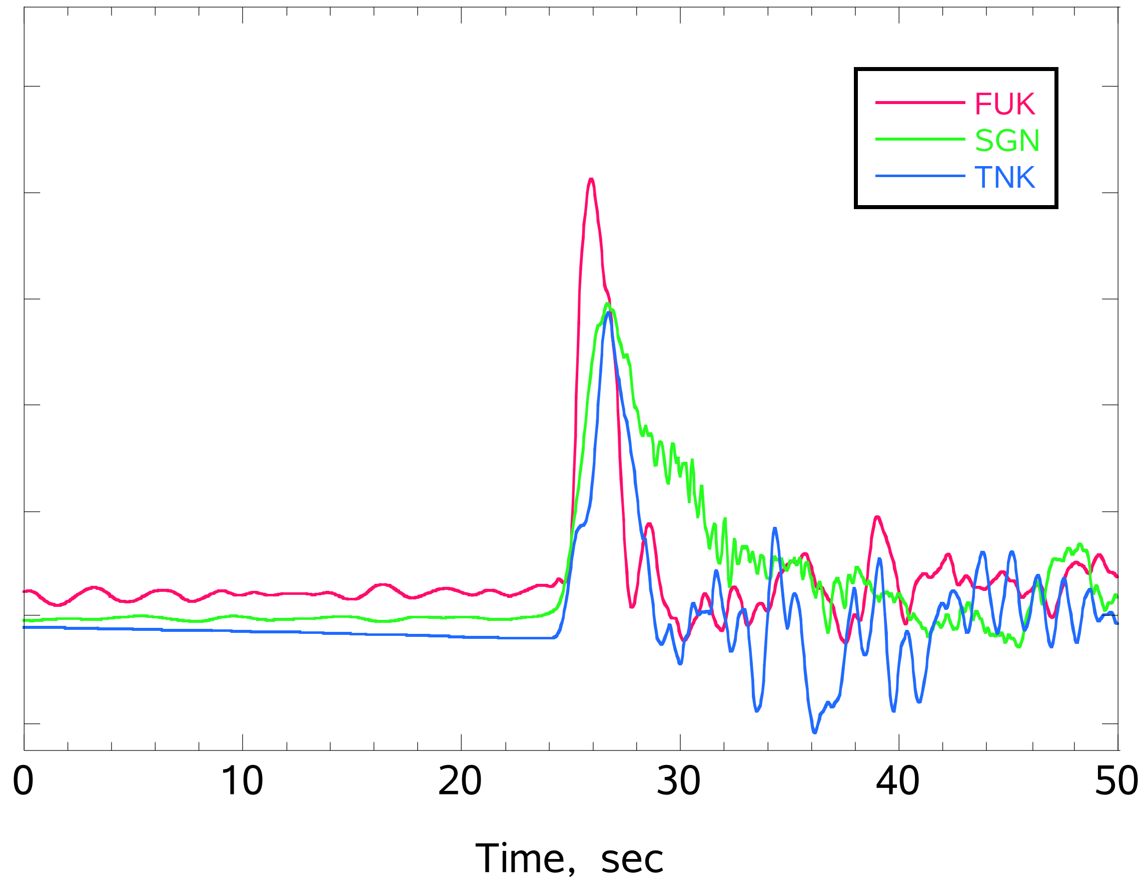


Deconvolved Displacement Waveform

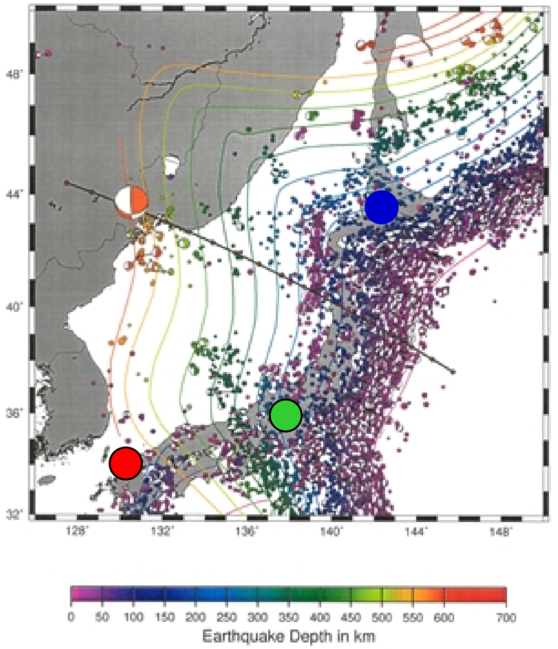


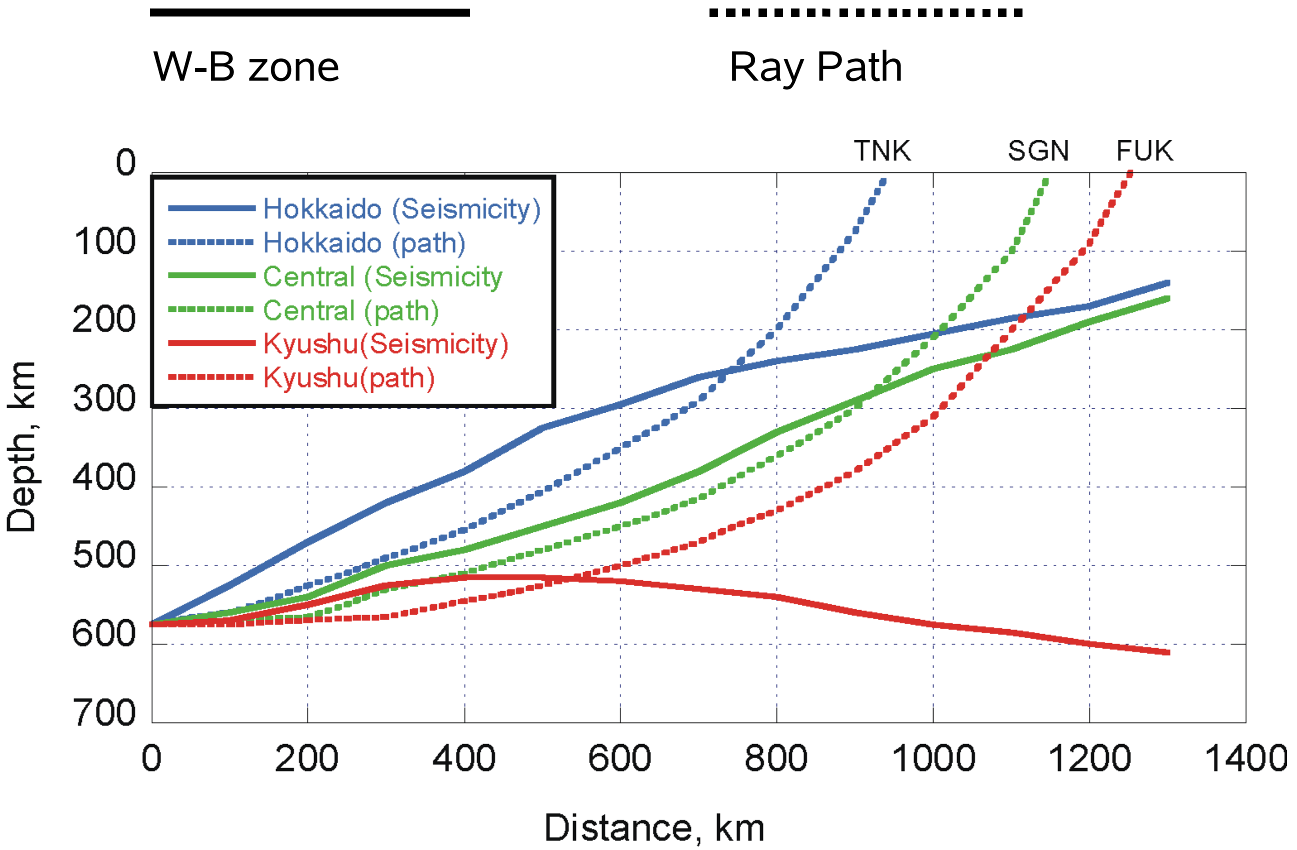
20020915 Russia-China Border Mw=6.4



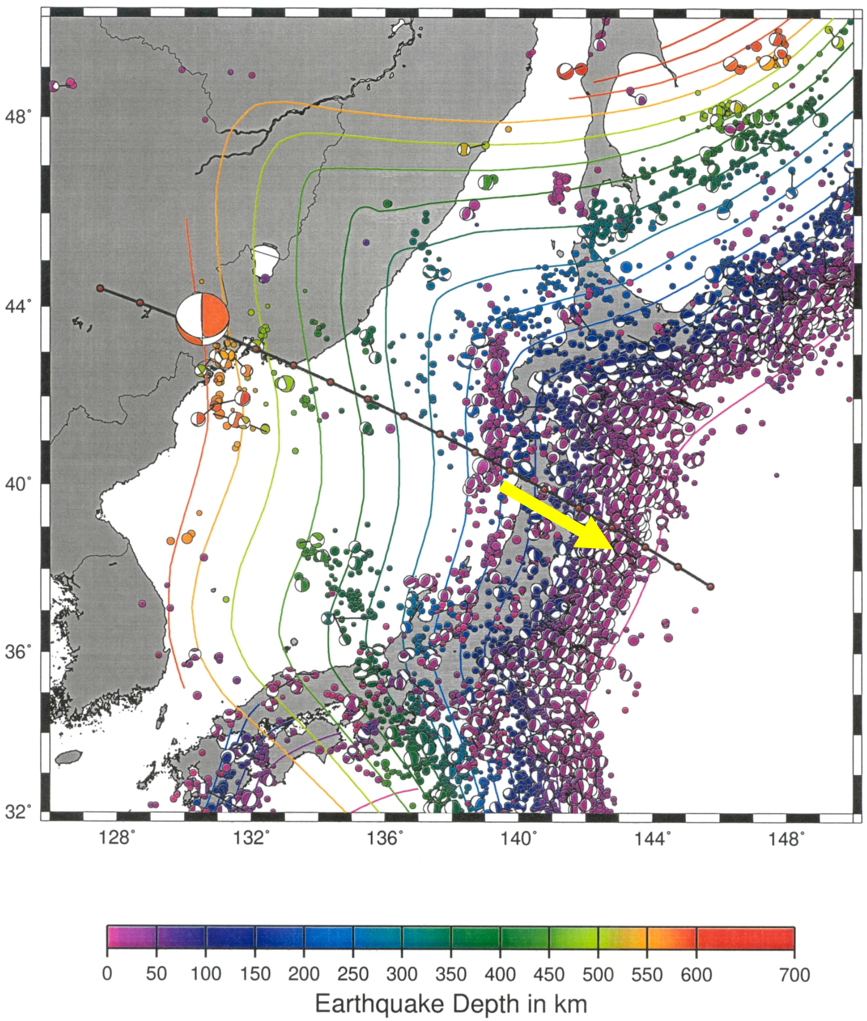


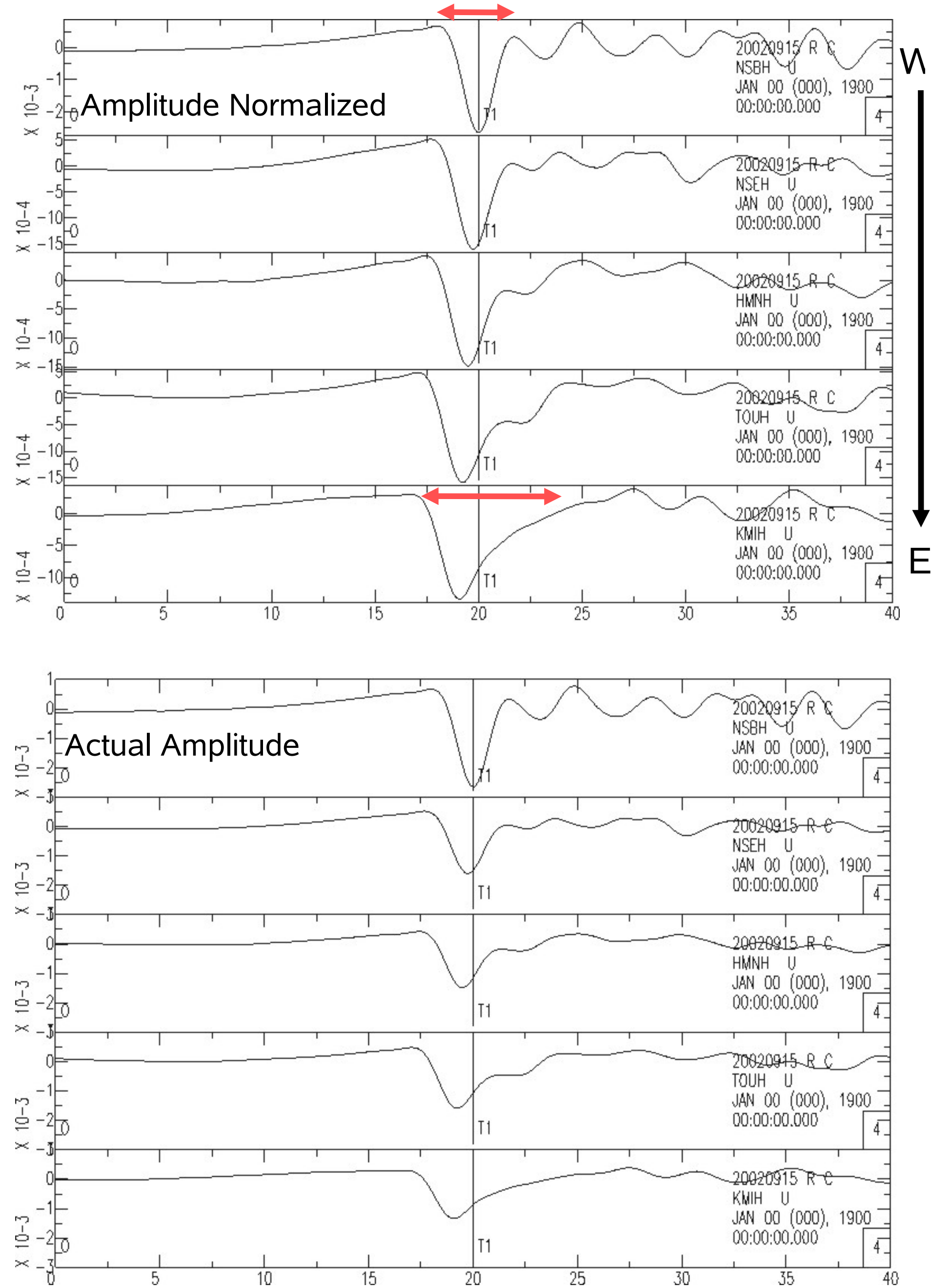
Hi-net Displacement
Waveforms of 20020915
Earthquake



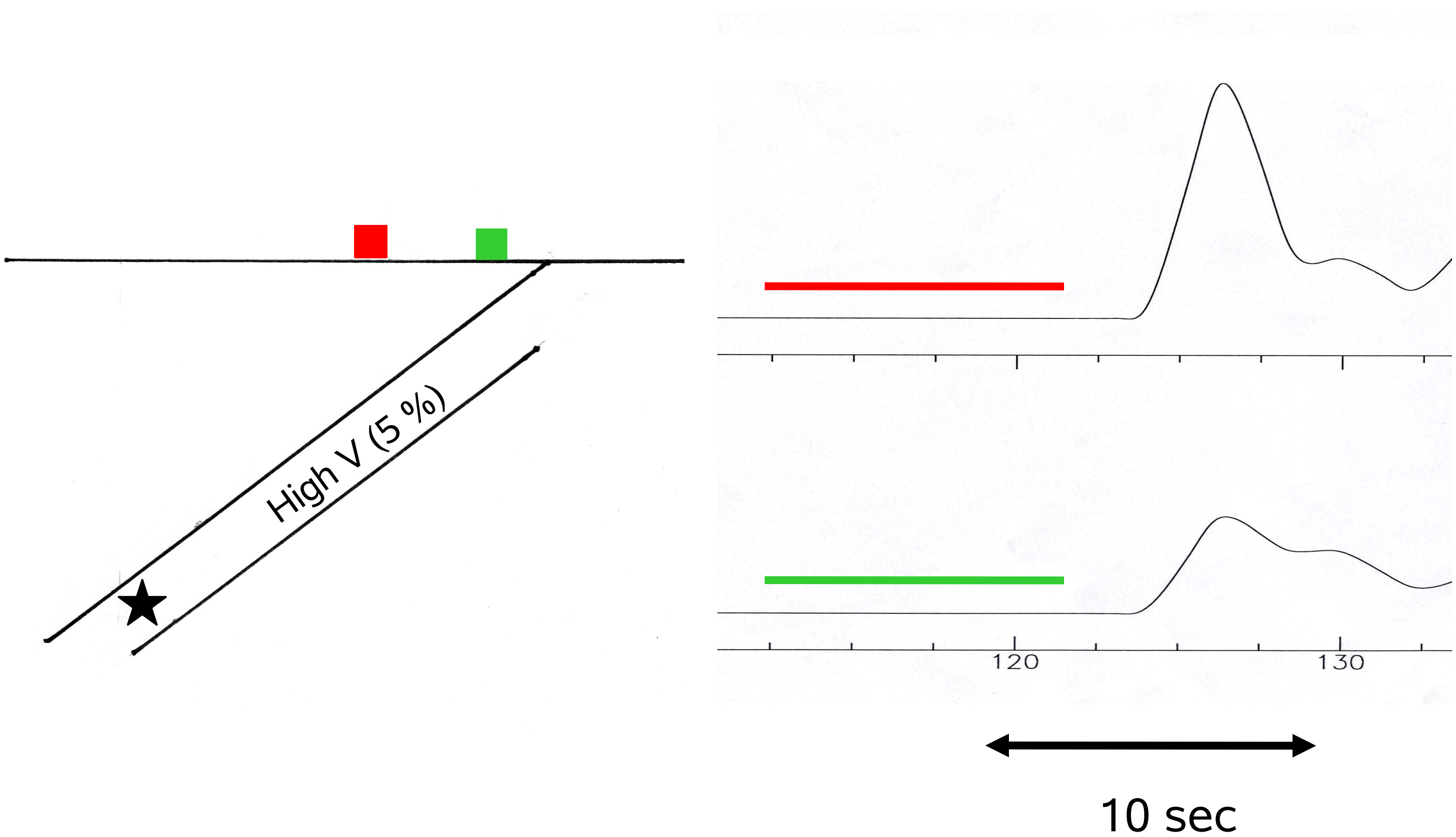


Tohoku-1 Profile



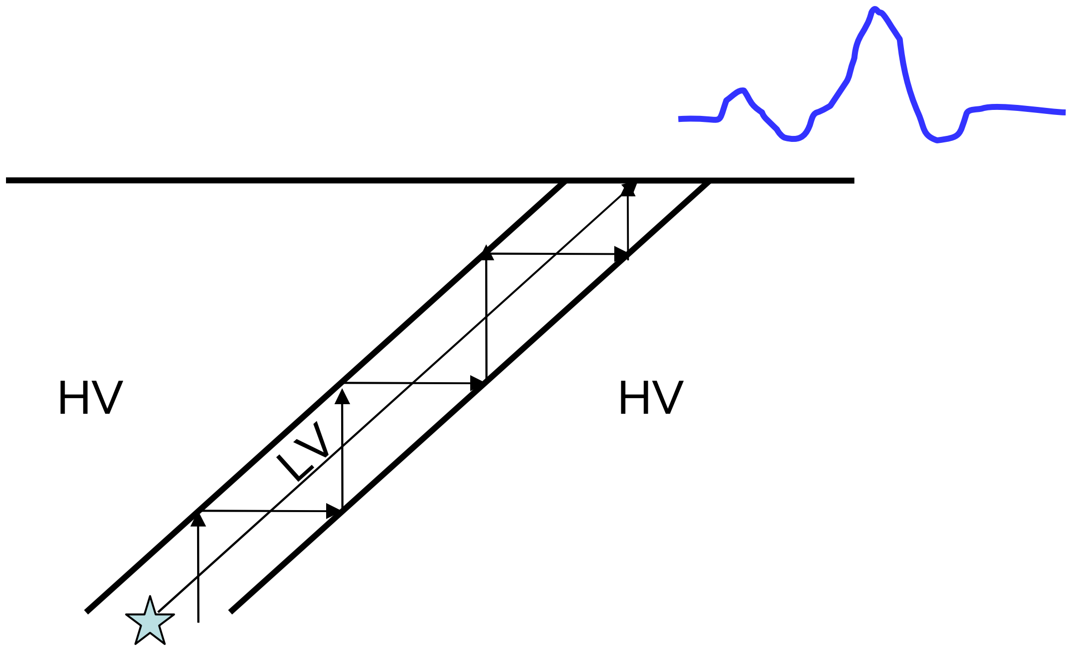


Slab Effect (Anti-waveguide, schematic)

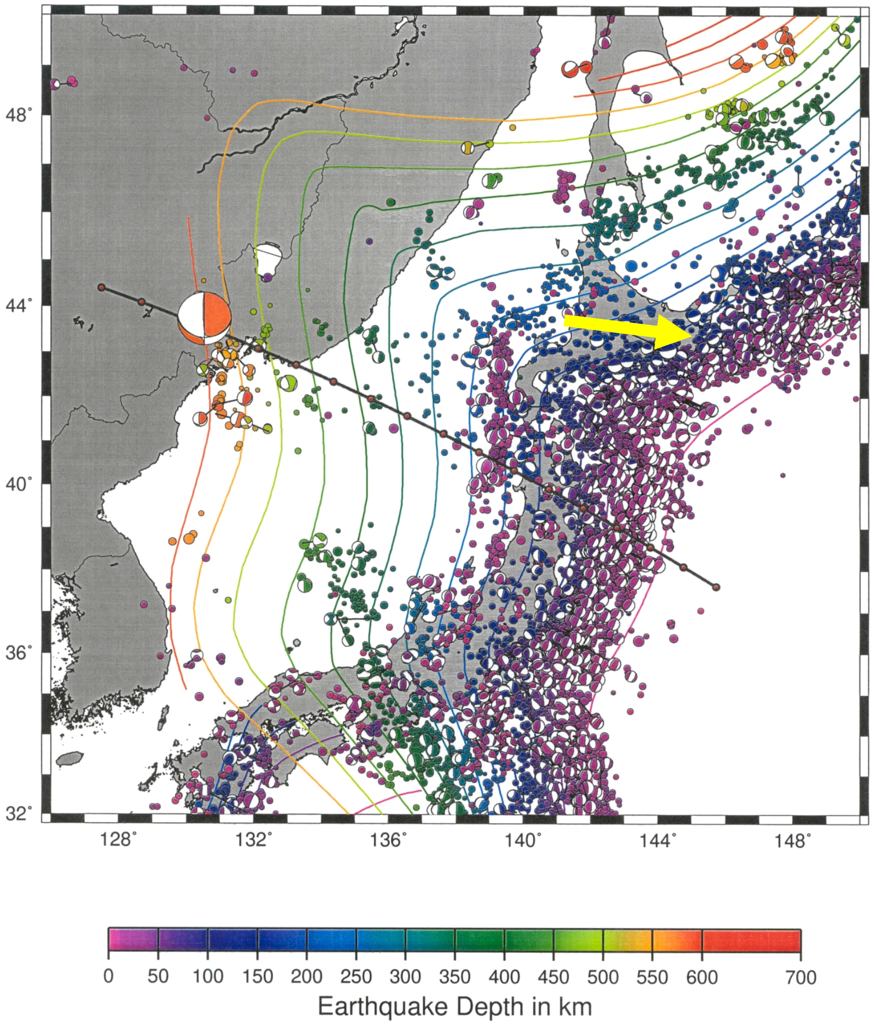


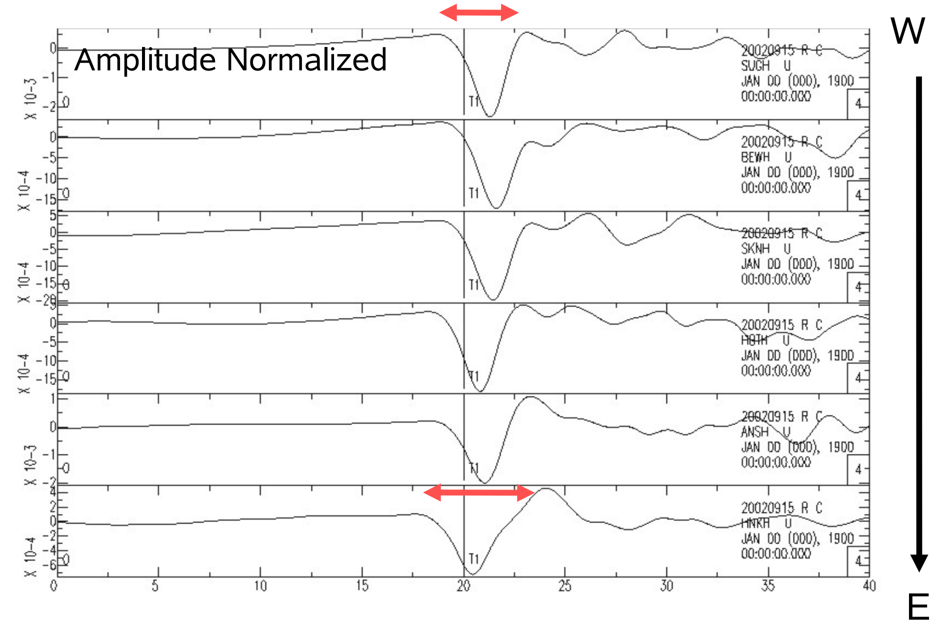
(Brian Savage)

