Seismogenesis of dual subduction beneath Kanto, central Japan controlled by fluid release

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Tectonic map

- Japan Trench
- Boso Triple Junction
- Sagami Trough
- Suruga Trough
- Tokyo
- Kanto
- Okhotsk Plate
- Amurian Plate
- Philippine Sea Plate
- Pacific Plate
Plate geometry model

Pacific - Philippine Sea slab contact zone

Pacific Plate

Philippine Sea Plate
Seismogenic zone in and around the PAC slab interface
Objectives

- To understand the effect of existence of the PHS slab on geodynamic process beneath Kanto, central Japan (thermal structure, dehydration, and mantle flow)

- To elucidate seismogenesis of inter- and intra-plate earthquakes (≥ M2) of the PAC slab, especially deepening of the seismogenic zone at the down-dip side of the slab-slab contact zone
Previous study

- 2-D model
  - Iwamori (EPSL, 2000)
  - Yoshioka et al. (GJI, 2015)

- 3-D model
  - Wada and He (GRL, 2017)
What’s new?

- 3-D
- time dependent
- subduction history
- a moving prescribed guide
- high-density heat flow data
- relationship between dehydration and inter- & intra-plate seismicity of the PAC slab, using phase diagrams of hydrous minerals
Geometry of the upper surfaces of the Pacific and the Philippine Sea slabs

Nakajima and Hasegawa (2006, 2009)
Kita et al. (2010)
We used original source code ‘stag3d’ provided by Dr. Tackley.
Phase diagram of water content for hydrous minerals included in a slab

Temperature (°C)

Pressure (GPa)

Hydrous MORB

PA: pumpellyite actinolite
PP: prehnite pumpellyite

Omori et al. (2009)

4-5 wt% jadeite
3.0 wt% lawsonite
<1.0 wt% eclogite
1.5-2.5 wt% amphibolite

Pressure (km)

Hacker et al. (2003)

ultramafic rock (harzburgite)

serpentinite chlorite brucite (15 wt%)
(-9 wt%) → serpentinite chlorite dunite (6.2 wt%)
(-5 - -6 wt%) → harzburgite (0-1.4 wt%)

PA: pumpellyite actinolite (4-5 wt%)

(-1.5 - -2.5 wt%) → greenschist (3.0 wt%)
(-0.5 - -1.5 wt%) → amphibolite (1.5-2.5 wt%)
(-1.5 - -2.5 wt%) → eclogite (0 wt%)
Distributions of temperature and water content on the upper surfaces of the slabs beneath Kanto

Pacific slab alone

Pacific slab + Philippine Sea slab

temperature distribution

water content distribution
Thermal structure on the upper surface of the slabs and flow pattern in the mantle wedge beneath Kanto

Pacific slab alone

Pacific slab + Philippine Sea slab
Distributions of temperature and water content in the Pacific slab at different depths beneath Kanto.
Seismicity and water content distributions in the Pacific slab at different depths beneath Kanto
Seismicity and water content distributions in the Pacific slab at different depths beneath Kanto.
Conclusions

• Constructed 3-D high-resolution thermal structure model associated with dual subduction beneath Kanto.

• Seismicity in the oceanic crust in the PAC slab (at depths of about 40 km) corresponds well to dehydrated area associated with the phase transformation.

• The effect of existence of the PHS slab on distributions of temperature, dehydration, and seismicity in the PAC slab
  → Temperature decreases at the slab-slab contact zone
  → Water is carried to the deeper portion there in a form of OH group due to delay of phase transformations
  → Water released area at the deeper portion of the contact zone coincides well with intraslab deep seismicity
Thank you for your attention

This presentation is based on Ji et al., Scientific Reports, 7, 16864 (2017)
Method

Governing equations for 3-D parallelepiped thermal convection model

Mass conservation
\[ \nabla \cdot [\rho_s(z)v] = 0 \]

Momentum equation
\[ -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \delta_{ij} \rho_s g \alpha_0 (T - T_s) = 0 \]

Energy equation
\[ \rho c_p \left( \frac{\partial T}{\partial t} + v \cdot \nabla T \right) = k \nabla^2 T + \eta (\nabla v)^2 + \rho g a T v + H_r \rho + \tau \dot{\varepsilon} \]

