Outer-rise Earthquakes
-Some Implications-

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Rat Is. earthquakes in 1965 (W. Stauder, JGR, 1968b)
(note: dilatational quadrants are shaded)
1933 Sanriku Earthquake ($M_w = 8.4$)

Ksara

- E
- W
- P

Mainka: $T_0 = 9.4$ sec, $\varepsilon = 3.0$, $V_0 = 220$

Göttingen

- U
- D
- P

Wiechert: $T_0 = 4.6$ sec, $\varepsilon = 4.6$, $V_0 = 165$

Paris

- S
- N
- P

Wiechert: $T_0 = 11.2$ sec, $\varepsilon = 4.2$, $V_0 = 216$

Kanamori (1971)
### Great ($M_w \geq 8$) Outer-rise Earthquakes

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>$M_w$</th>
<th>Centroid Depth</th>
<th>Depth Extent of Rupture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1933 Sanriku</td>
<td>$M_w=8.4$</td>
<td>?</td>
<td>?</td>
<td>“the entire thickness of the lithosphere” (Kanamori, 1971) (tsunami, aftershocks)</td>
</tr>
<tr>
<td>1977 Sumbawa</td>
<td>$M_w=8.3$</td>
<td>23.3 km</td>
<td>30-50 km</td>
<td>(Lynnes and Lay, 1988), 50-80 km (Zhang, 1988 thesis)</td>
</tr>
<tr>
<td>2007 Kuril</td>
<td>$M_w=8.1$</td>
<td>12.0 km</td>
<td>?</td>
<td></td>
</tr>
</tbody>
</table>
Kuril Island Earthquake $M_w=8.1$

January 13, 2007

(Doublet: Nov. 15, 2006  Megathrust, $M_w=8.3$
Jan. 13, 2007  Outer-rise, $M_w=8.1$)
Outer-rise earthquake

fore-arc basin  fore-arc high  Tr.  Outer-rise event

megathrust

Outer-rise earthquake
Nov. 15, 2006 Megathrust earthquake
Jan. 13, 2007 Outer-rise earthquake
Yamanaka mechanism
North-dipping
V=2.5 km/s
Ng=128, 2.-2.-8
Large fault
Difference in Moment-rate Spectrum


B

0.001 0.01 C 0.1 1

10^9

10^8

10^7

10^6

10^5

10^4

0.001 0.01 1

Frequency, Hz

Moment, 10^3 N-m

Jan. 13, 2007

(M_w=8.1)

Nov. 15, 2006

(M_w=8.3)

MAJO Displacement

2007

2006

disp.

hp 0.5 Hz

lp 0.005 Hz

(M_w=8.1)
Scaled Energy: $E_R/M_0$

$10^{-6}$
slow tsunami earthquake

$5 \times 10^{-6}$ to $10^{-5}$
mega-thrust earthquake

$5 \times 10^{-5}$ to $10^{-4}$
outer-rise earthquake

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

$\eta =$ radiation efficiency $\propto 1 / G_c$

$\Delta \sigma =$ 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.

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.

Composition of land mass
- Reclaimed land
- Granite

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.

Regulation/Building Codes
- Buildings are designed to withstand wind speeds of up to 110km/h, 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.
Coupled

Trench

Recent Slip

Seismic Gap

Plate Motion

Slab Pull

Uncoupled

Trench

Plate Motion

Slab Pull

After Christensen and Ruff, 1988
Centroid Depth of the Jan. 13 Kuril Is. Earthquake (Mw=8.1)

(J. Polet, written communication, 2007)
Centroid Depth ($Z_c$) and Slip Distribution

- Uniform
- Linear
- Localized

Slip distribution from P wave

Normal-fault aftershock $Z=26.6$ km
Slab Structure Beneath Japan and Intra-slab Structure
Tohoku (Japan) Cross Section
(local+regional+teleseismic)
[Zhao, Hasegawa, and Kanamori, 1994]
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

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
20020915  Russia-China Border  Mw=6.4
Hi-net Displacement
Waveforms of 20020915 Earthquake

W-B zone

Ray Path
Slab Effect (Anti-waveguide, schematic)

(Brian Savage)
Low-velocity waveguide
Kinki Profile

Amplitude Normalized

Actual Amplitude

Earthquake Depth in km
Waveform Modeling of the Slab Beneath Japan

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

• 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°
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 separation 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.
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
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$_2$O)
- B – serpentine–chlorite–phase A (12 wt.% H$_2$O)
- C – serpentine–chlorite–dunite (6.2 wt.% H$_2$O)
- D – chlorite–harzburgite (1.4 wt.% H$_2$O)
- E – talc–chlorite–dunite (1.7 wt.% H$_2$O)
- F – anthigorite–chlorite–dunite (1.7 wt.% H$_2$O)
- G – spinel–harzburgite (0.0 wt.% H$_2$O)
- H – garnet–harzburgite (0.0 wt.% H$_2$O)
- I – chlorite–orthopyroxene–phase A (6.8 wt.% H$_2$O)

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 $\alpha$ increases by 6%, and the upper-boundary dip angle of the slab is $\sim 24^\circ$.

• **Inside transition zone**: The slab has a dip angle $> 33^\circ$ on the eastern side, and becomes flat to the west, $\beta$ increases by 5% w.r.t. normal mantle.

• There is a thin low velocity layer (LVL) on top of the slab.
  – Maximum depth : $\sim 300$ km
  – Thickness of LVL can be biased by its $\beta$ reduction, 10 km thick LVL requires 28% $\beta$ reduction.
  – LVL can be explained as hydrated thick serpentinized zone rather than thin oceanic crust in the depth range between 200 – 300 km.
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:
\[ f = \frac{\delta \ln \beta}{\delta \ln \alpha} = 1.5 - 2 \]

S-wave speed: \( \alpha \)

P-wave speed: \( \beta \)
Cross-correlation between SV-wave data and synthetics

(a) Radial S waves
(b) Vertical S waves
Movie of SH wave propagation
P waveform 01/13/2007 Kuril Is.
Yamanaka mechanism
North-dipping
V=3.5 km/s
Ng=128
2.-2.-8
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

Intensity Distribution

1896 Sanriku E.
1933 Sanriku E.
1896 Sanriku E.
Regional P-wave model

After Zhao et al. (1994)
Cross-correlation between P-wave data and synthetics

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

NE Japan

Mantle Wedge
200 km

LVL
300 km

410 km

Mantle

Slab

Transition zone

LVL (300 km 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)
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

(bpn4c0.00250.01p2)
Seno and Yamanaka (1996)

○ Normal fault
● Thrust

DEPT VERSUS SEAFLOOR (km)

AGE (Ma)

0 20 40 60 80 100 120 140 160 180 200

0 10 20 30 40 50 60 70

400 °C

600 °C

750 °C

Ker74

Kur63

Ton75

Chi81nc

pr

rk

ma

sc

al

ph

nl

K

Ton77

Sum77

Seno and Yamanaka (1996)