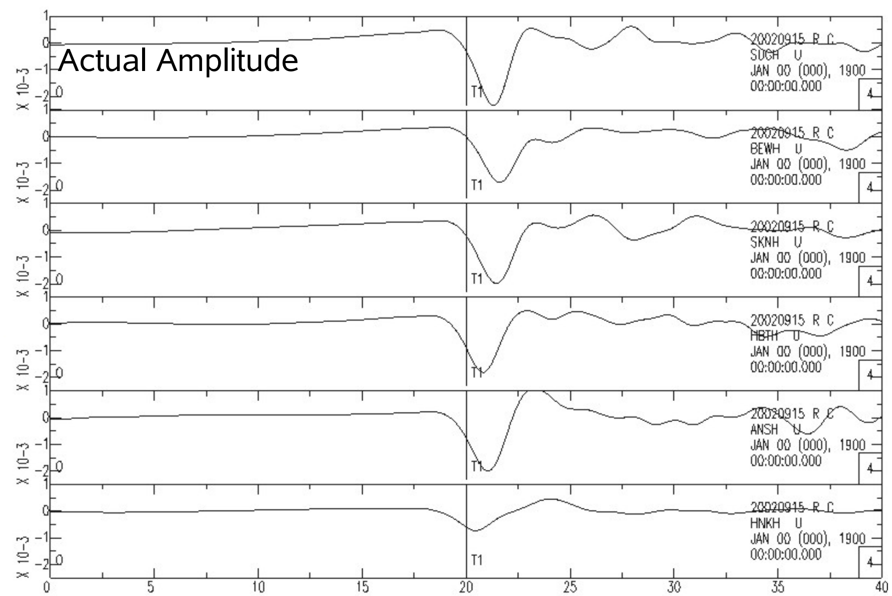
Low-velocity waveguide



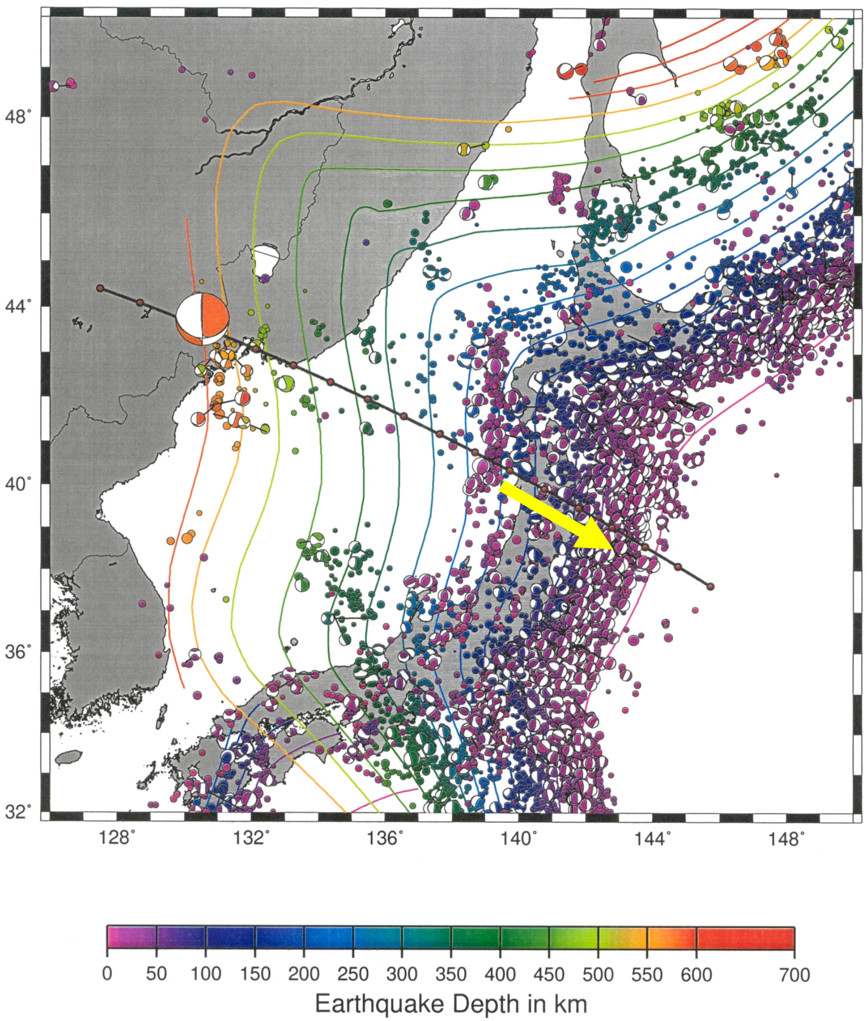
Hokkaido Profile

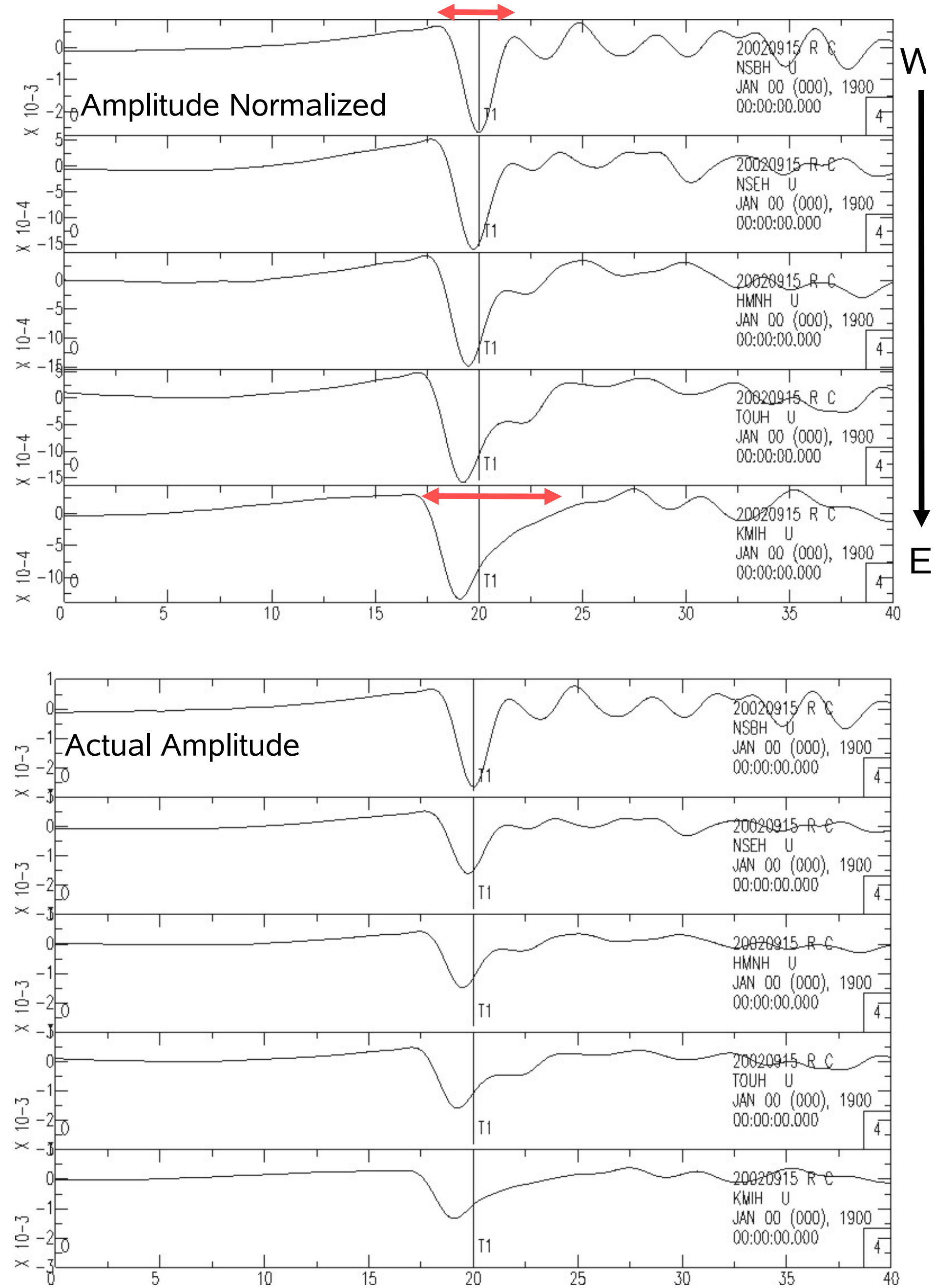




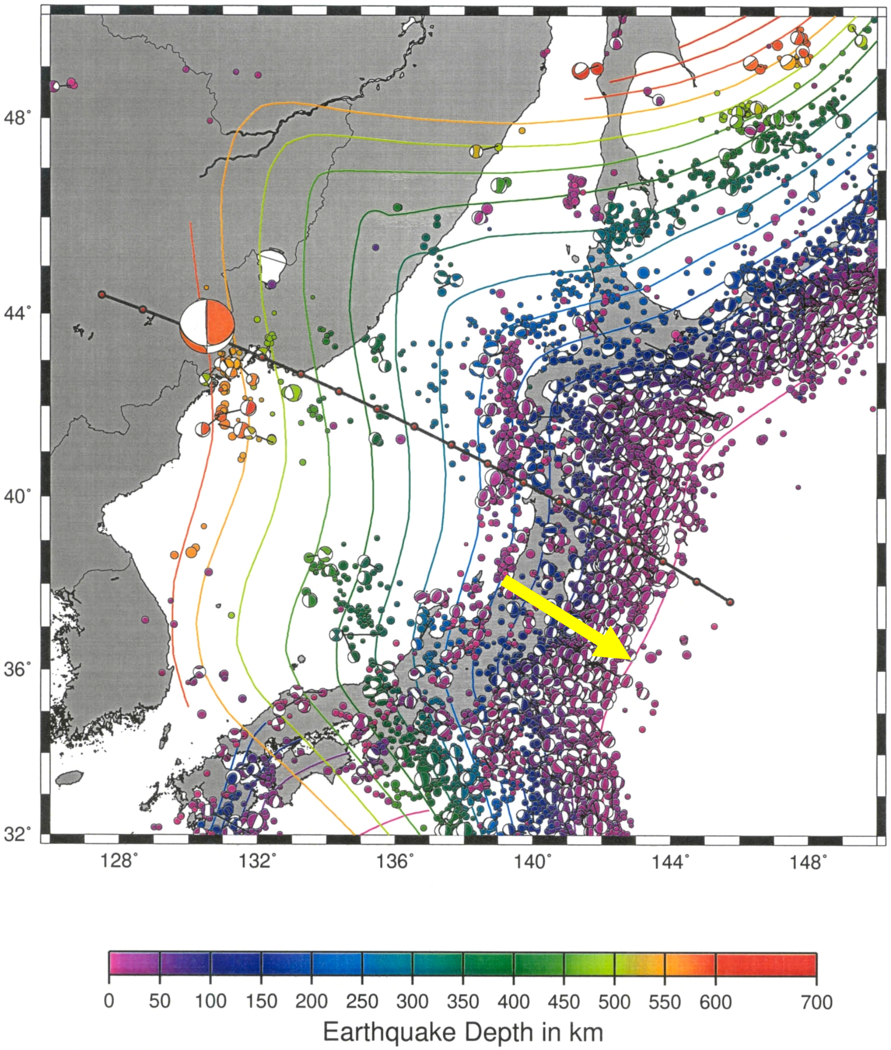


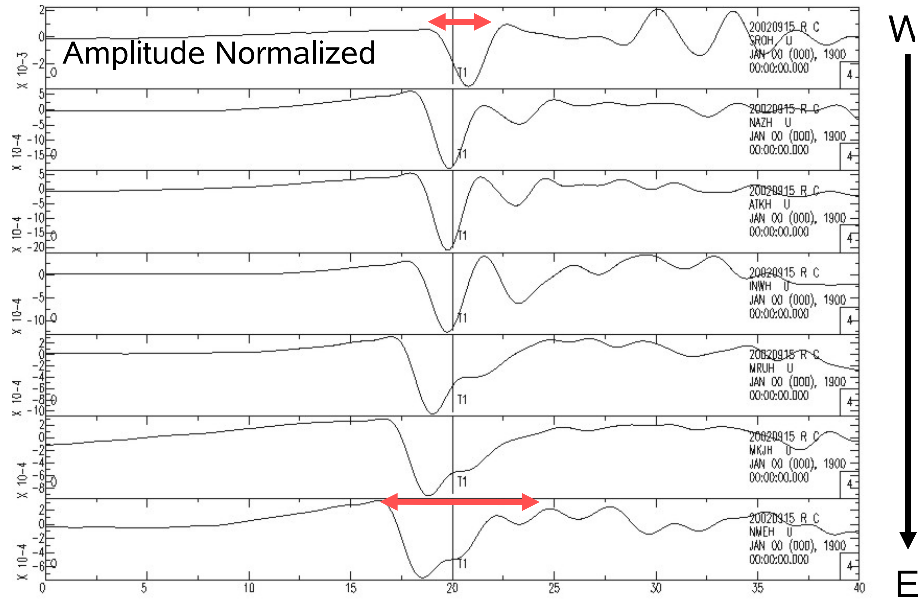
Tohoku-1 Profile

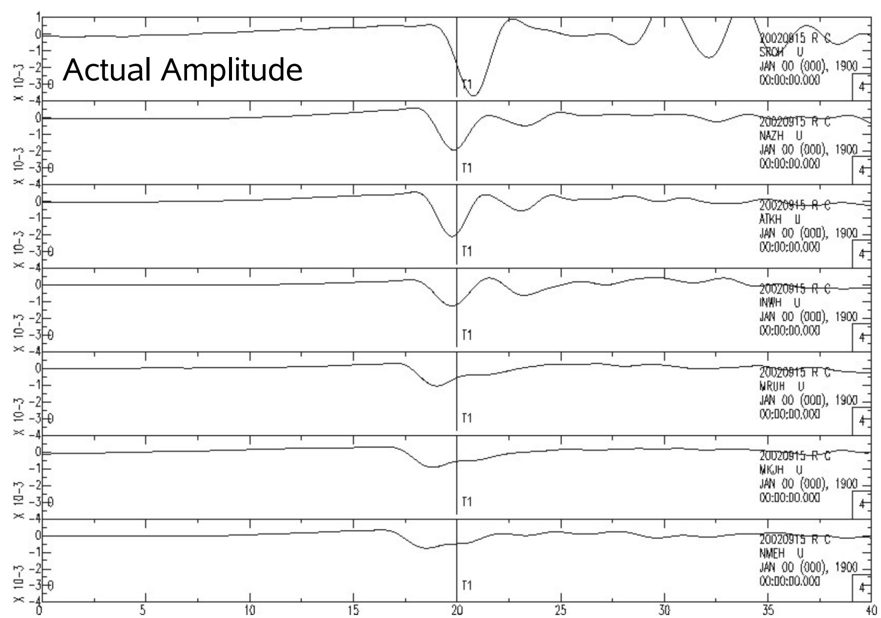




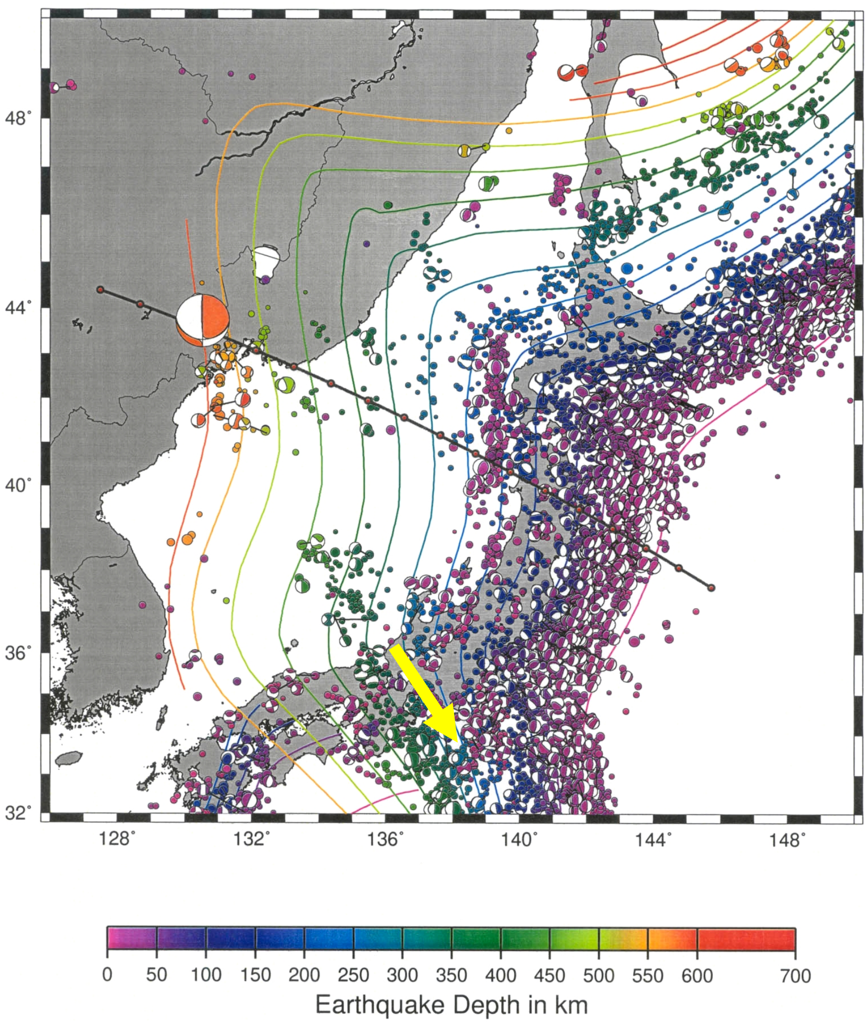
Tohoku-2 Profile

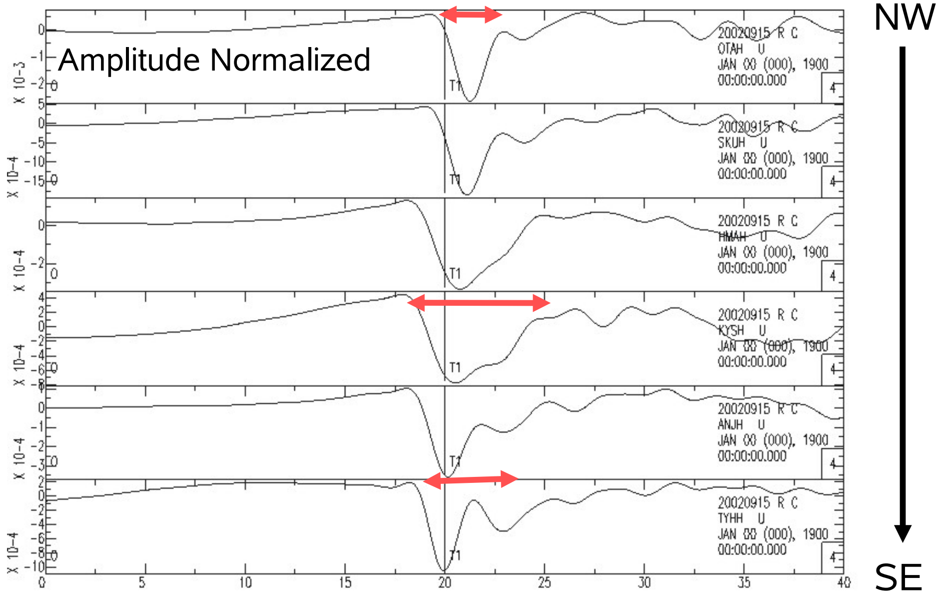


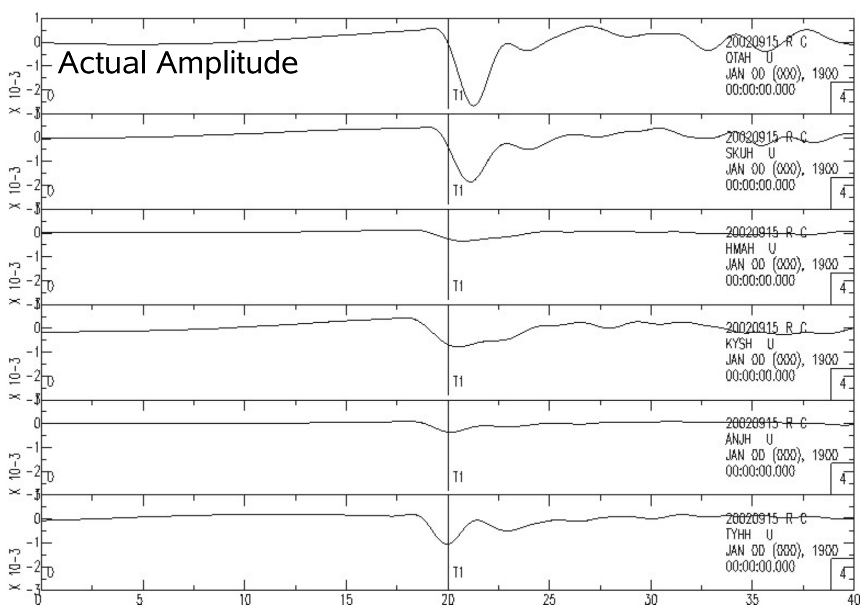




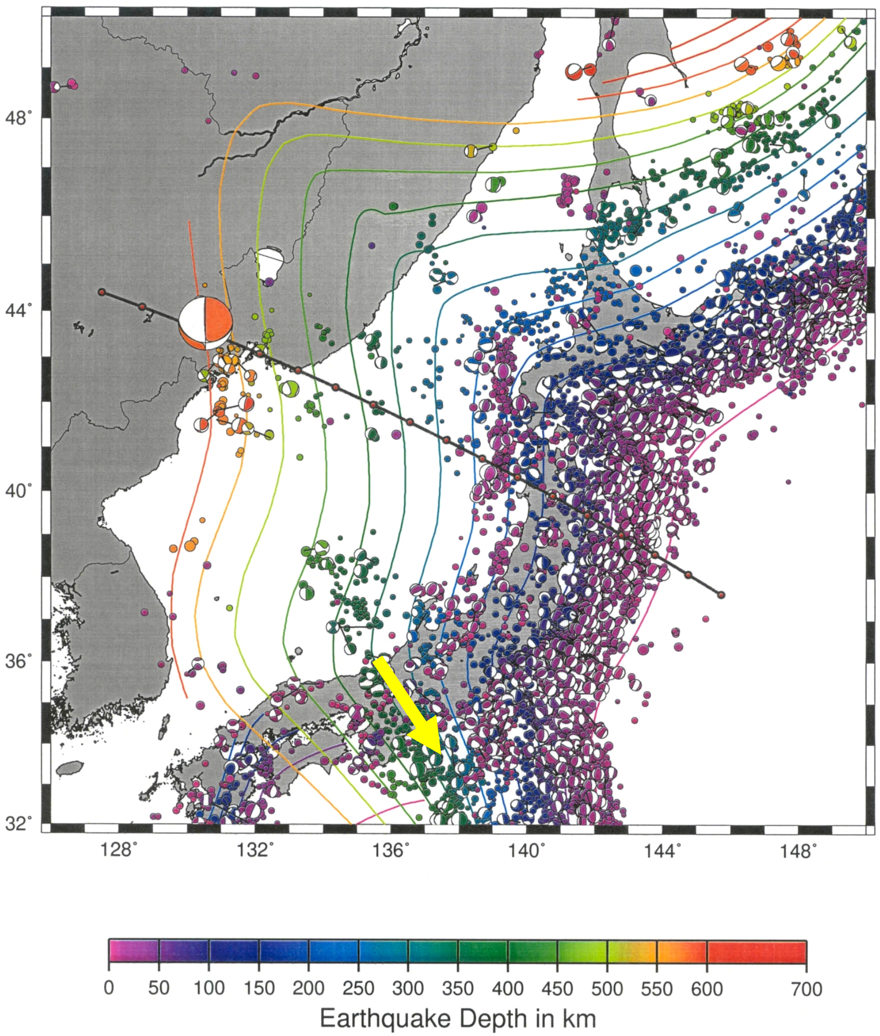
Chubu Profile

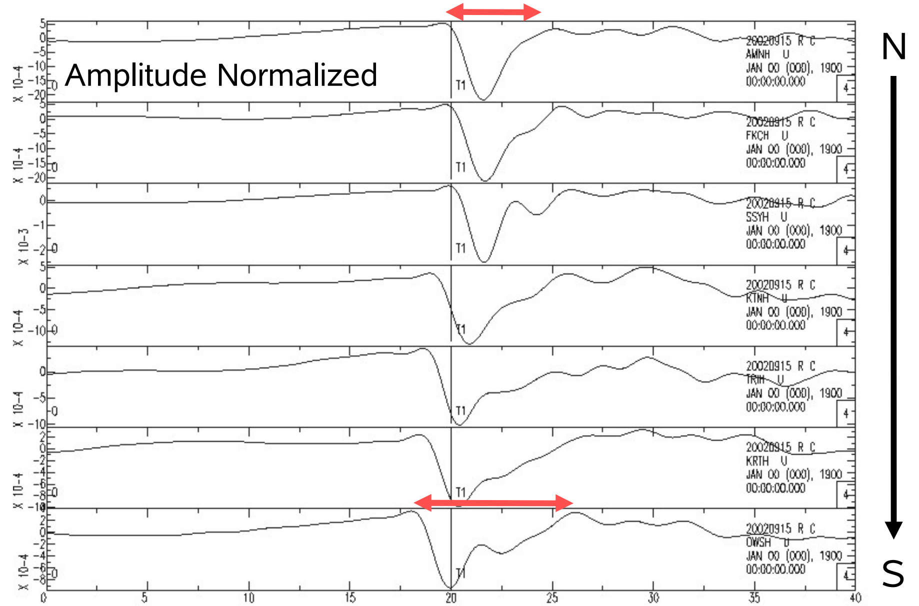


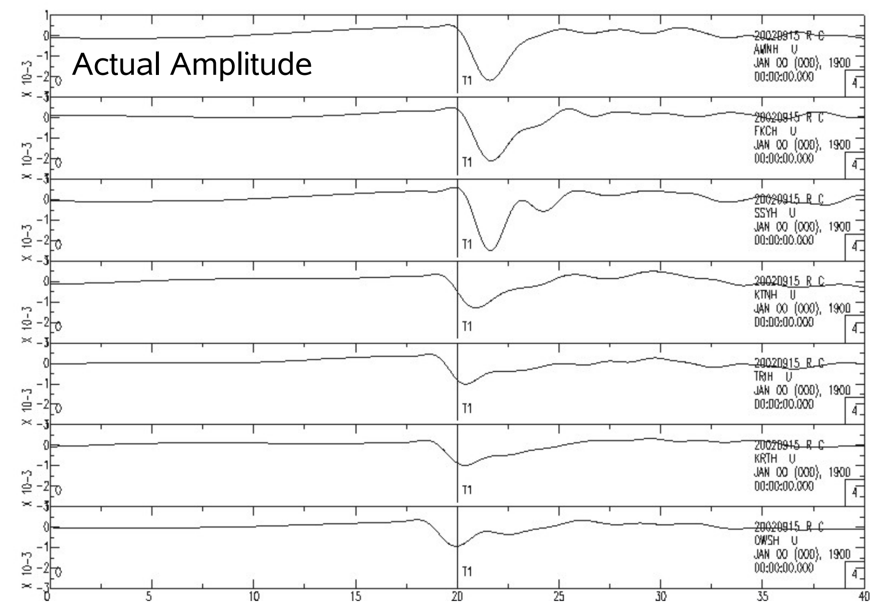




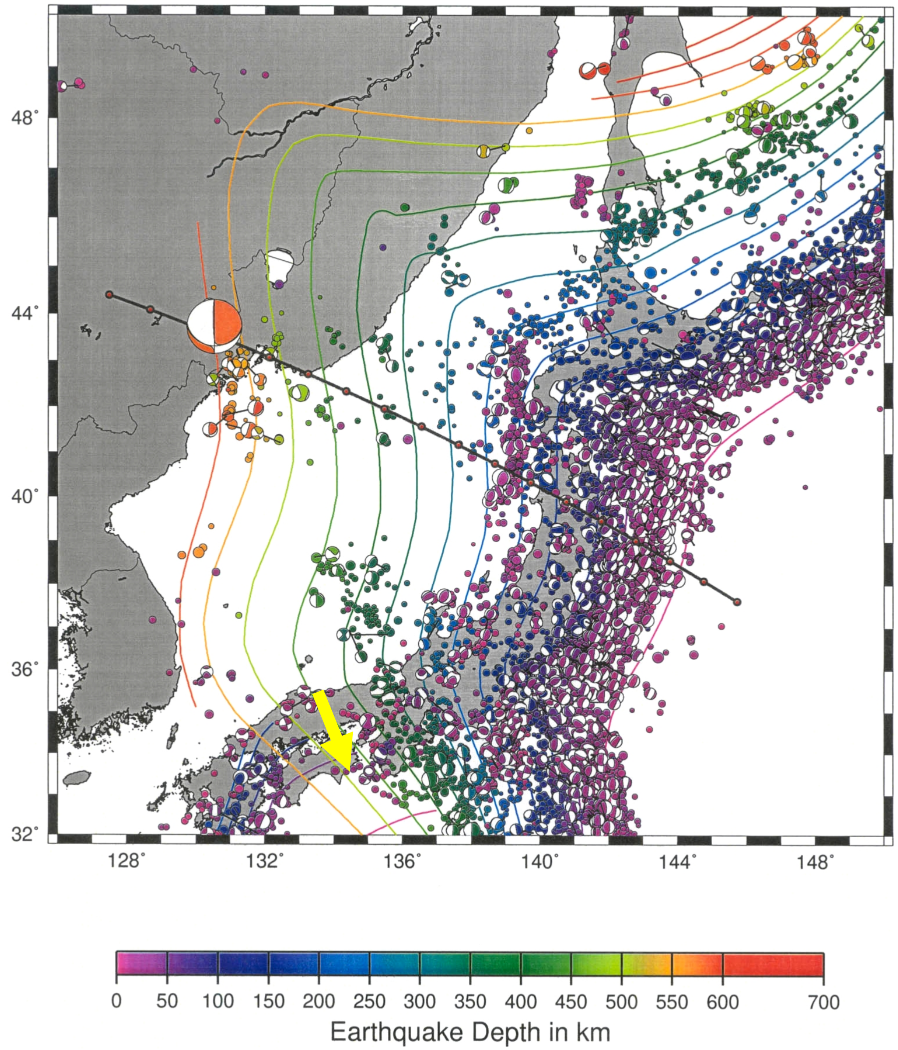
Kinki Profile

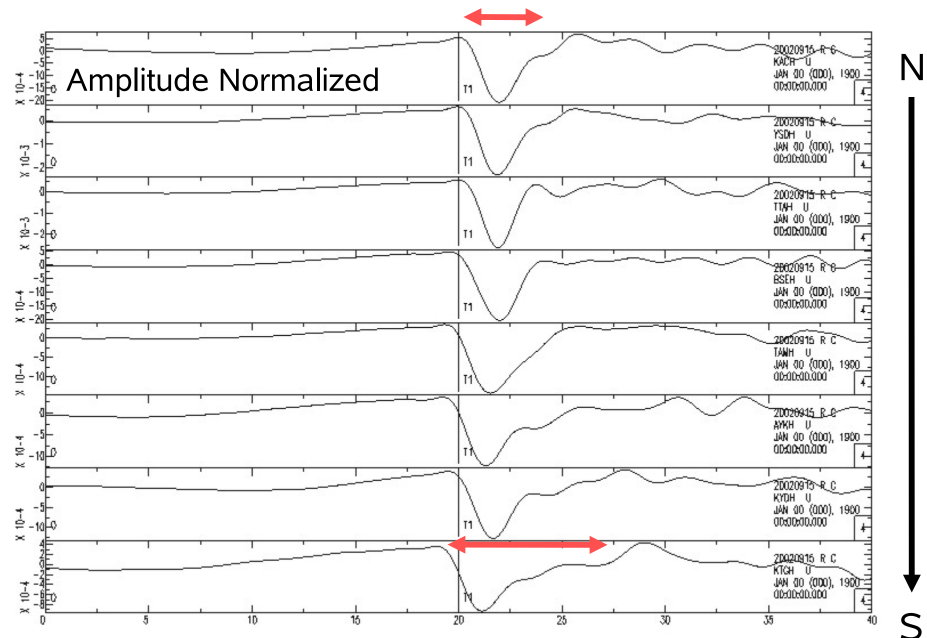


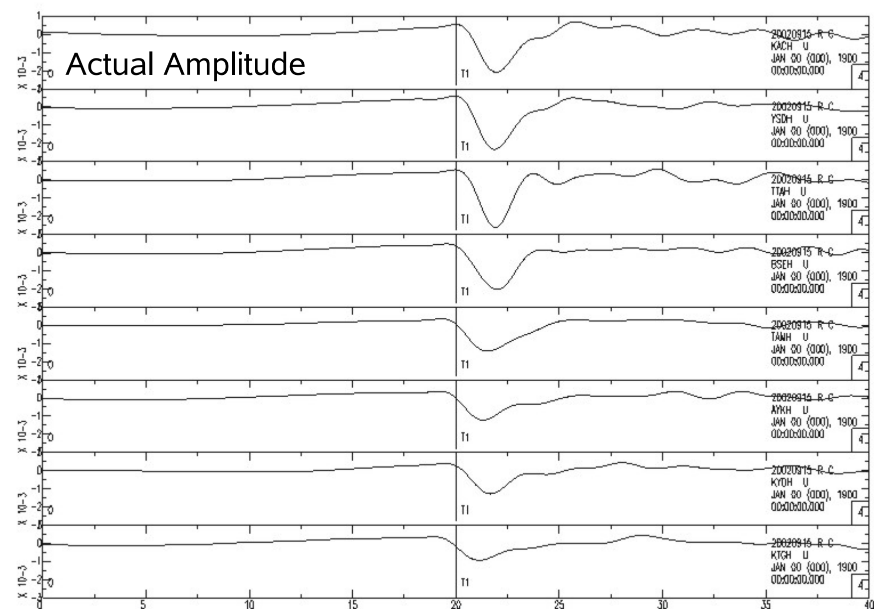




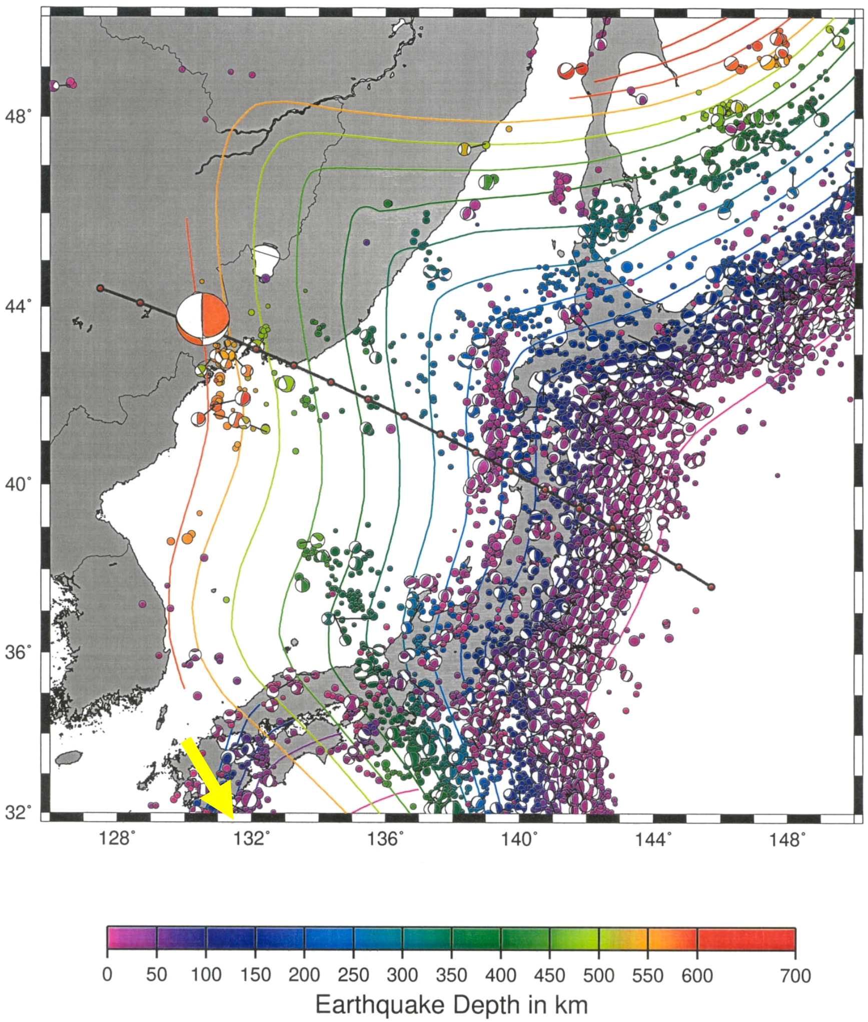
Shikoku Profile

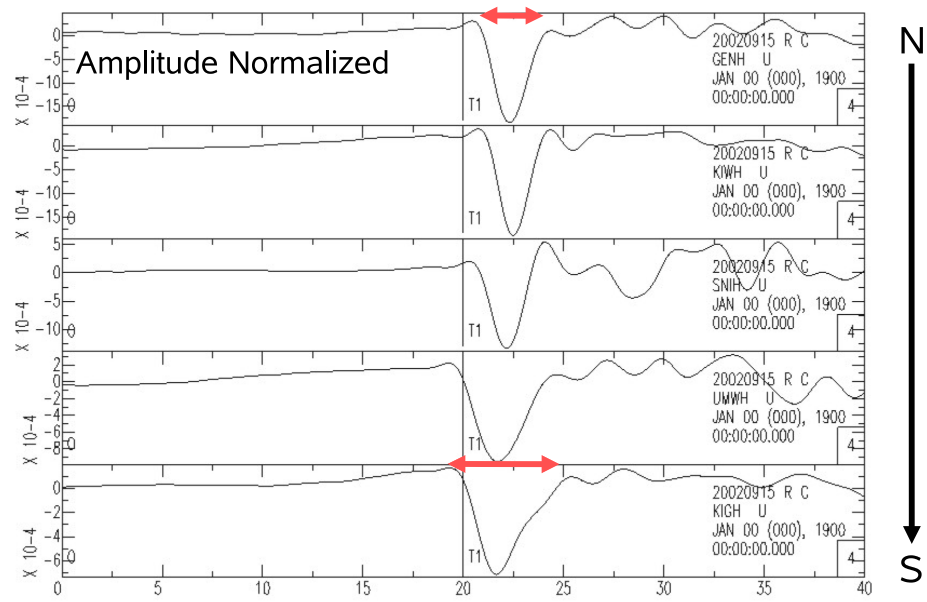


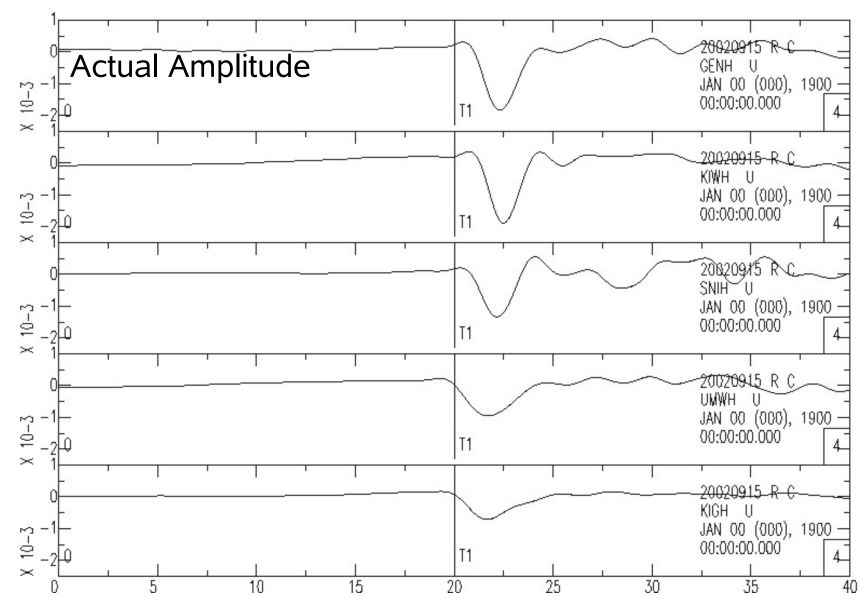




Kyushu Profile