Viscosity
\[ \eta = \frac{\eta_{\text{diff}} \eta_{\text{disl}}}{\eta_{\text{diff}} + \eta_{\text{disl}}} \quad \eta_{\text{diff,disl}} = \left( \frac{d^p}{AC_{OH}^r} \right)^{\frac{1}{n}} \varepsilon^{(1-n)/n} \exp \left[ \frac{E + P_{lc}}{nRT} \right] \text{Burkett and Billen (2010)} \]
Age of the Pacific and the Philippine Sea plates

Image from Liu and Zhao (2016)
Subduction history of the Pacific and the Philippine Sea plates from 20 Ma to the present

Hall et al. (1995); Faccenna et al. (2017)
Heat flow distribution

Yoshioka et al. (2015)
## Parameters in our 3D Modeling

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho_0$</td>
<td>Standard density</td>
<td>3300$^{(1)}$</td>
<td>kg/$m^3$</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Temperature difference between top and bottom of model</td>
<td>1600</td>
<td>K</td>
</tr>
<tr>
<td>$k_0$</td>
<td>Standard thermal conductivity</td>
<td>2.9$^{(3)}$</td>
<td>W/$mK$</td>
</tr>
<tr>
<td>$Hr$</td>
<td>Radioactive heat generation rate in the mantle</td>
<td>2.245$\times 10^{-13}$</td>
<td>W/$m^3$</td>
</tr>
<tr>
<td>$C_{p_0}$</td>
<td>Standard specific heat at constant pressure</td>
<td>1200 $^{(1)}$</td>
<td>J/kgK</td>
</tr>
<tr>
<td>$\kappa_0$</td>
<td>Standard thermal diffusivity</td>
<td>7.6$\times 10^{-7}$ $^{(4)}$</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>Standard viscosity</td>
<td>10$^{20}$ $^{(3)}$</td>
<td>Pa·s</td>
</tr>
<tr>
<td>$\alpha_0$</td>
<td>Standard thermal expansion</td>
<td>3$\times 10^{-5}$ $^{(2)}$</td>
<td>/ K</td>
</tr>
<tr>
<td>$v_1$</td>
<td>Straight subduction velocity</td>
<td>4.0$^{(1)}$</td>
<td>cm/yr</td>
</tr>
<tr>
<td>$v_2$</td>
<td>Oblique subduction velocity</td>
<td>6.3$^{(5)}$</td>
<td>cm/yr</td>
</tr>
</tbody>
</table>

Table 1. Thermal properties used for the temperature calculations.

<table>
<thead>
<tr>
<th>Geological unit</th>
<th>Thermal conductivity W m$^{-1}$ k$^{-1}$</th>
<th>Heat production W k$^{-1}$</th>
<th>Density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper crust (0–16 km)</td>
<td>2.5$^a$</td>
<td>7.3 $\times$ 10$^{-10}$$^a$</td>
<td>2600$^a$</td>
</tr>
<tr>
<td>Lower crust (16–32 km)</td>
<td>2.5$^a$</td>
<td>1.4 $\times$ 10$^{-10}$$^a$</td>
<td>2900$^a$</td>
</tr>
<tr>
<td>Mantle and oceanic plate</td>
<td>2.5</td>
<td>2.245 $\times$ 10$^{-13}$$^a$</td>
<td>3300$^a$</td>
</tr>
<tr>
<td>Accretionary prism</td>
<td>1.4$^b$</td>
<td>7.3 $\times$ 10$^{-10}$$^a$</td>
<td>2600$^a$</td>
</tr>
</tbody>
</table>

$^a$Wang et al. (1995).
$^b$Ashi et al. (2002).
\[ \eta_{comp} = \frac{\eta_{df}\eta_{ds}}{\eta_{df} + \eta_{ds}}. \]

\[ \eta_{df,ds} = \left( \frac{d^p}{A_0 C_{OH}^r} \right)^{\frac{1}{n}} \dot{\varepsilon}_E^{\frac{1-n}{n}} \exp\left( \frac{E_0 + PV_0}{n_0 RT_a} \right), \]