Waveform Modeling of the Slab Beneath Japan

Min Chen, Jeroen Tromp, Don Helmberger,
and Hiroo Kanamori

(JGR, 112, B02305, doi:10.1029/2006JB004394, 2007)

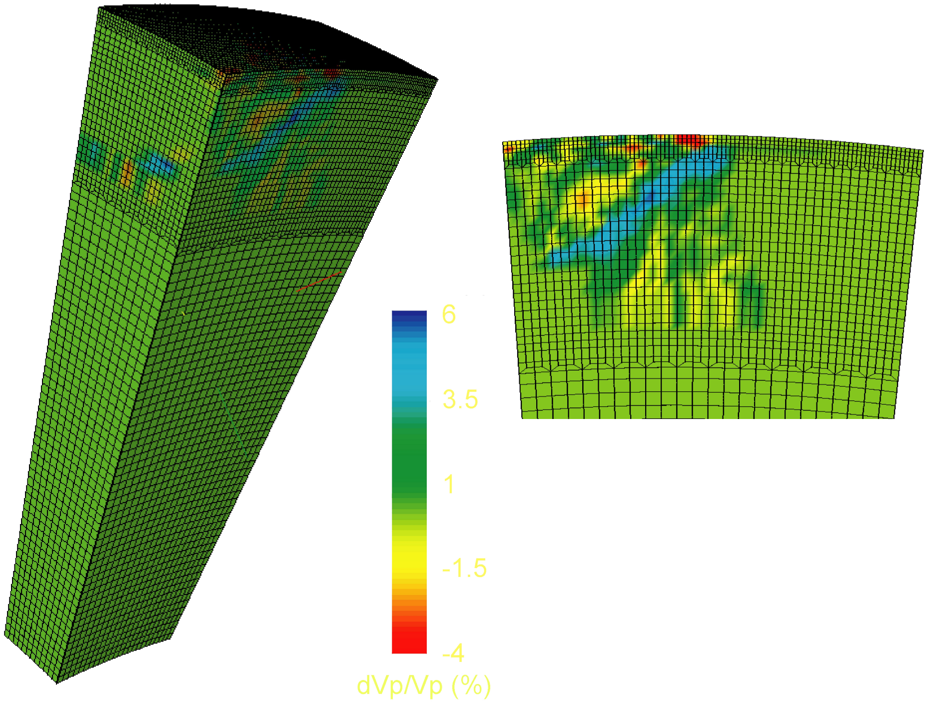
- **Numerical methods of forward waveform modeling**:
  - **SEM** : 3D Spectral Element Method (***Komatitsch & Tromp***).
  - **FDM** : 2D Finite Difference Method (***Vidale, Helmberger & Clayton***)

Numerical simulations

Benchmark of regional P-model (Zhao et al., 1994)

- 3D spectral element method (SEM)
  - Larger grid size (3.5 km in the upper mantle)
  - > 3s accuracy of synthetics
  - 4 hours on 25 dell parallel processors, 3-component synthetics for all stations

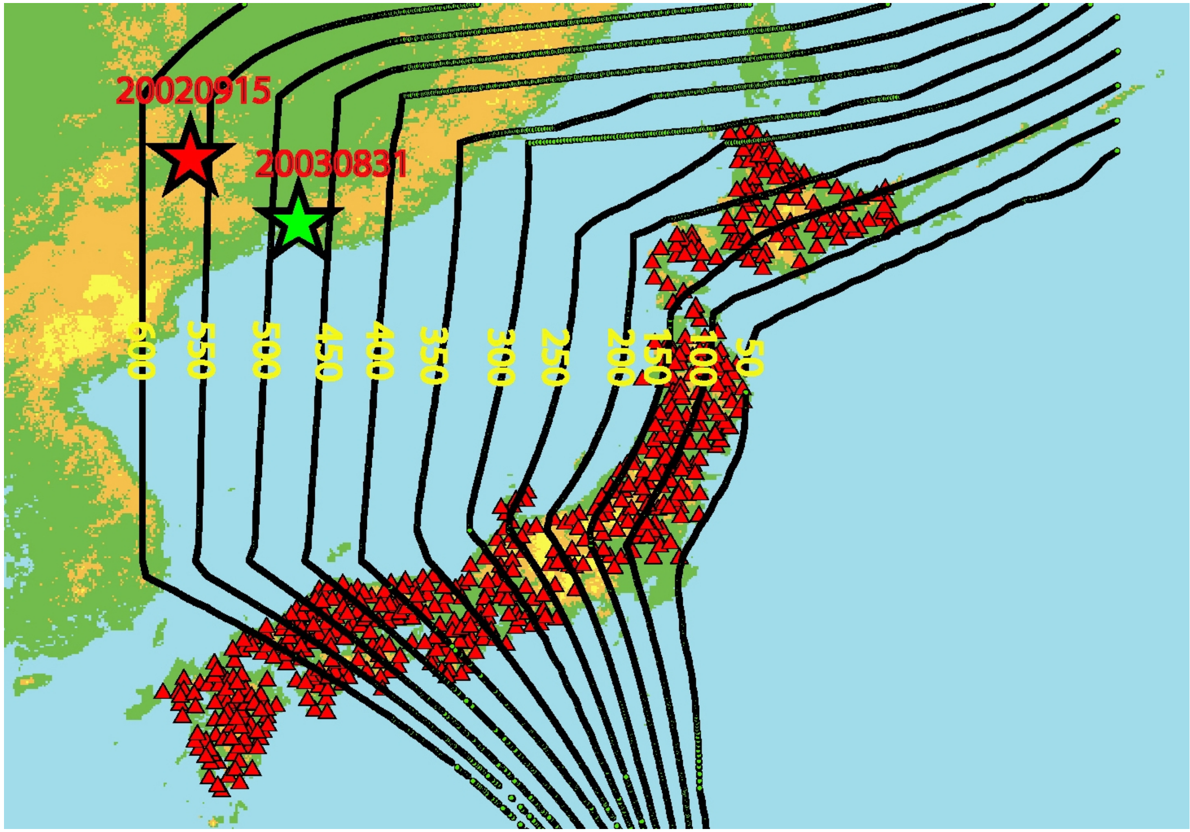
- 2D Finite Difference Method (FD)
  - Smaller grid size (1km at all depths)
  - > 1s accuracy of synthetics
  - Several minutes on one single CPU, synthetics for stations in each 2-degree azimuthal interval



SEM mesh configuration

2 of the total 25 slices

Hi-Net stations and 2 deep events

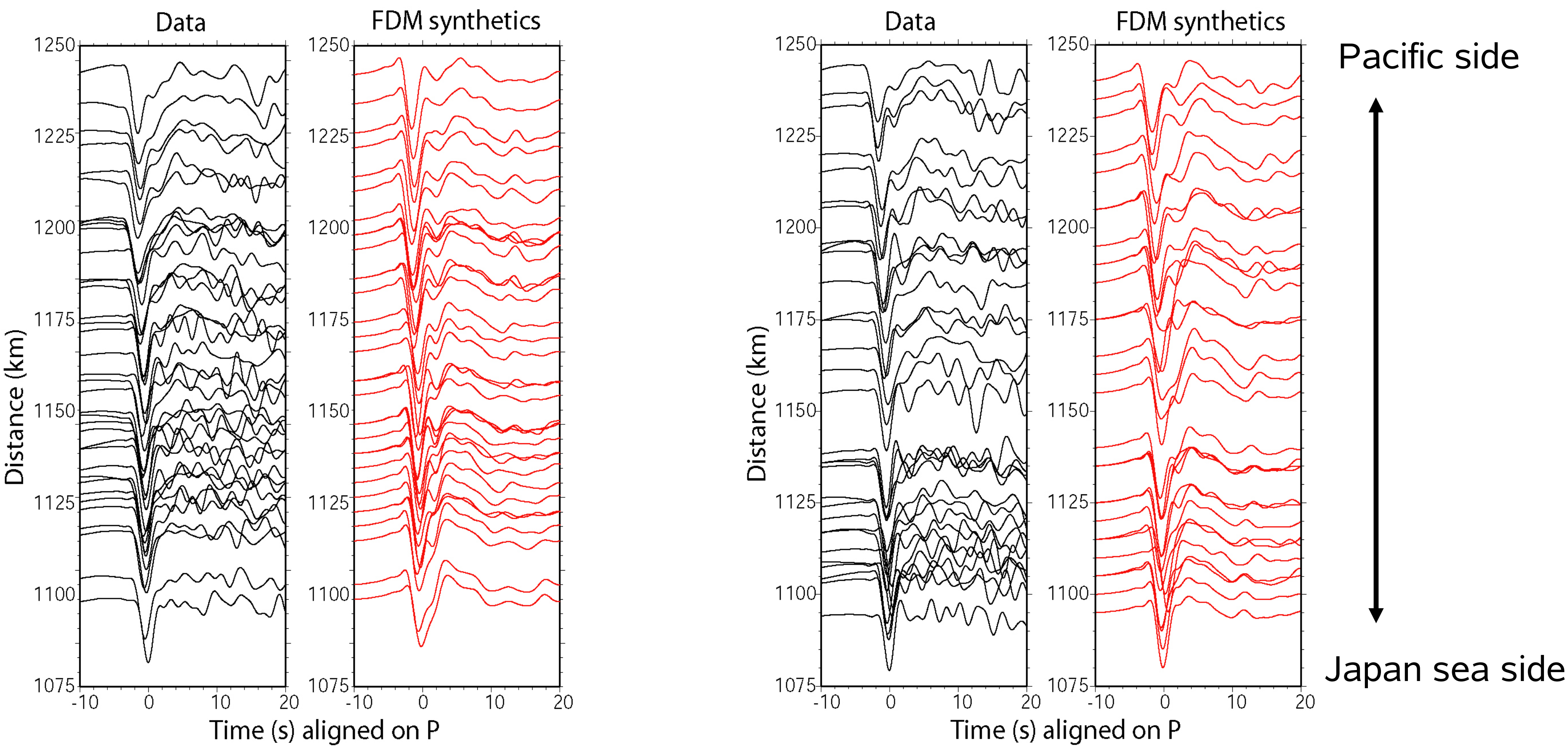


Hi-Net stations : > 600

Event 20020915 : 589 km

Event 20030831 : 492 km

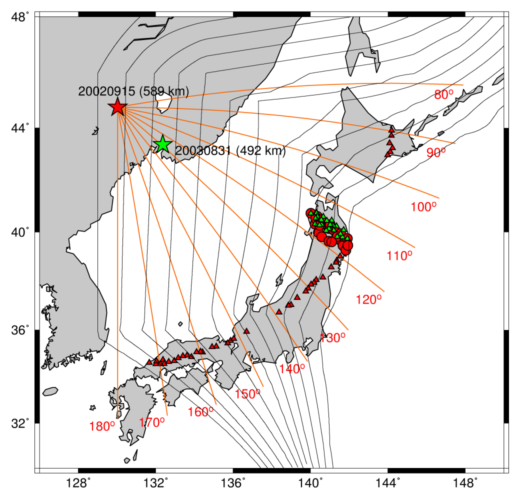
Comparison between P-wave data and FDM synthetics

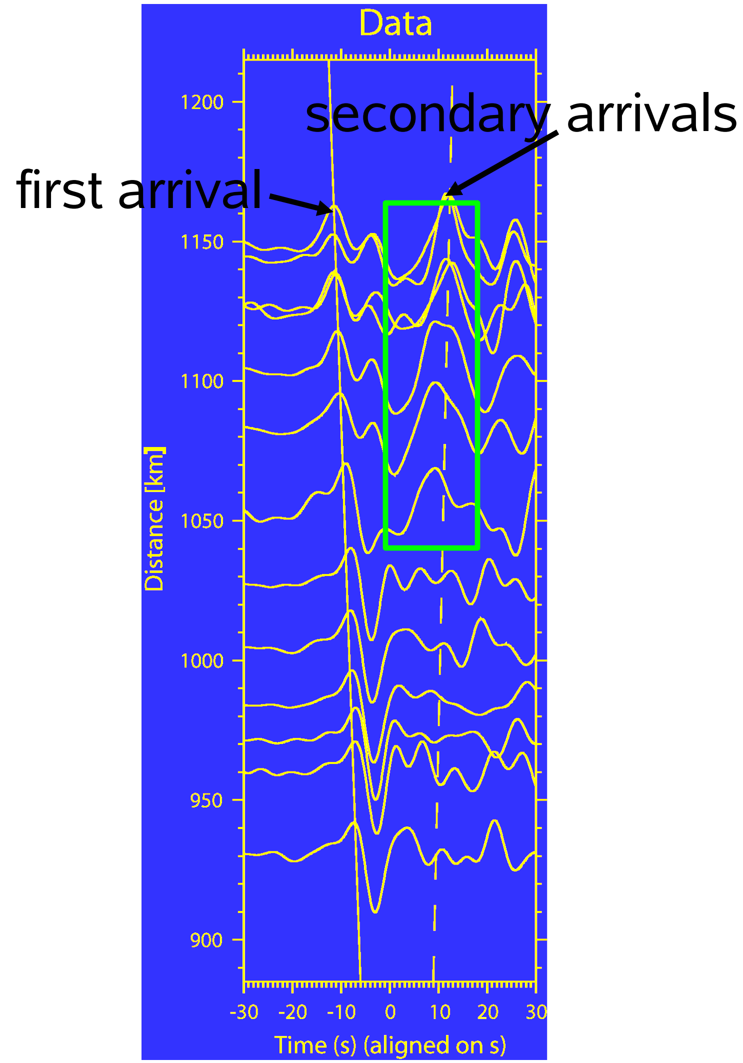


Azimuthal range : 120 – 130 °

Azimuthal range : 130 – 140 °

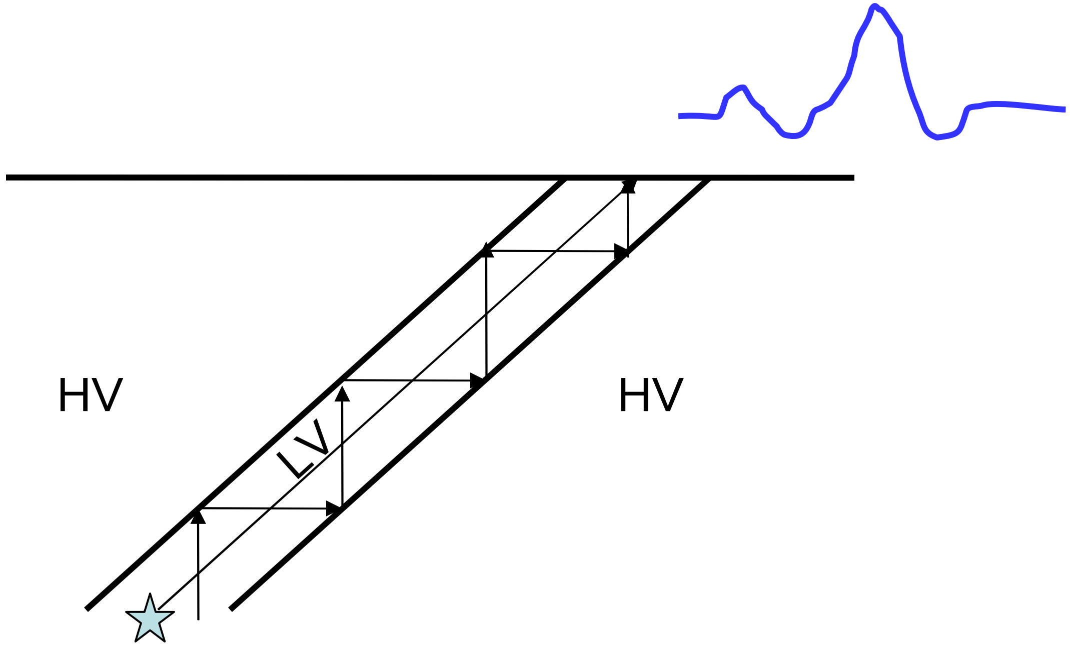
SH wave 2D waveform modeling



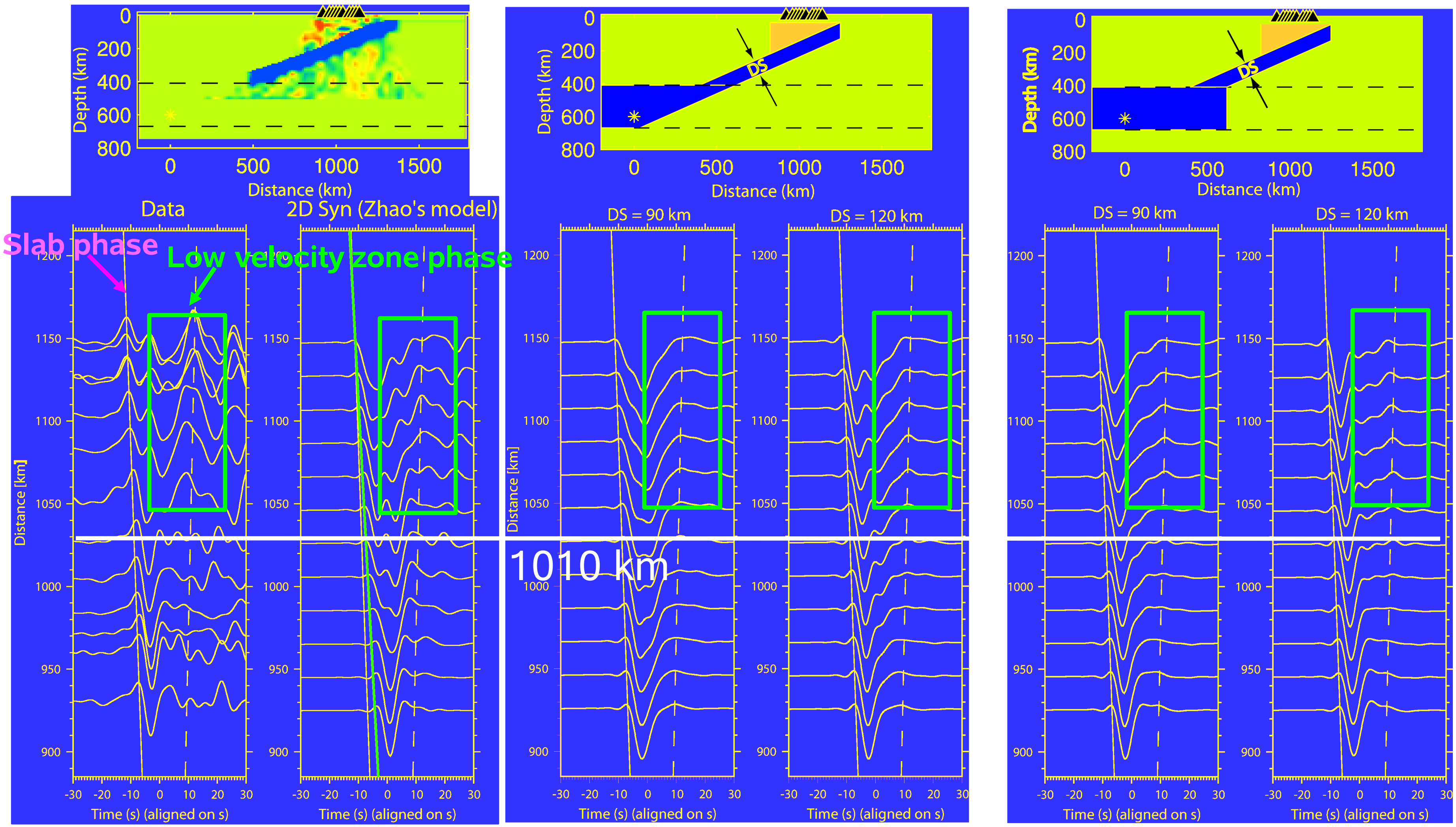


- Stack SH-wave data for station in NE Japan (2D corridor) from a single deep event.
- Construct the base model to produce correct first arrivals at all distances by adding slab in the transition zone.
- Model the secondary SH arrivals by adding a low velocity layer (LVL).

Low-velocity waveguide



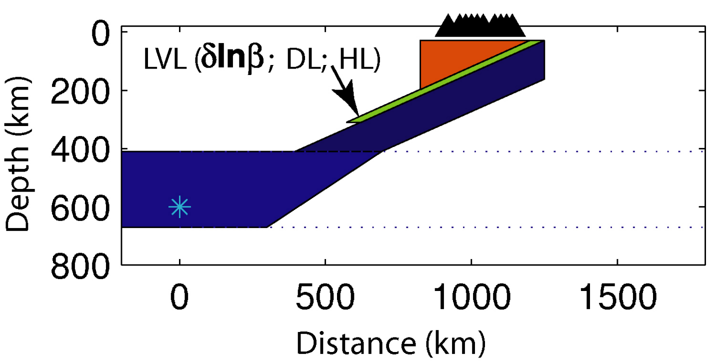
Construction of the base model
slab in the transition zone

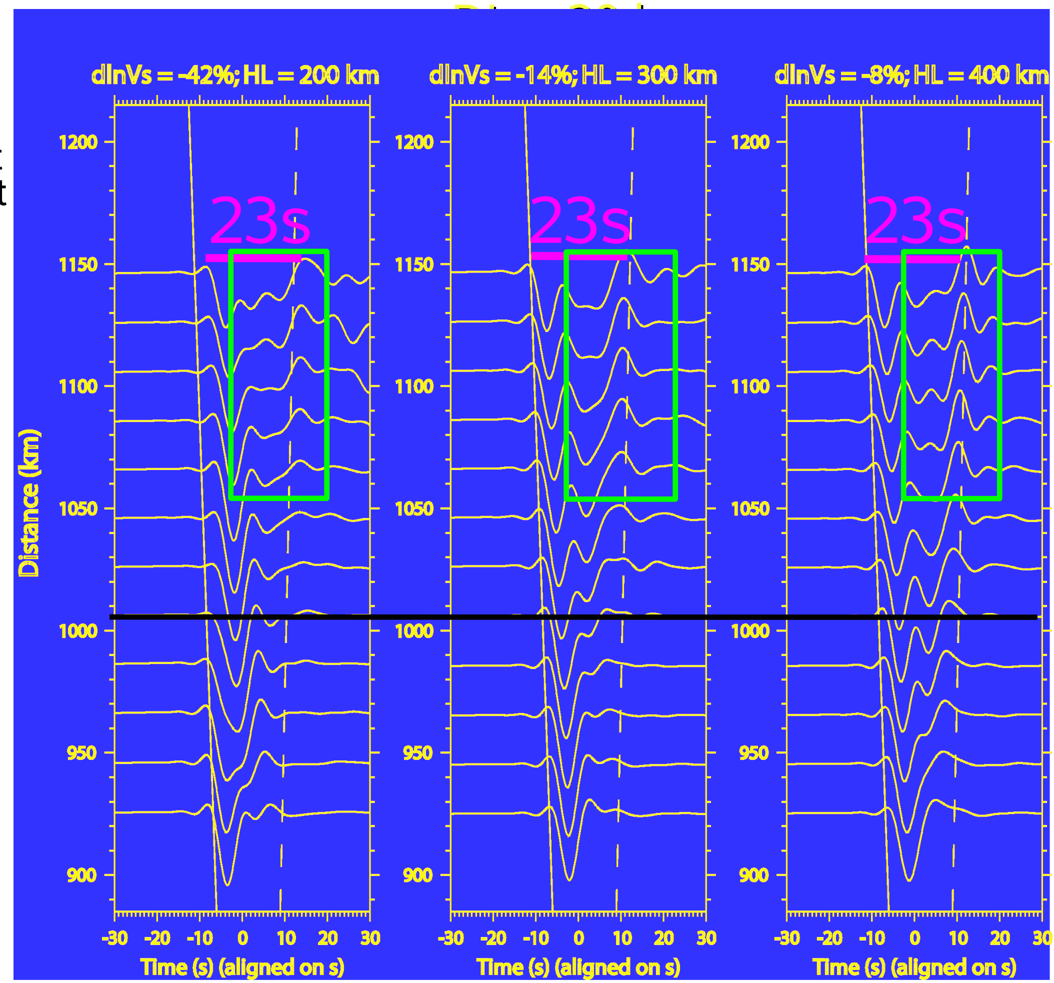


Secondary arrivals appear at distances > 1010 km

Waveform modeling of LVL

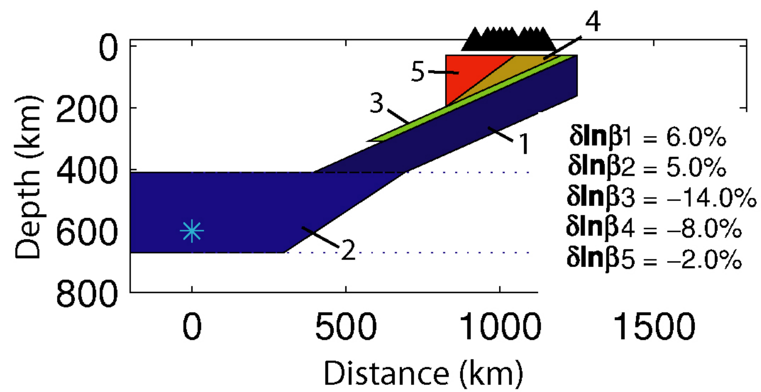
- Depth : HL (200 km, 300 km & 400 km)
- Thickness : DL (10 km, 20 km & 30 km)
- Vs reduction: grid search of dlnVs to get a pulse separartion of 23 s at the largest distance
- Best models : HL = 300 km. Tradeoff between DL and dlnVs
  - DL = 10 km, dlnβ = -28%
  - DL = 20 km, dlnβ = -14%
  - DL = 30 km, dlnβ = -8%

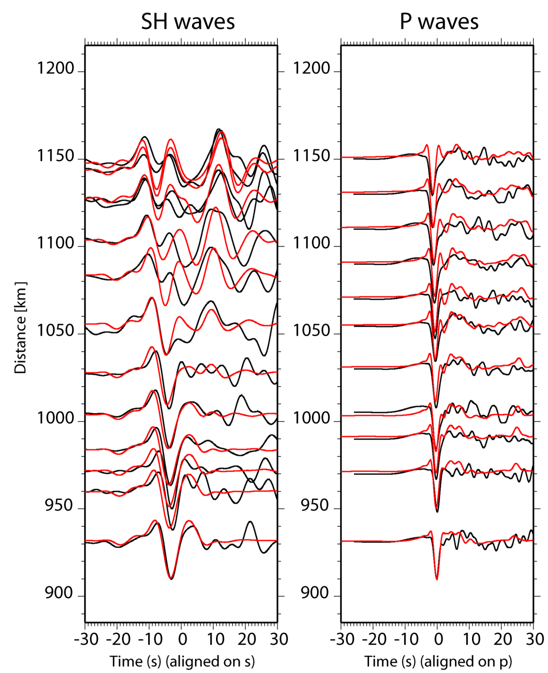




Characteristics of the final model

- Slab above transition zone: $d\ln\beta_1 = 6\%$
- Slab inside the transition zone: $d\ln\beta_2 = 5\%$
- LVL : DL = 20 km; HL = 300 km; $d\ln\beta_3 = -14\%$
- Slow mantle wedge adjacent to LVL: $d\ln\beta_4 = -8\%$
- Mantle wedge: $d\ln\beta_5 = -2\%$

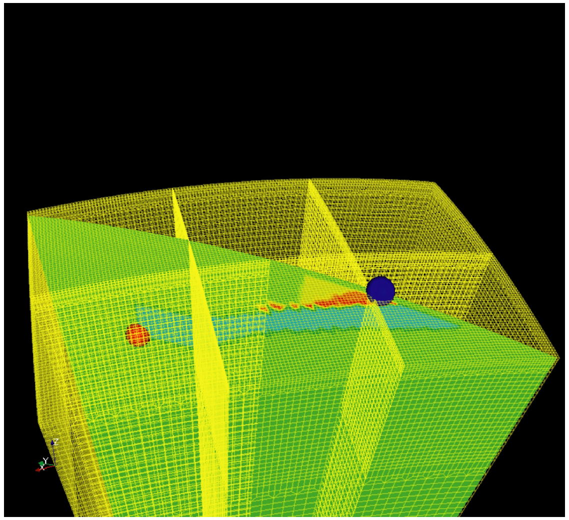


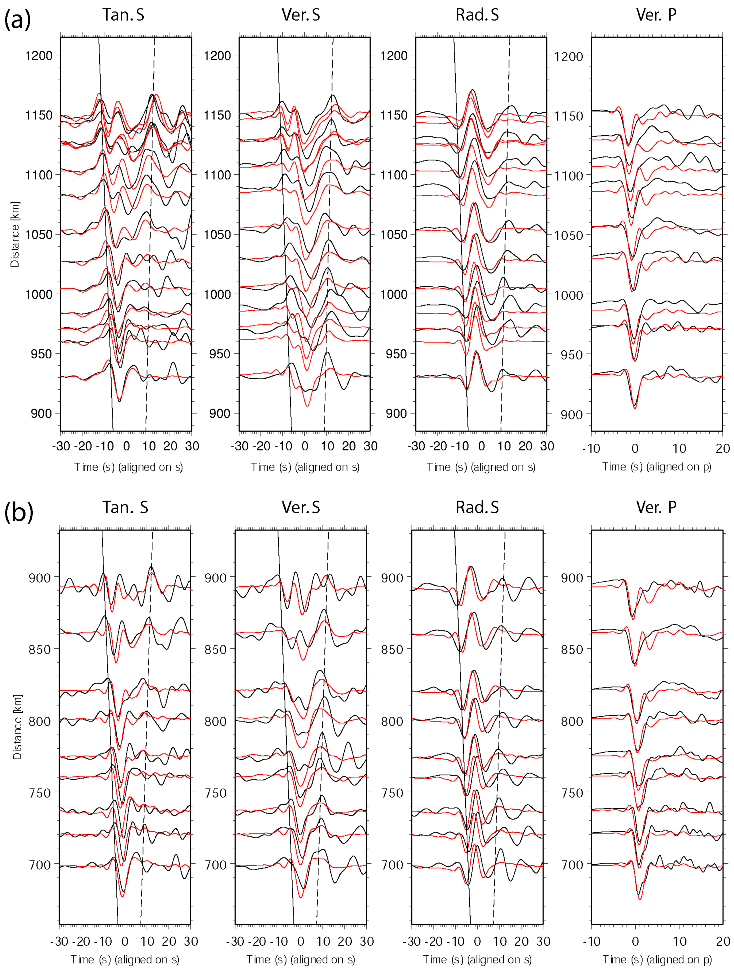


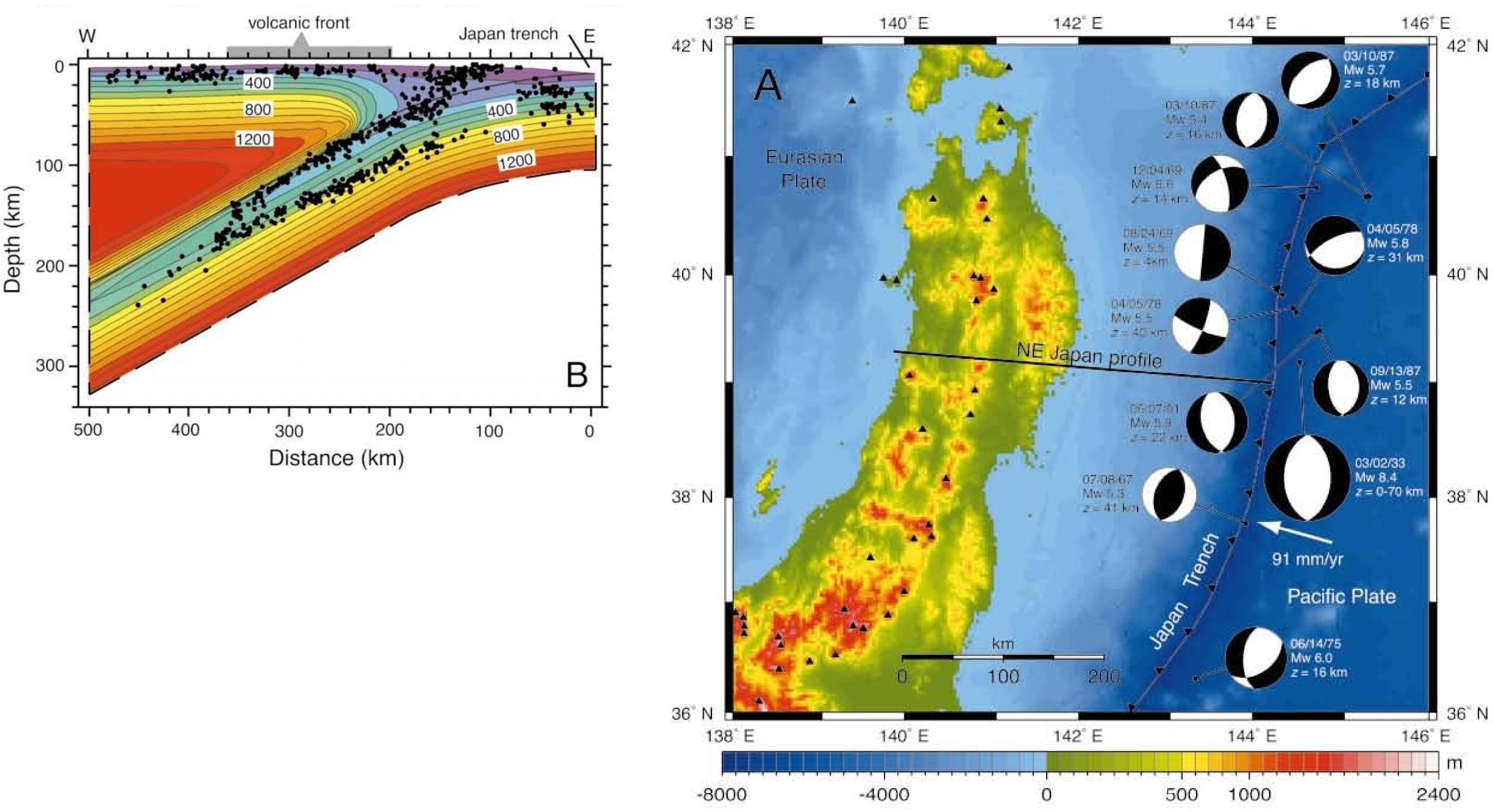
SH Data – FDM synthetics fit for event 20020915 with a source depth of 589 km.

SEM Verification

•Top panel : event 20020915 (depth 589 km).
•Bottom panel : event 20030831 (depth 492 km).
•P waves filtered between 3 - 150 s.
•S waves filtered between 6 – 150 s.





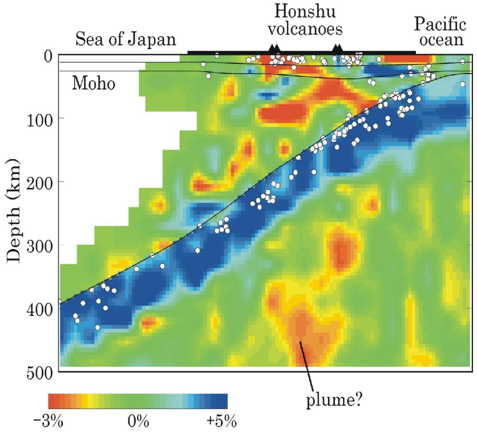


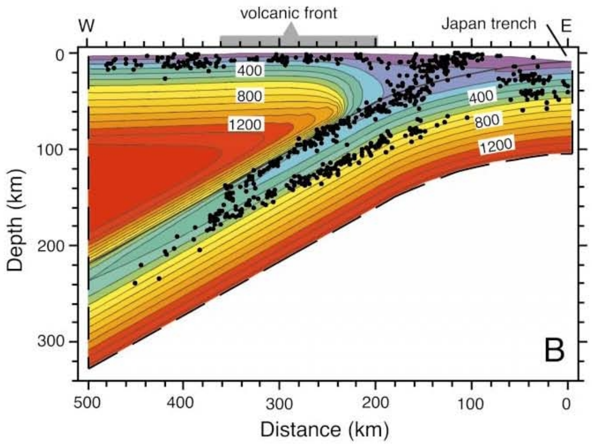
(taken from Peacock, Geology, 2001)

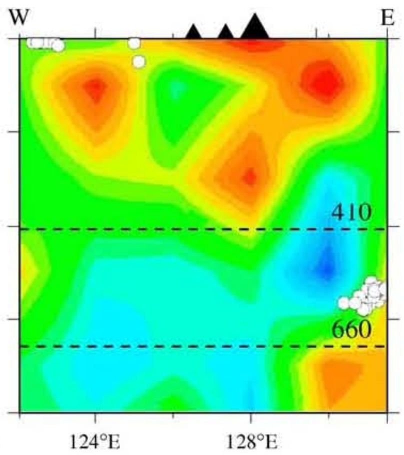
Conclusion

- Large outer-rise earthquake(s) is (are) enriched in high-frequency radiation
- Rupture in the mantle
- Large stress drop, small fracture energy, or both
- Higher hazard potential
- Fracture in the mantle provides a pathway for water penetration
- Evidence for an extensive low-velocity waveguide in the subducting slab

End


Sea of Japan
Honshu volcanoes
Pacific ocean
Moho
Depth (km)
0
100
200
300
400
500
plume?
−3%
0%
+5%

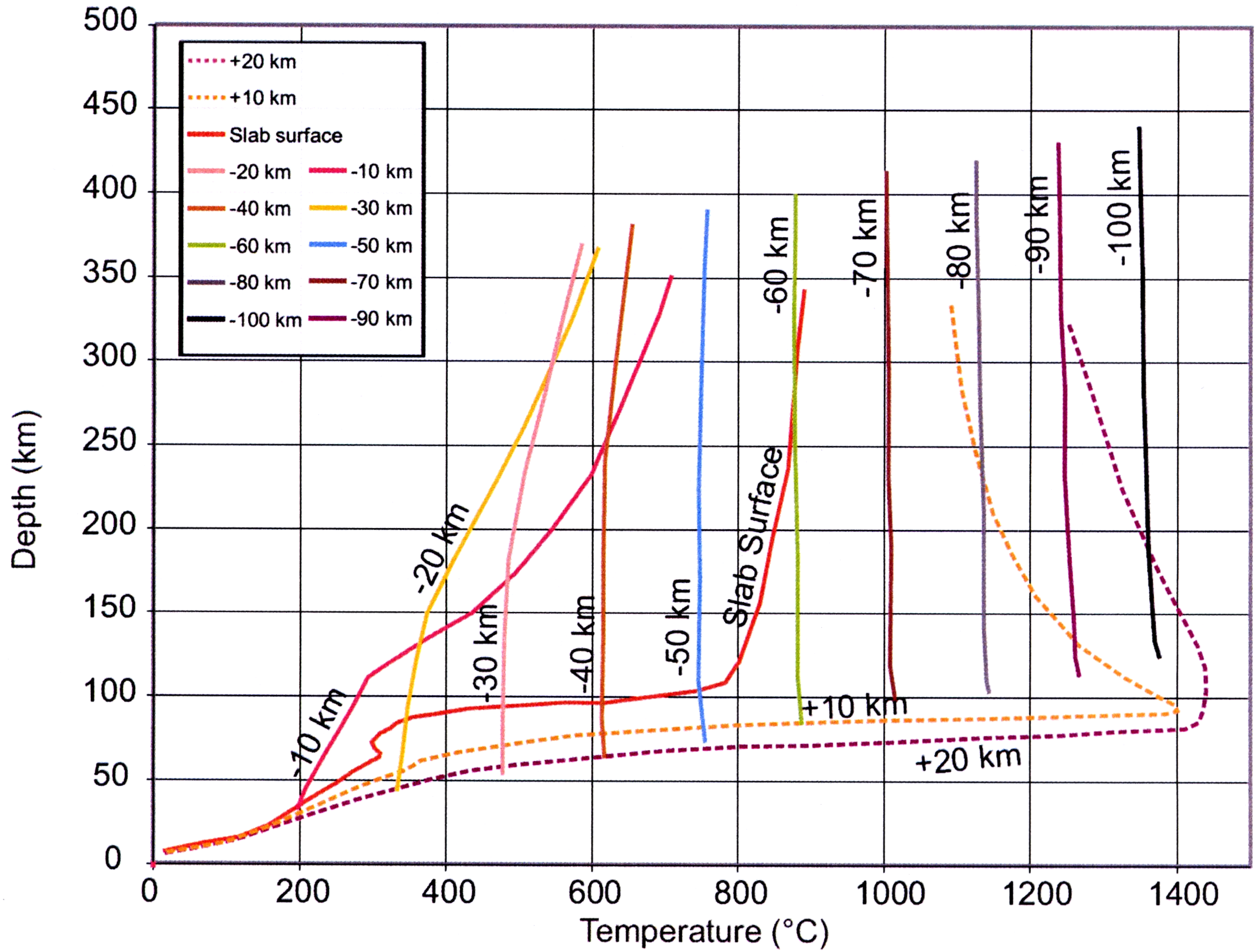

W
volcanic front
Japan trench
E
400
800
1200
400
800
1200
Depth (km)
0
100
200
300
B
500
400
300
200
100
0
Distance (km)


W
E
410
660
124°E
128°E

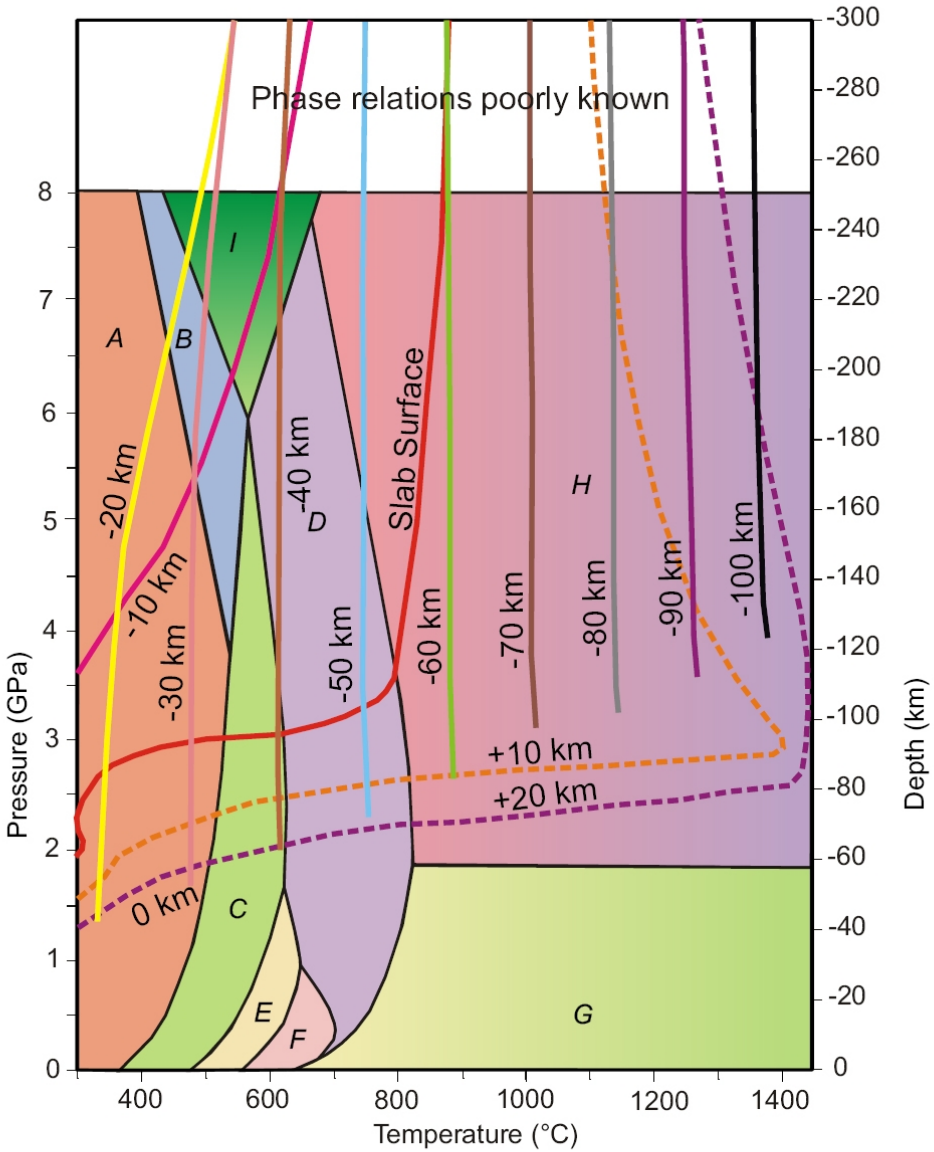
End

Intra-slab Temperature as a function of depth. Age=130 Ma, V=9.1 cm/yr.

Vlad Manea



Phase diagram and P-T paths for NE Japan subduction zone



Parameters used in P-T-path calculation (provided by *Vlad Manea @ Caltech*):

- Plate age : 130 Ma.
- Plate convergence rate : 9.1 cm/yr.

Phase diagram of ultra-mafic rocks (after *Hacker et al. 2003*) :

- A – serpentine–chlorite–brucite (14.6 wt.% H_2O)
- B – serpentine–chlorite–phase A (12 wt.% H_2O)
- C – serpentine–chlorite–dunite (6.2 wt.% H_2O)
- D – chlorite–harzburgite (1.4 wt.% H_2O)
- E – talc–chlorite–dunite (1.7 wt.% H_2O)
- F – anthigorite–chlorite–dunite (1.7 wt.% H_2O)
- G –spinel–harzburgite (0.0 wt.% H_2O)
- H – garnet–harzburgite (0.0 wt.% H_2O)
- I – chlorite–orthopyroxene–phase A (6.8 wt.% H_2O)

P-T paths for regions < 30 km into the slab are cold enough to maintain hydrous phases at larger depth.

Conclusion

- Spatially dense seismic waveforms

  → Dual waveguide, HV and LV (to 300 km)

- Rupture of large outer-rise earthquakes extends to at least 30 to 40 km.

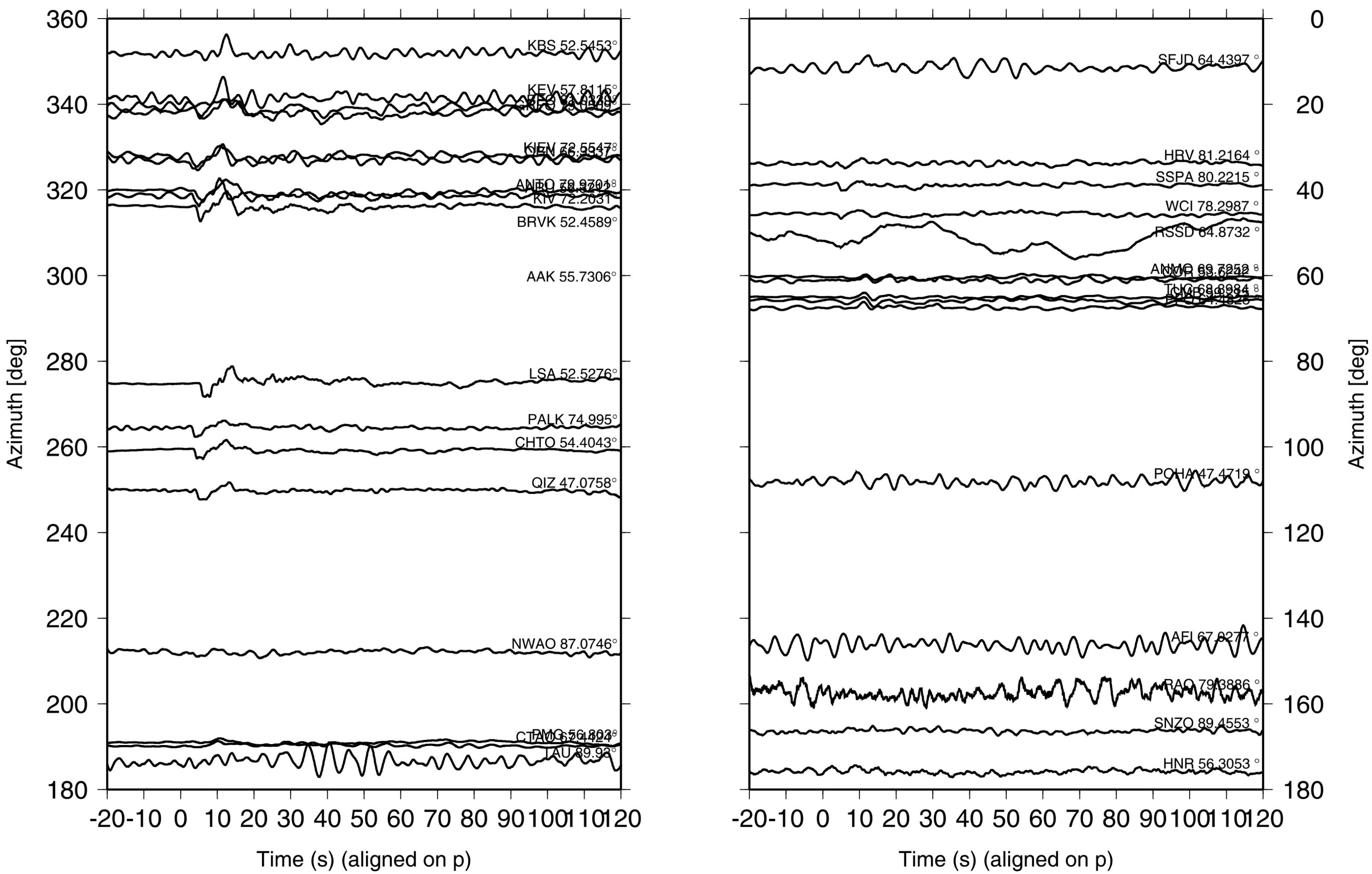
- Seismological data suggest a mechanism and evidence for significant "water" transport to deeper parts of the mantle wedge.

Conclusions

Beneath North-Eastern Japan:

- **Above 410 discontinuity :** The thickness of the slab is > 120 km, the average α increases by 6%, and the upper-boundary dip angle of the slab is ~24^o
- **Inside transition zone:** The slab has a dip angle > 33^o on the eastern side, and becomes flat to the west, β increases by 5 % w.r.t normal mantle
- There is a thin low velocity layer (LVL) on top of the slab.
  - Maximum depth : ~ 300 km
  - Thickness of LVL can be biased by its β reduction, 10 km thick LVL requires 28% β reduction
  - LVL can be explained as hydrated thick serpentinized zone rather than thin oceanic crust in the depth range between 200 – 300 km.

2007 Kuril after: P-wave



Low Velocity Layer

- Observation of low velocity layer (LVL) at the top of the slab beneath North-eastern Japan
  - Difference in PS-P time between events in the upper seismic plane and low seismic plane (Matsuzawa et. al., 1986)
  - Less than 10 km
  - At least in the depth range from 60 km to 150 km
  - $d\ln\alpha$ jumps from -6% to +6%

- Observations of LVL at other places
  - LVL up to ~ 20 km thick exist at the top of the subducting slab at Alaska
  - LVL of 5~10km for the other subduction zones: Mariana, N. Japan, Kurile, Aleutian, Alaska, Nicaragua

- Possible explanations of LVL ($d\ln\alpha$ ~ -6%)
  - Thin LVL (5~10km) : The hydrated oceanic crust
  - Thick LVL (>20km) : The hydrated zone with hydrous phases, such as serpentine, gabbro

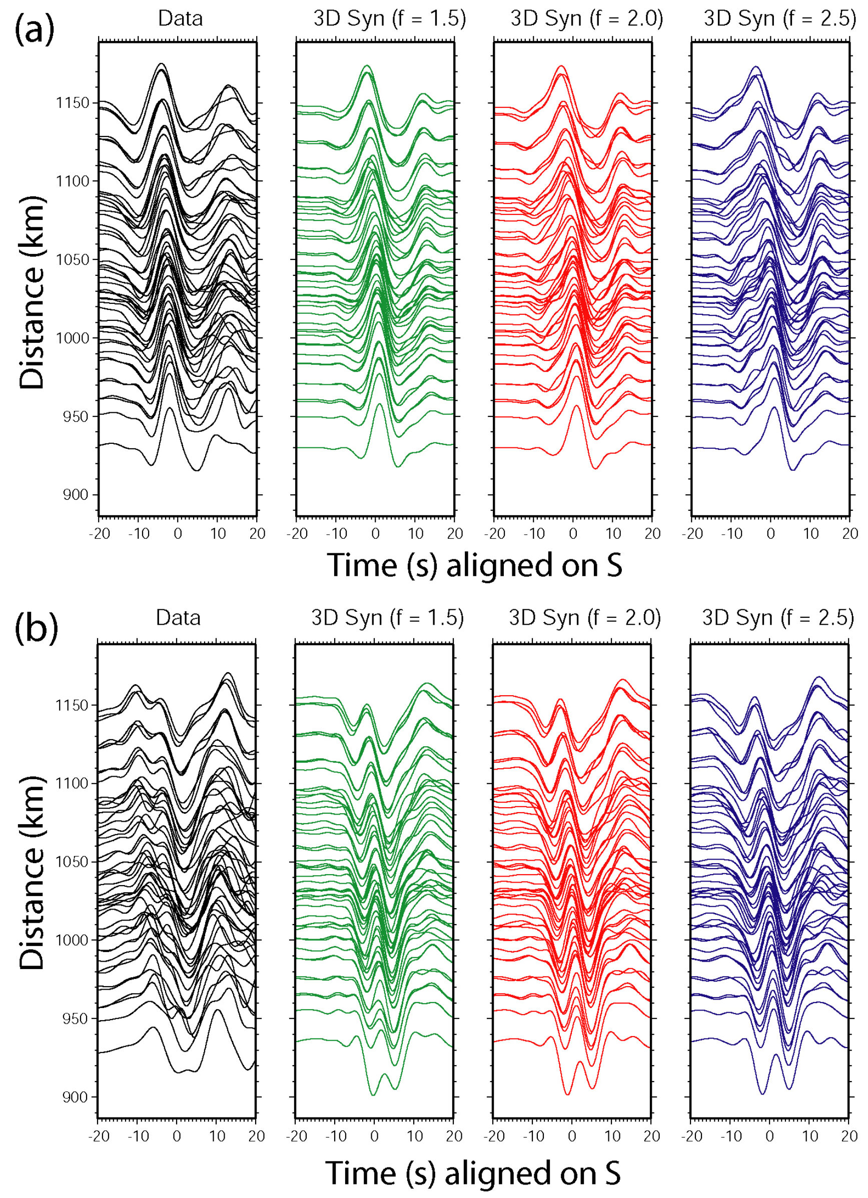
Distance profiles for the SV waves and synthetics

Preferred P-to-S scaling value :

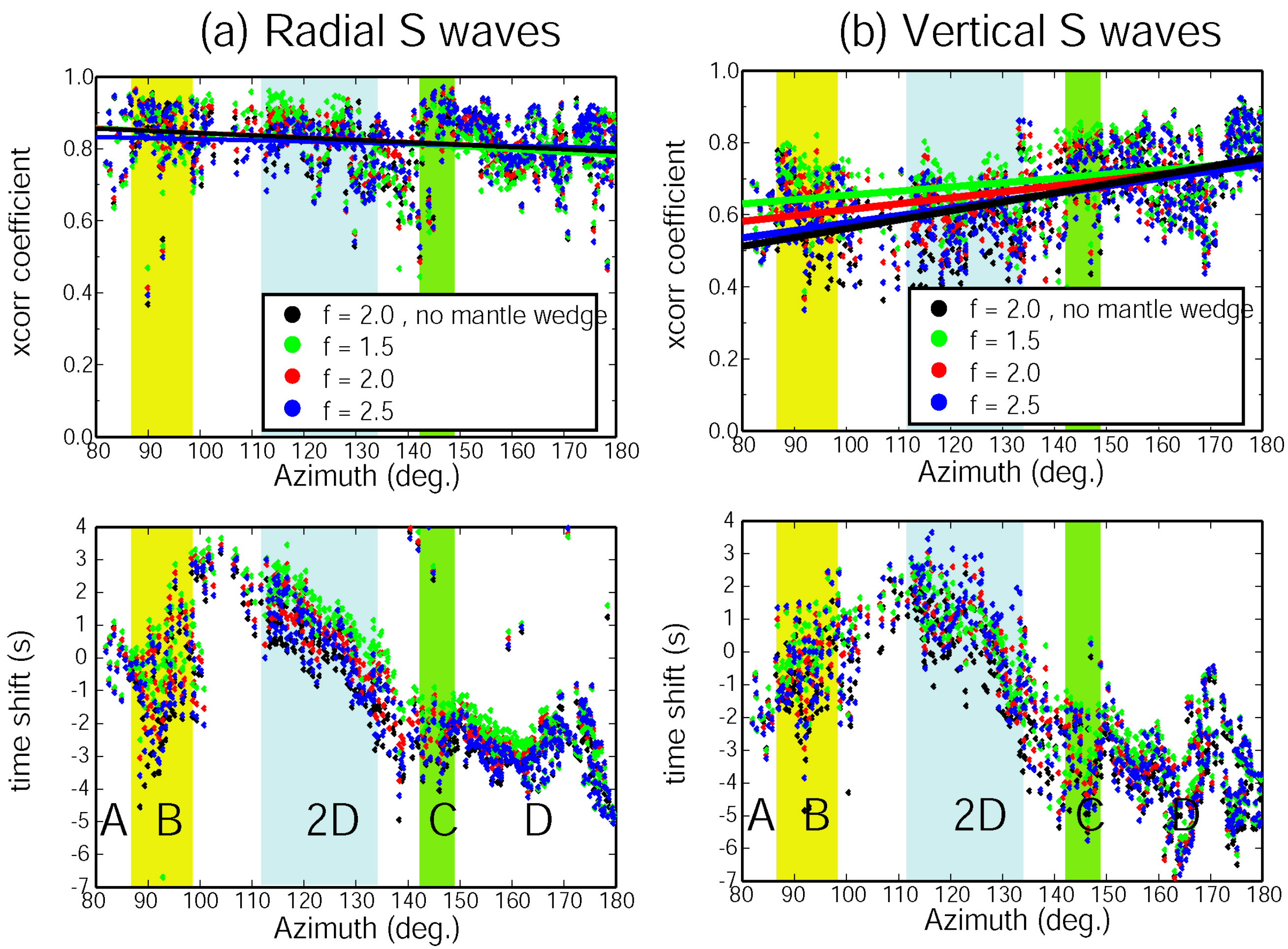
f = δlnβ / δlnα = 1.5 – 2

S-wave speed : α

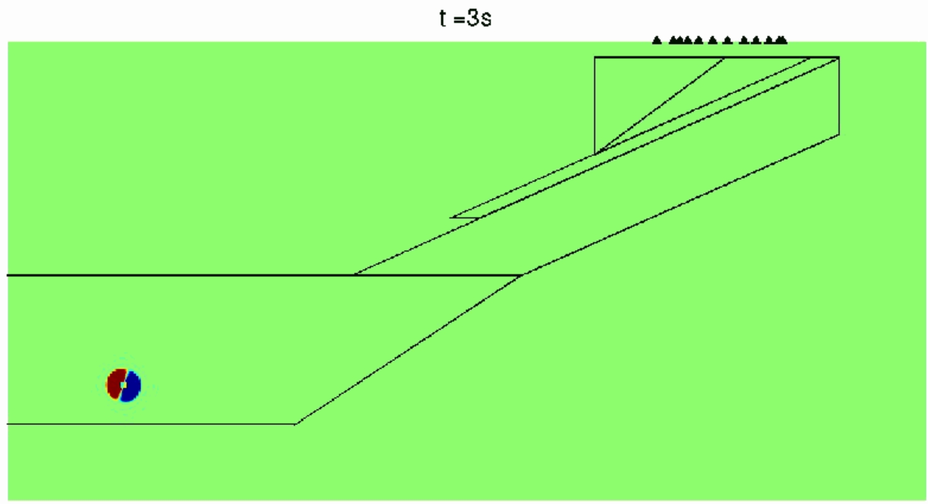
P-wave speed : β



Cross-correlation between SV-wave data and synthetics



Movie of SH wave propagation

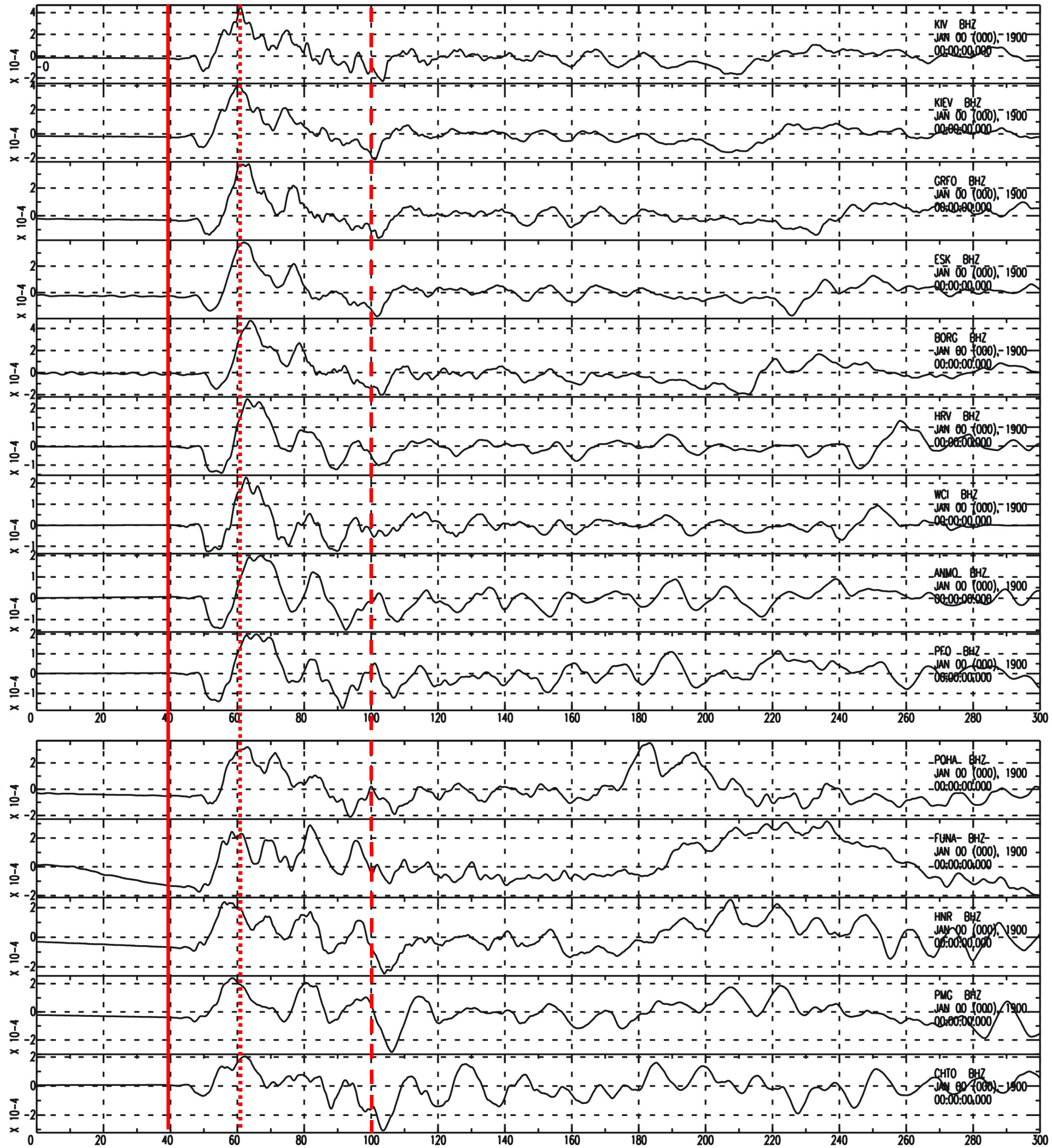


P waveform 01/13/2007 Kuril Is.

N Hemisphere

West

East



S Hemisphere

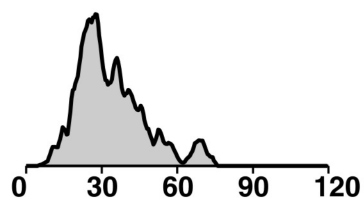
East

West

Kuril_20070113_yamanaka_m_3.5_north-dipp

Mo = 0.238E+22 Nm Mw = 8.18

H = 7.0km T = s var. = 0.3254



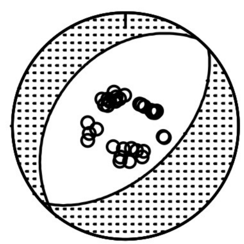
Yamanaka mechanism

North-dipping

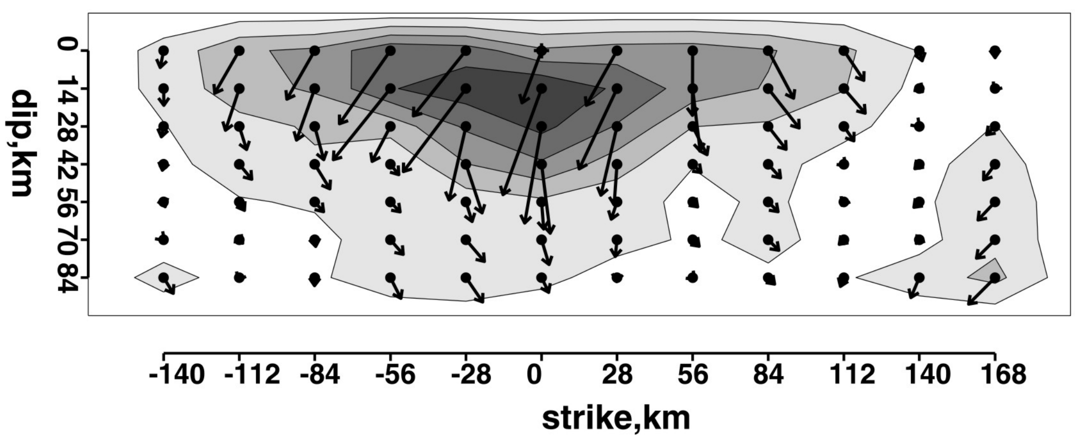
V=3.5 km/s

Ng=128

2.-2.-8

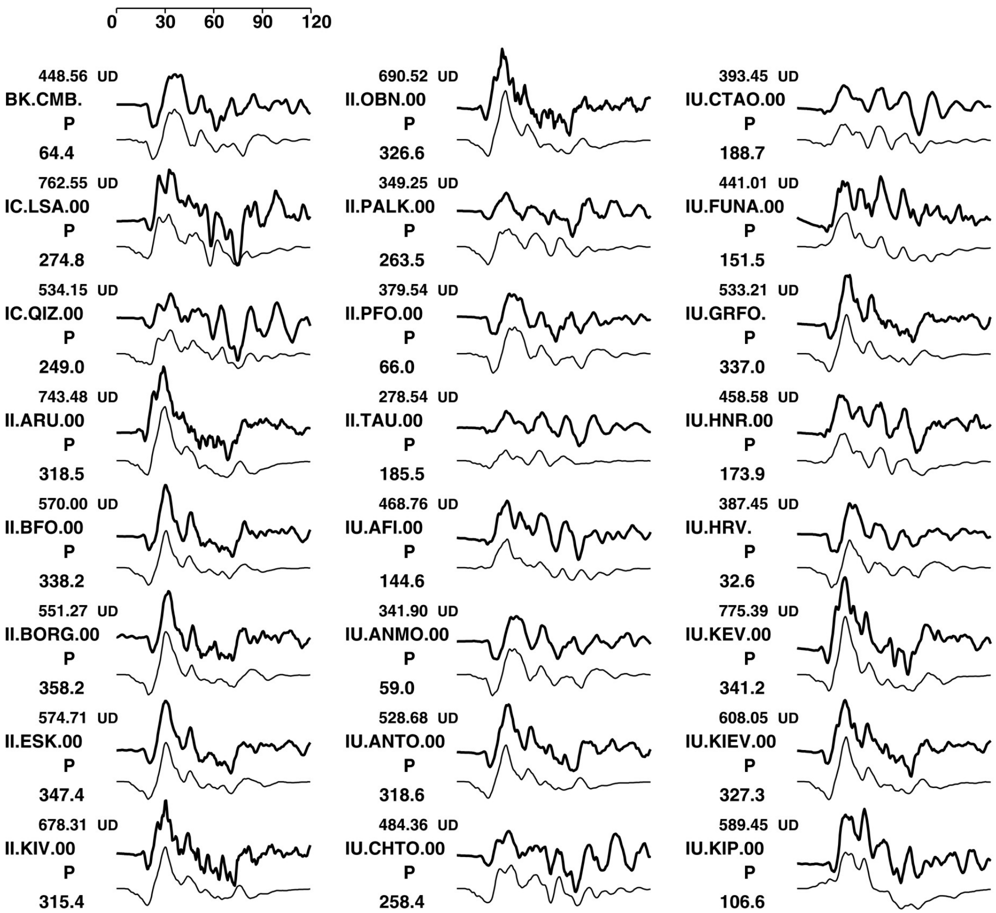


(220.,37., -96.)



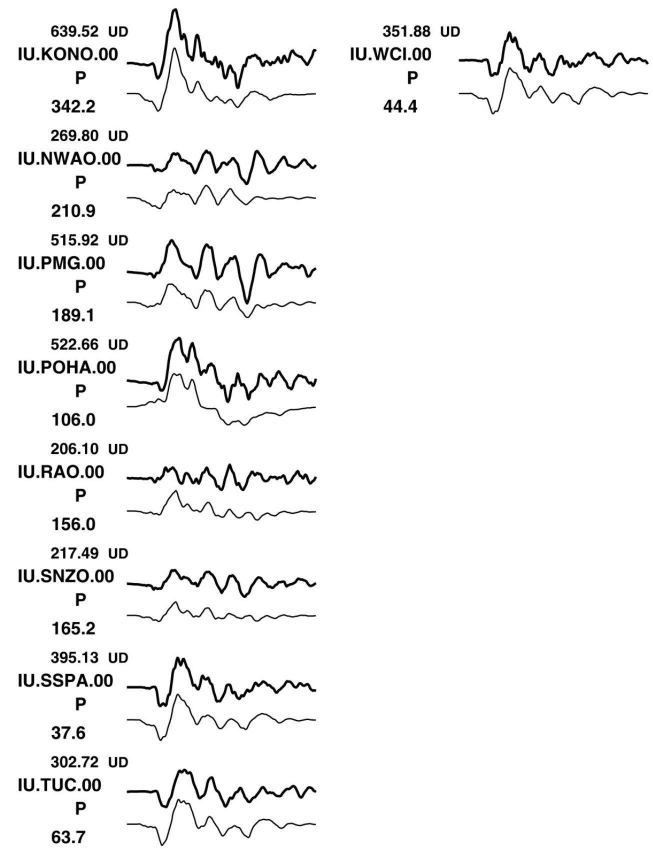
Kuril_20070113_yamanaka_m_3.5_north-dipp

0.3254



Kuril_20070113_yamanaka_m_3.5_north-dipp

0.3254



Santa Cruz Department Seminar

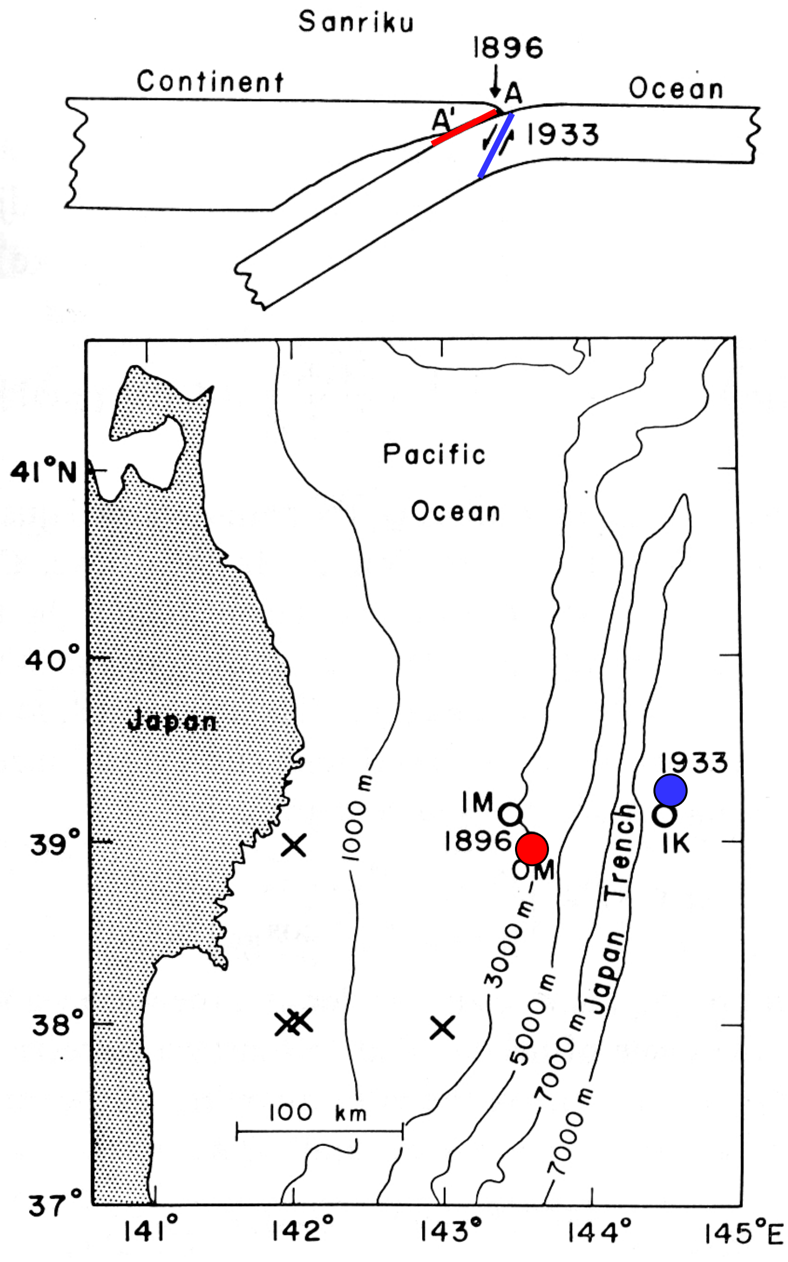
- Slab structure, LV channel, water
- Hi-net waveforms, overall structure
- Min’s S LV structure
- Phase diagram, temperature etc
- Peacock’s outer-rise events
- History of outer-rise events
    - Stauder, Bending, Sanriku (great outer-rise events), Sumba
- 2007 Kuril
    - Map, magnitude, comparison with 2006 event, tsunami
    - Body=wave inversion, CMT, aftershock

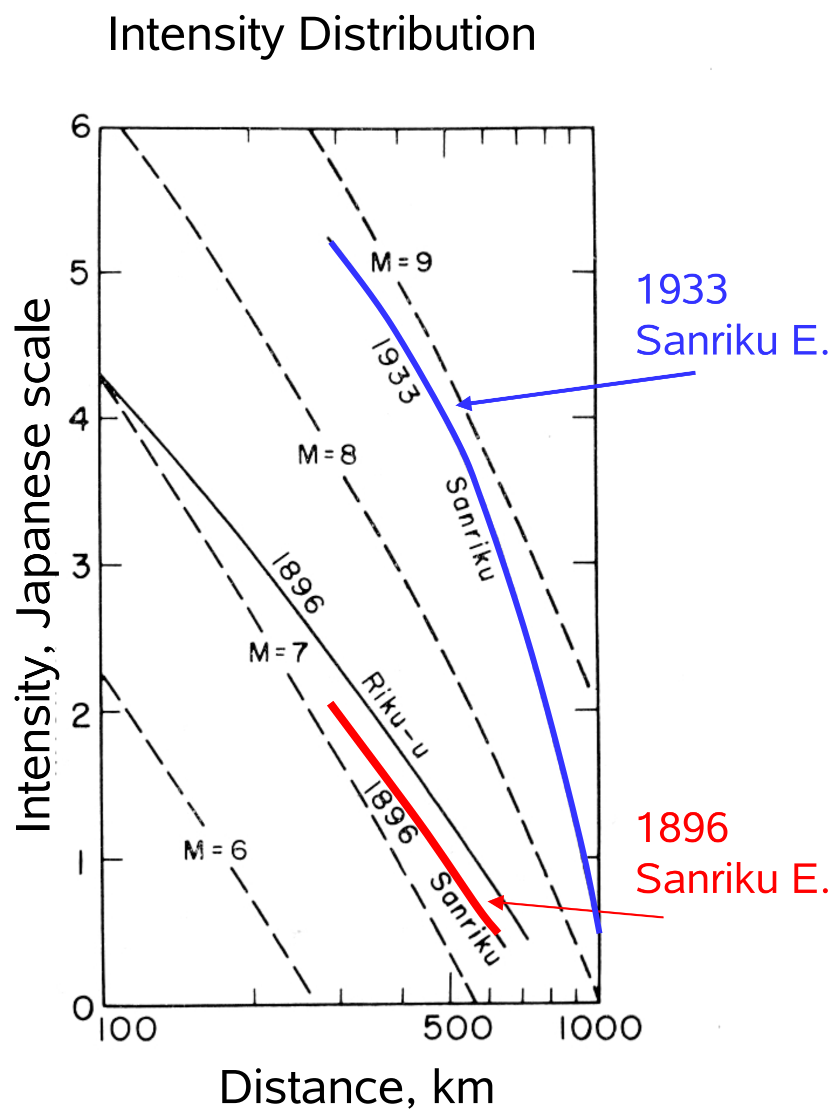
more Min’s results

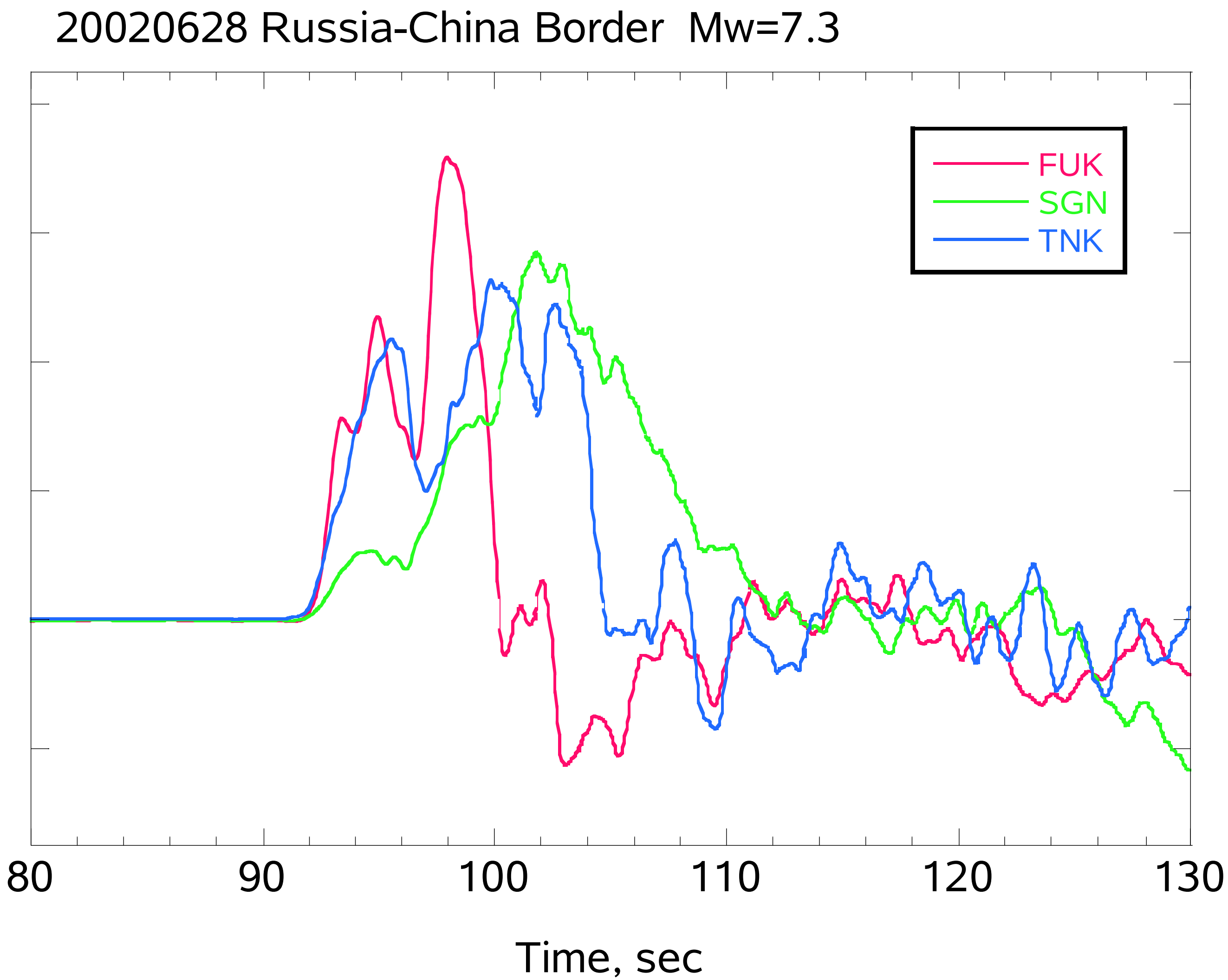
Receiver function

More Hi-net waveforms

Comparison of the 1896 (Tsunami E.) and 1933 Sanriku (Normal E.) Earthquakes

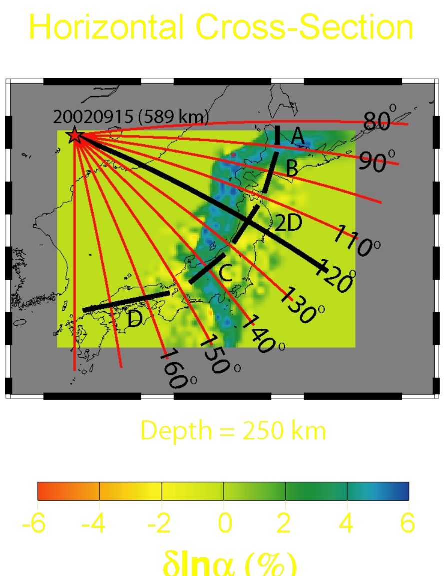


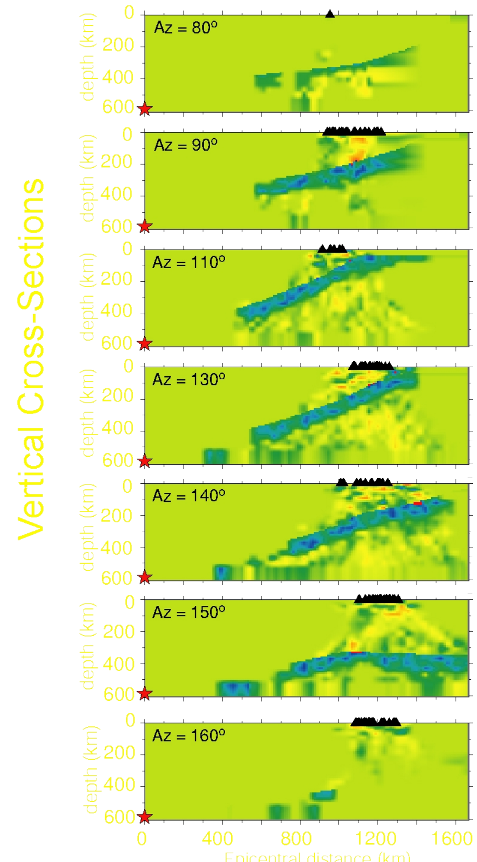




20020628 Russia-China Border Mw=7.3
FUK
SGN
TNK
80
90
100
110
120
130
Time, sec

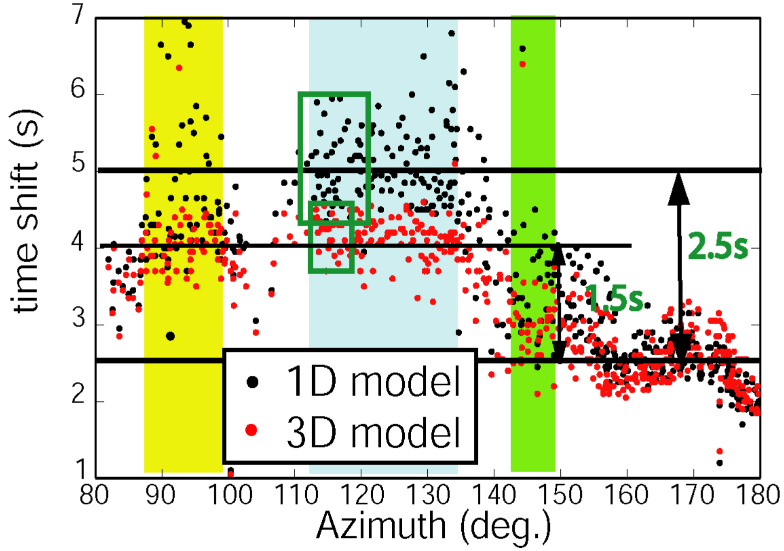
Regional P-wave model

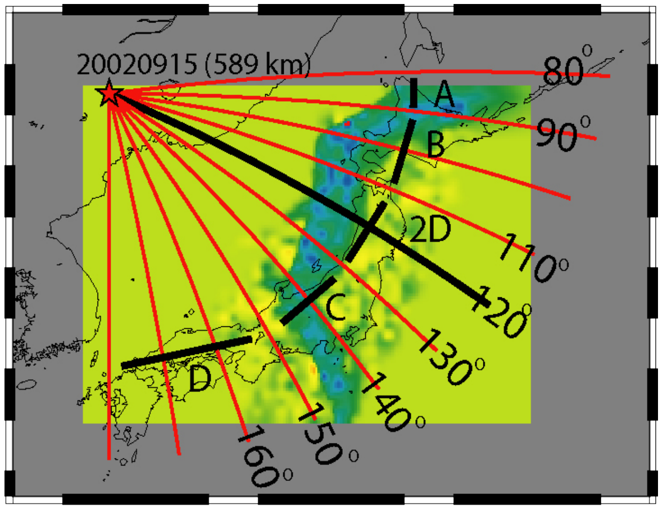




After Zhao et al. (1994)

Cross-correlation between P-wave data and synthetics

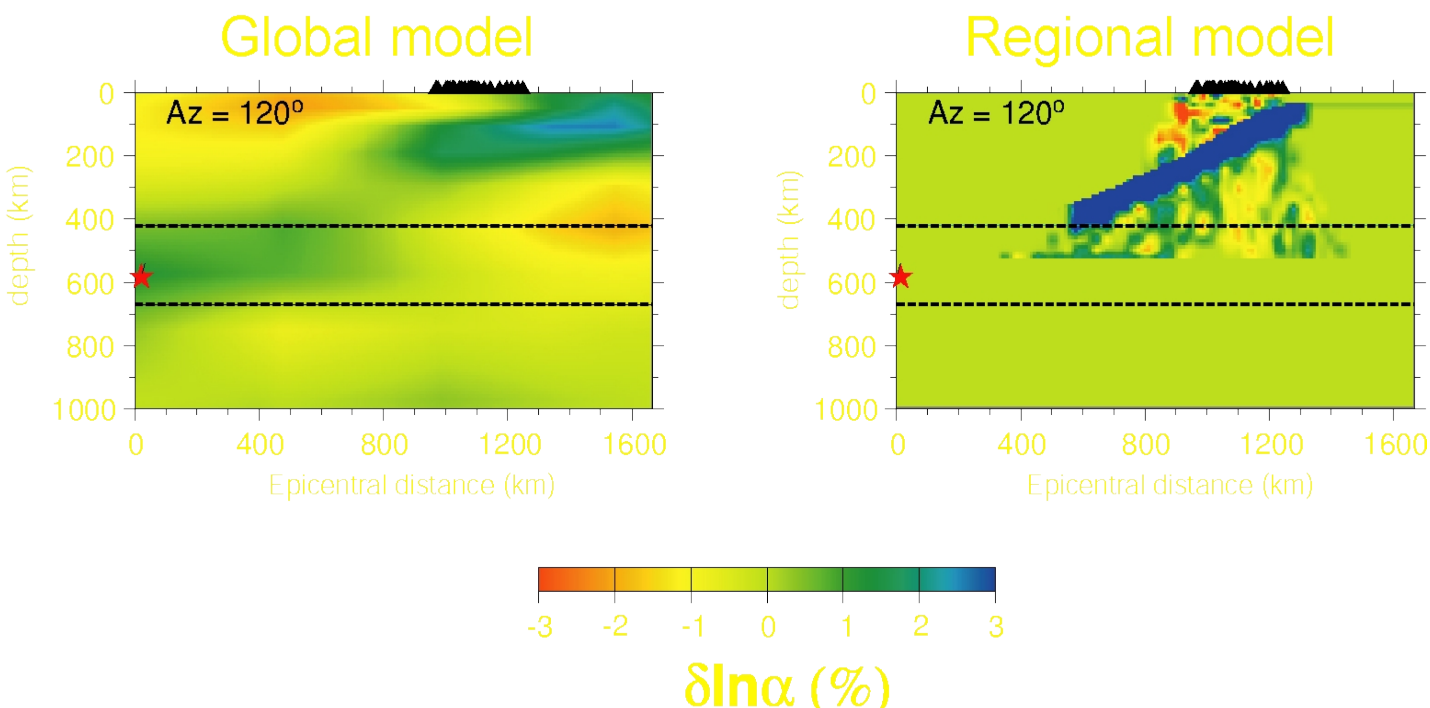




Depth = 250 km

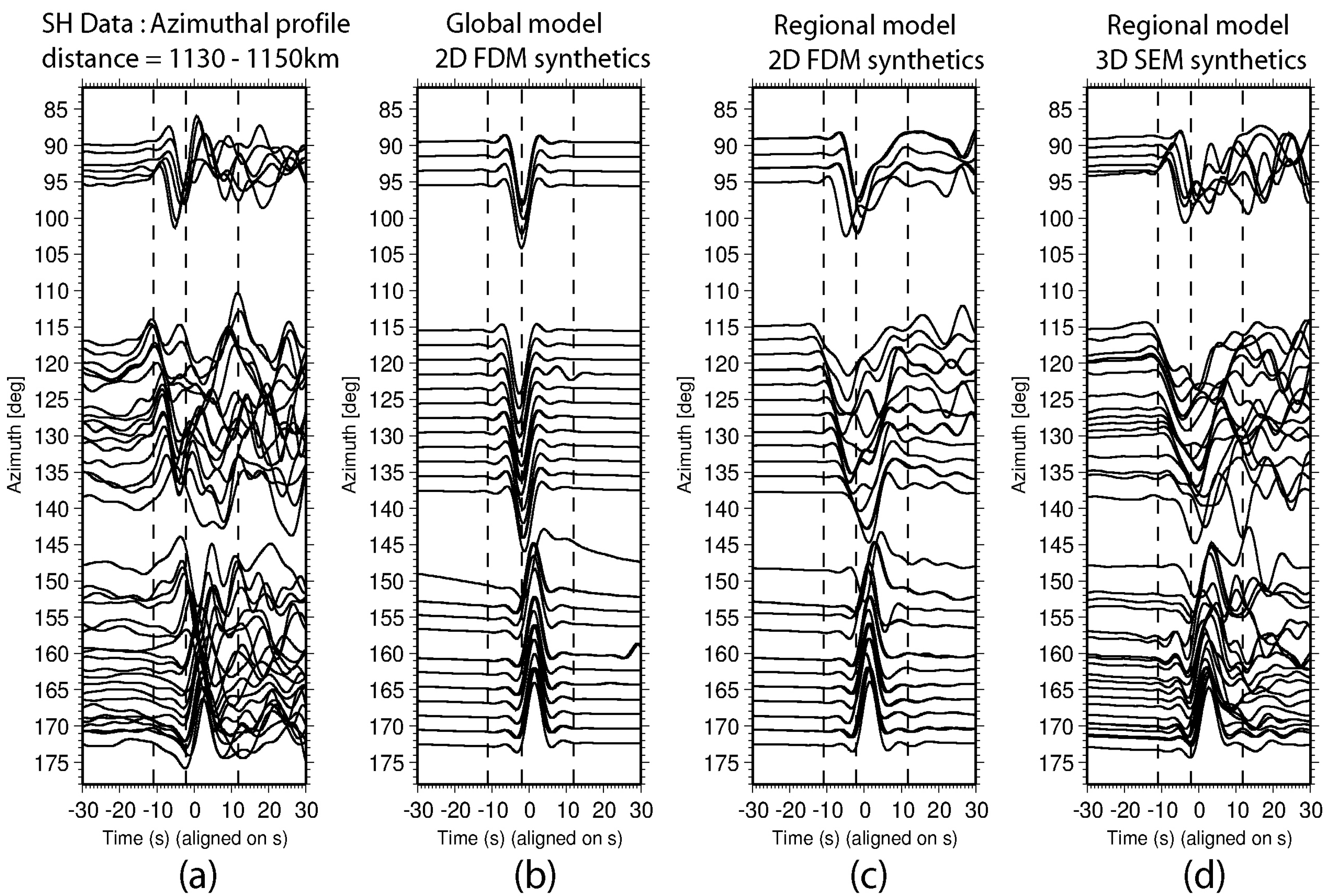
Zhao et al.'s 3D P-wave model [1994] reduces the scatter in traveltime anomalies by half for stations in 2D corridor (light-blue highlighted)

Comparison between global and regional P-wave model

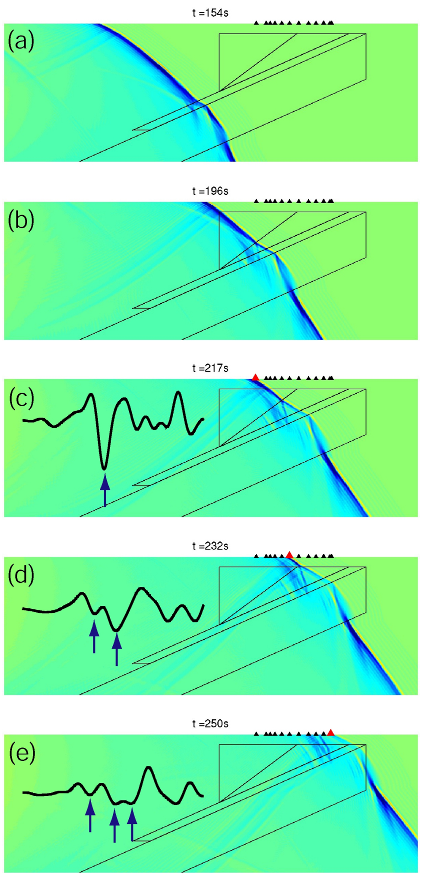


After Zhao et al. (1994) and Zhao (2001)

Azimuthal (‘fan-shot’) profiles for the SH waves and synthetics

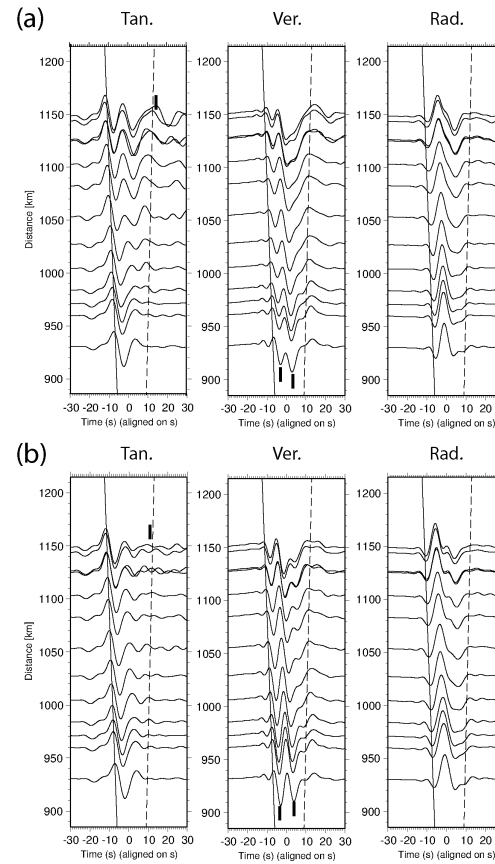


Waveguide phenomena



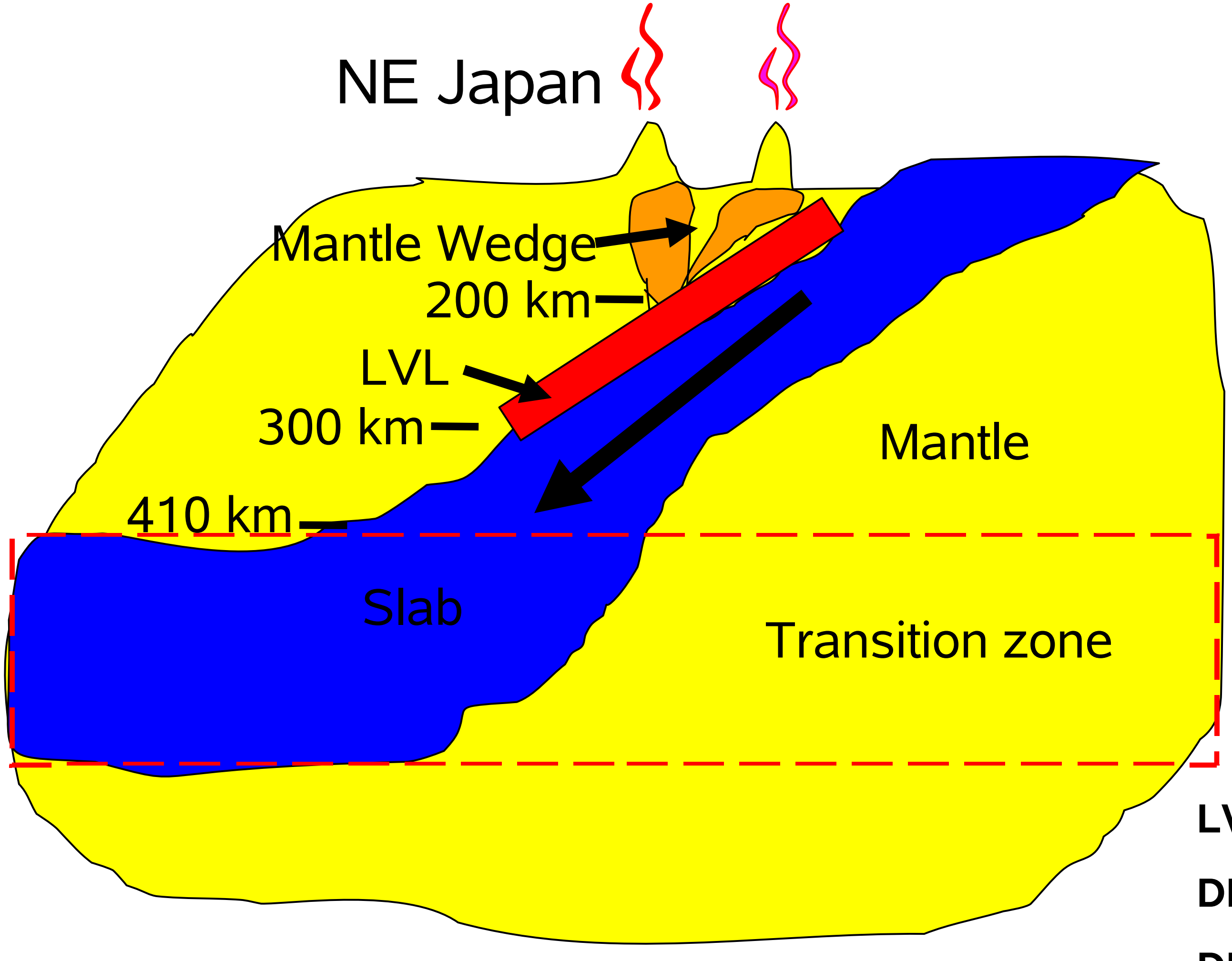
FDM snapshots of SH-wave propagation

in the slab model with LVL



SEM waveforms in 2 models :
•Top panel : the slab model without a mantle wedge but with a LVL.
• Bottom panel : the slab model without a mantle wedge or a LVL.

Cartoon of the slab



LVL (300km deep)

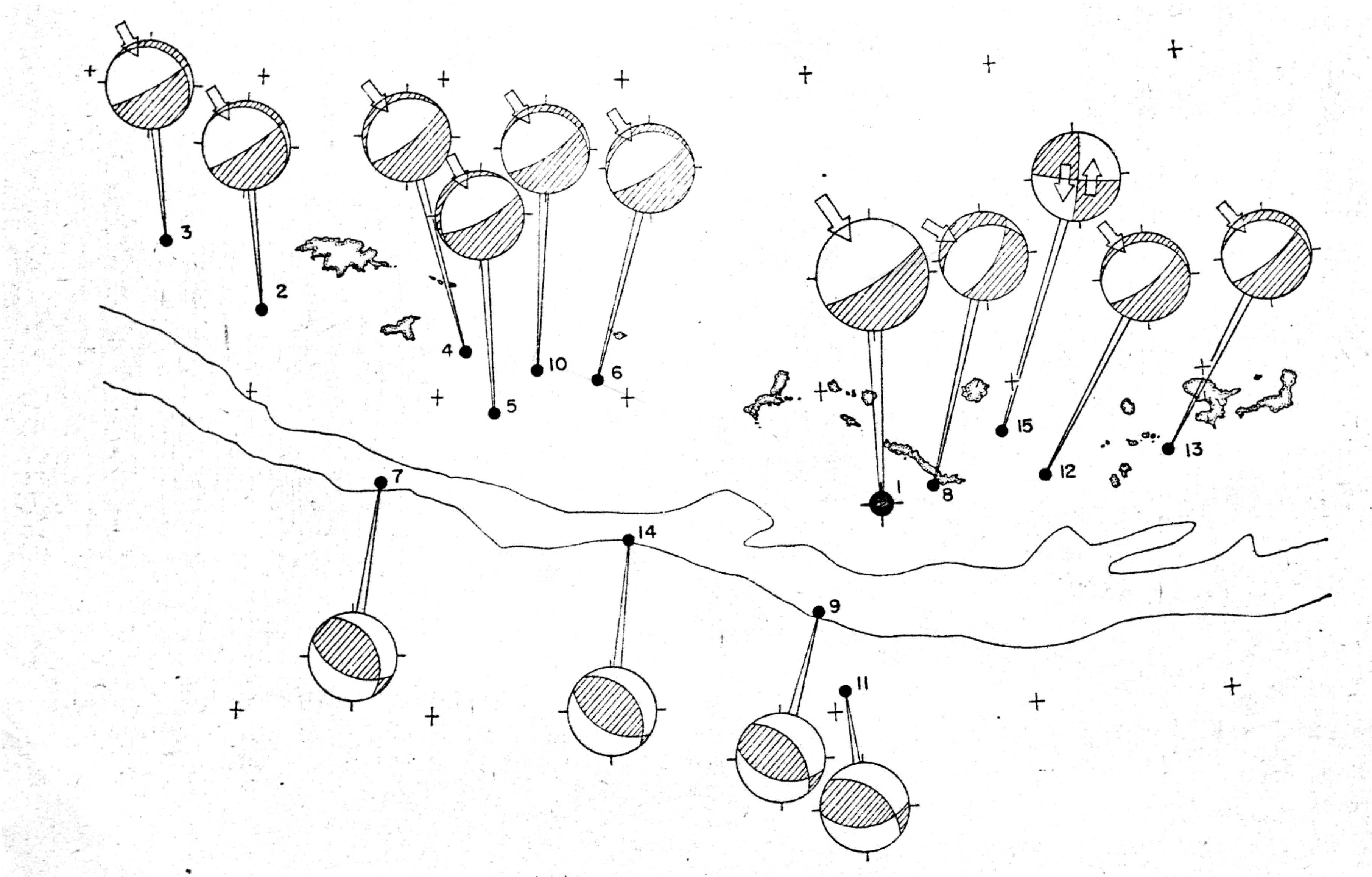
DL = 10 km ; dlnβ = - 28%

DL = 20 km ; dlnβ = - 14%

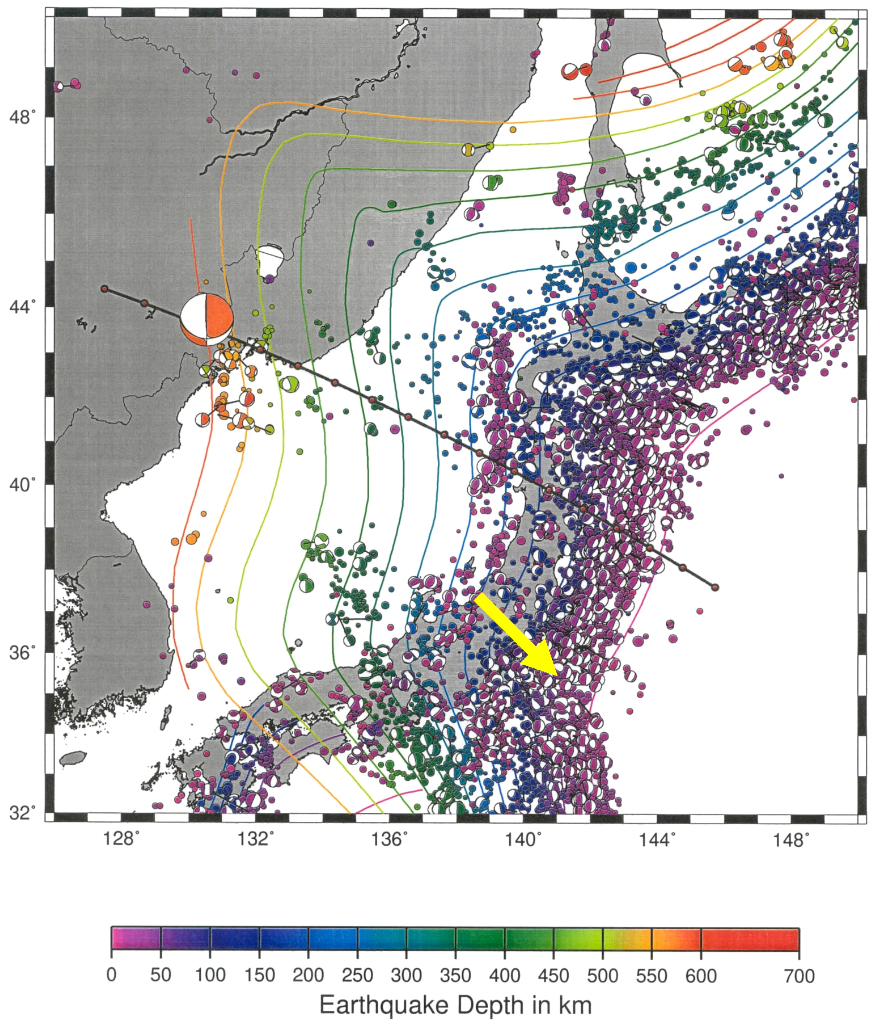
DL = 30 km ; dlnβ = - 8%

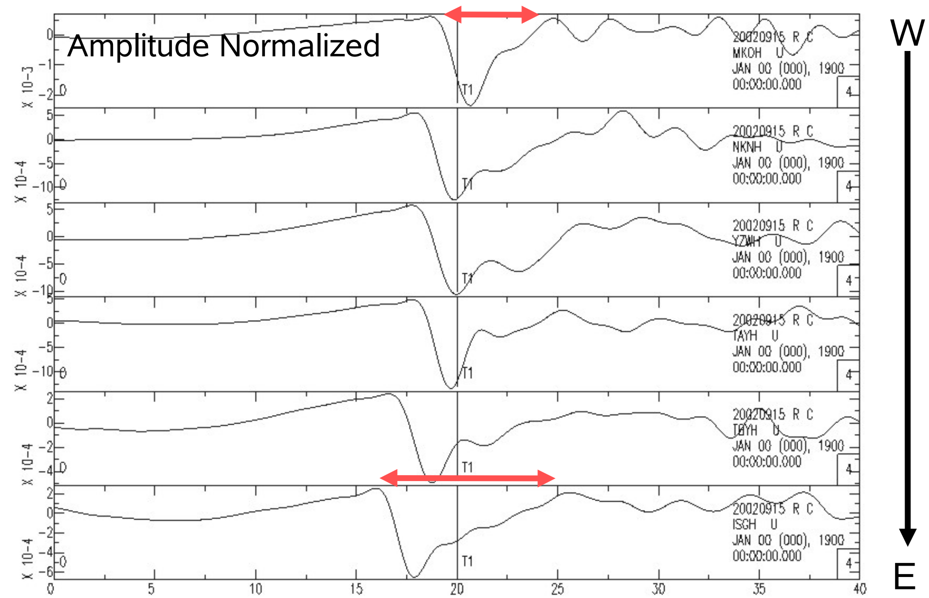
Rat Is. earthquakes in 1965 (W. Stauder, JGR, 1968)

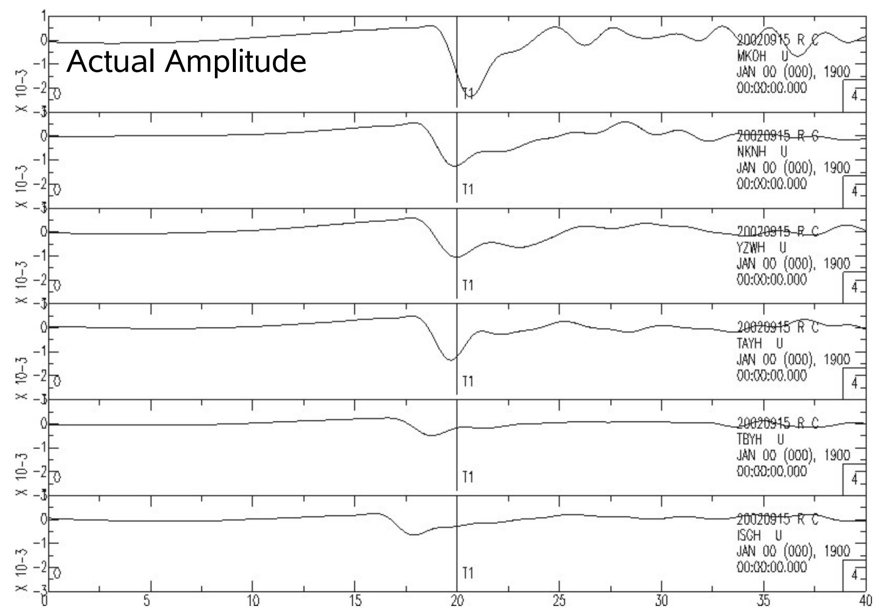
(note: dilatational quadrants are shaded)

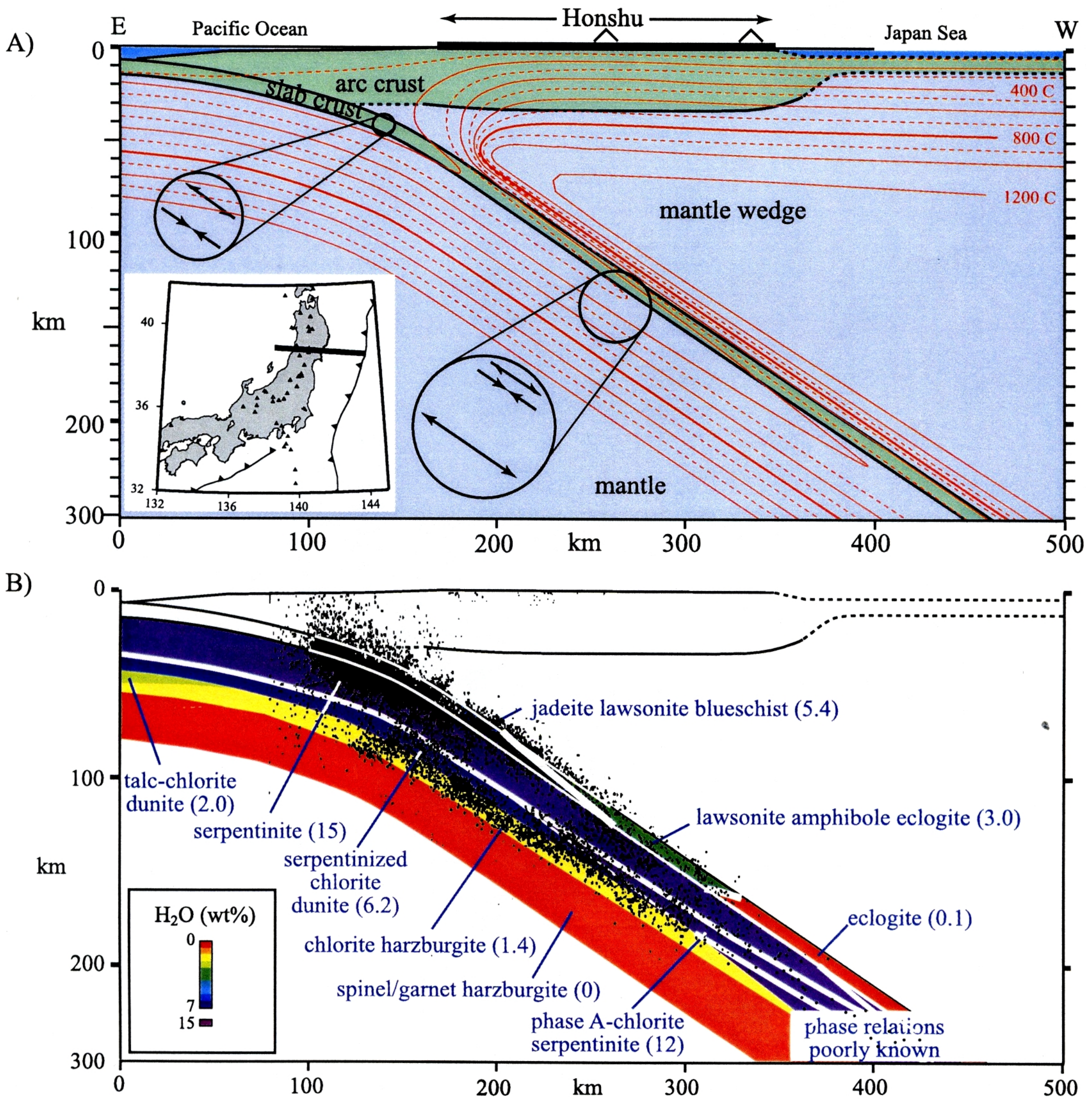


Kanto Profile

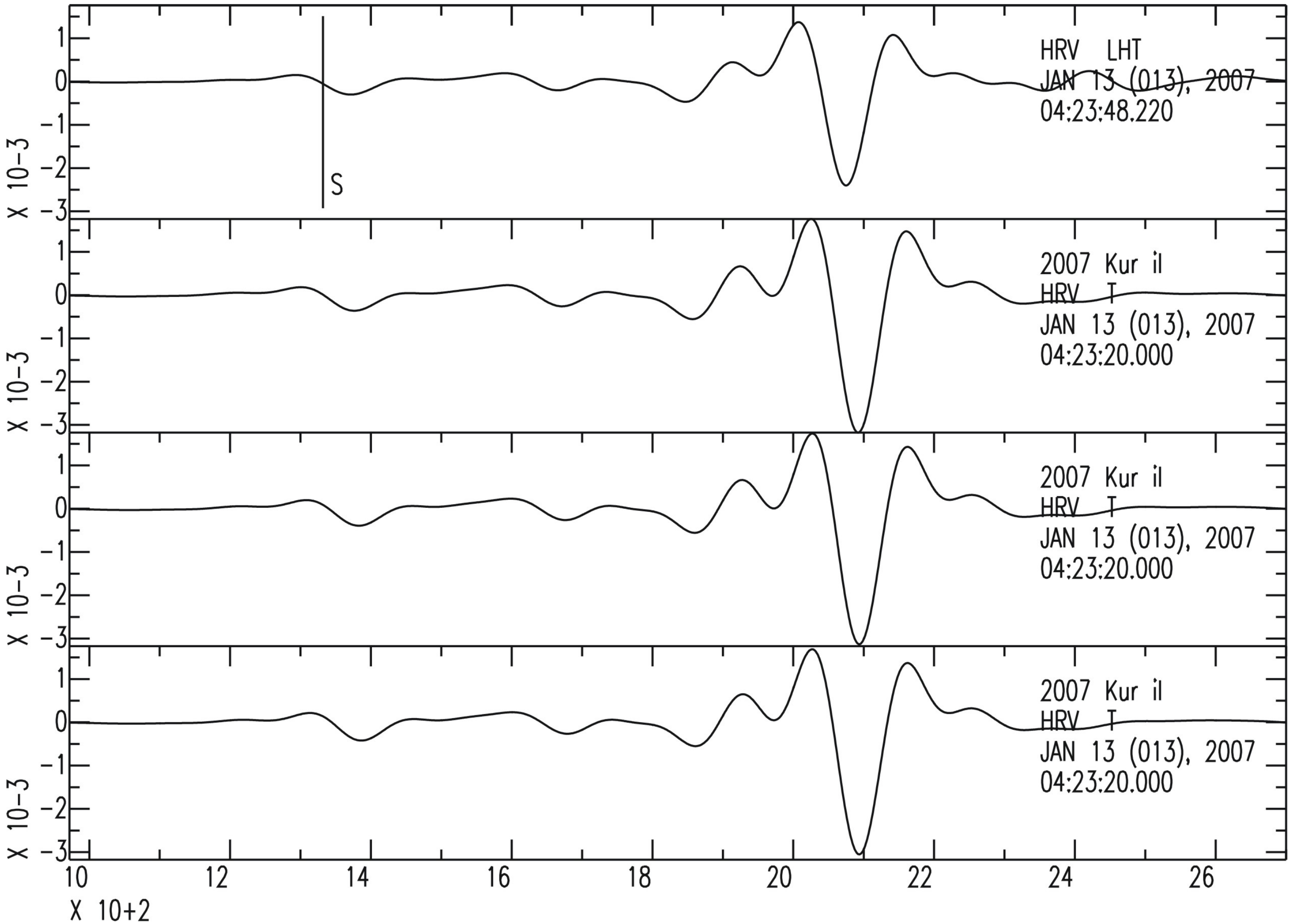







A)
E
Pacific Ocean
Honshu
Japan Sea
W
arc crust
slab crust
400 C
800 C
1200 C
mantle wedge
mantle
km
0
100
200
300
400
500
40
36
32
132
136
140
144
B)
jadeite lawsonite blueschist (5.4)
talc-chlorite dunite (2.0)
serpentinite (15)
serpentinized chlorite dunite (6.2)
lawsonite amphibole eclogite (3.0)
chlorite harzburgite (1.4)
eclogite (0.1)
spinel/garnet harzburgite (0)
phase A-chlorite serpentinite (12)
phase relations poorly known
H_2O (wt%)
0
7
15
km

HRV G1 observed and synthetics at different depths



Obs.

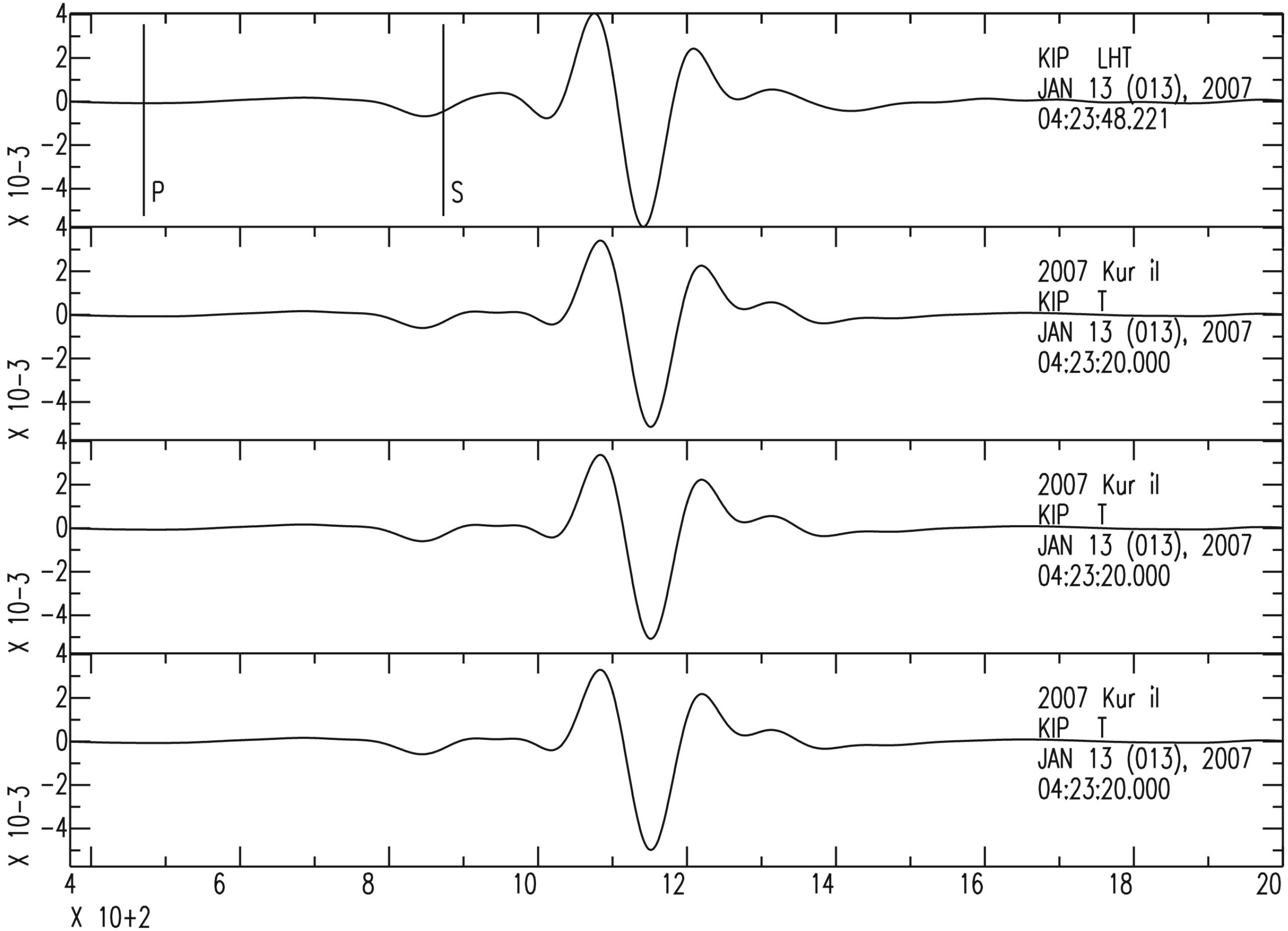
d=5 km

20 km

40 km

(bp n 4 c 0.0025 0.01 p 2)

KIP G1 observed and synthetics at different depths



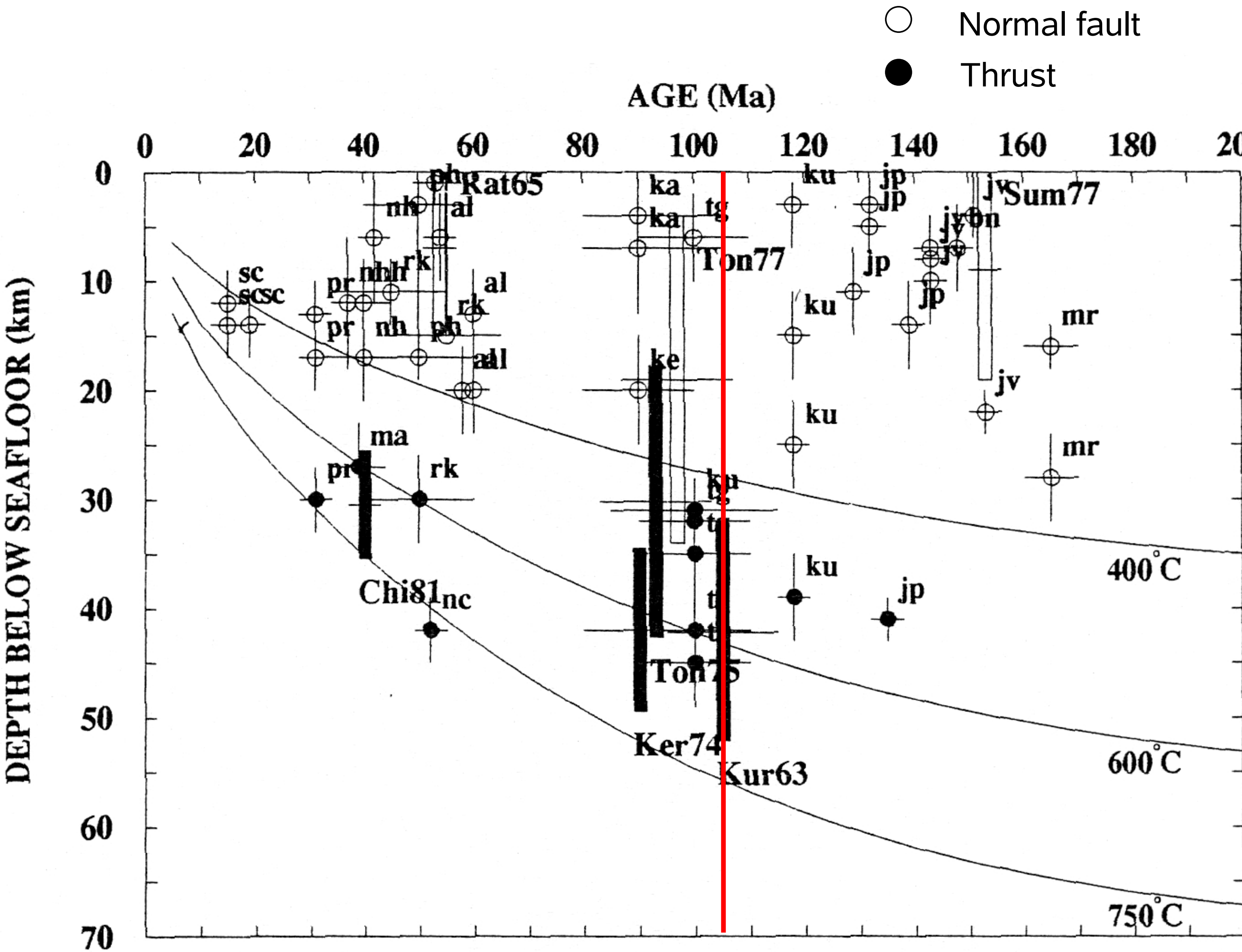
Obs.

d=5 km

20 km

40 km

(bp n 4 c 0.0025 0.01 p 2)



Seno and Yamanaka (1996)