### Flow law parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Diffusion creep</th>
<th>Dislocation creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_0 ) Stress exponent</td>
<td>1.0</td>
<td>3.5</td>
</tr>
<tr>
<td>( A_0 ) Preexponential factor (s^{-n}Pa^{-m}\mu m^{-r}H^{-t} 10^{6}\si{Si})</td>
<td>1.0</td>
<td>9.0\times10^{-20}</td>
</tr>
<tr>
<td>( E_0 ) Activation energy (kJ/mol)</td>
<td>335</td>
<td>480</td>
</tr>
<tr>
<td>( V_0 ) Activation volume (m^3/mol)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper mantle</td>
<td>4.0\times10^{-6}</td>
<td>11.0\times10^{-6}</td>
</tr>
<tr>
<td>Lower mantle</td>
<td>1.5\times10^{-6}</td>
<td>-</td>
</tr>
<tr>
<td>( d ) Grain size (\mu m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper mantle</td>
<td>10,000</td>
<td>-</td>
</tr>
<tr>
<td>Lower mantle</td>
<td>40,000</td>
<td>-</td>
</tr>
<tr>
<td>( P ) Grain size exponent</td>
<td>3.0</td>
<td>-</td>
</tr>
<tr>
<td>( C_{OH} ) OH concentration (H/10^6\si{Si})</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>( r ) ( C_{OH} ) exponent</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Model parameters** for the diffusion and dislocation creep of olivine (Armienti and Tarquini, 2002; Hirth and Kohlstedt, 2003; Burkett and Billen, 2010)
The model parameters (Table 2) were tested for sensitivity by changing them by ±5 per cent, and changes in the 150, 350 and 450 °C isotherm locations were determined (Fig. 10). A change of ±65 °C in ΔT, which contributes to \( Ra_0 \), \( \xi \) and \( Rh_0 \), changed the average locations of the eight profiles by ±2, ±9 and ±12 km, respectively. Changing mantle thermal diffusivity, defined by \( \rho \), \( k \) and \( Cp \), by \( ±3.2 \times 10^{-8} \text{ m}^2 \text{ s}^{-1} \) moved the average locations by ±1, ±4 and ±3 km, respectively. Changes in \( D \), \( Rh_{\text{mantle}} \) and \( \alpha_0 \), which also affect \( Di_0 \), \( \Gamma_0 \) and \( \xi \), had negligible effects on the average locations. If the continental Moho depth was 30 km, which was 2 km shallower than the depth used in this model, the average locations would change by ±0, ±0 and ±3 km, respectively. We used
Temperature and H₂O variations for mantle density variation of -50 kg/m³ (mantle density of 3250 kg/m³)
Temperature and H$_2$O variations for mantle density variation of +50 kg/m$^3$ (mantle density of 3350 kg/m$^3$)
Temperature and H$_2$O variations for mantle viscosity variation of $-0.1 \times 10^{20}$ Pa s (mantle viscosity of $0.9 \times 10^{20}$ Pa s)
Temperature and H$_2$O variations for mantle viscosity variation of $+0.1 \times 10^{20}$ Pa s (mantle viscosity of $1.1 \times 10^{20}$ Pa s)
Previous study (1)

- 2-D model
  Iwamori (EPSL, 2000)
  Yoshioka et al. (GJI, 2015)
- 3-D model
  Wada and He (GRL, 2017)
Previous study (2)

Yoshioka et al. (GJI, 2015)
Previous study (3)

Yoshioka et al. (GJI, 2015)
Necessary data for model construction

- Slab geometry
- Age of the oceanic plates at the Trench or Trough
- Subduction history
- Heat flow
Yoshioka et al. (GJI, 2015)

Previous study (3)

temperature

stream function

clockwise rotation

anti-clockwise rotation

Yoshioka et al. (GJI, 2015)
Objectives

To understand geodynamic process associated with subduction of two oceanic plates beneath Kanto, using 3-D thermal convection subduction model

• Thermal structure associated with subduction of plates with 3-D complex geometry
• Spatial distributions of maximum solubility and dehydration
• Mantle flow in the mantle wedge

To elucidate seismogenesis of inter- and intra-plate earthquakes (≥M2) beneath Kanto
Plate geometry model and distribution of interplate microearthquakes in the study area
temperature

stream function

clockwise rotation

anti-clockwise rotation

Yoshioka et al. (GJI, 2015)
Seismogenesis of dual subduction beneath Kanto, central Japan controlled by fluid release

Yingfei Ji1,2, Shinichiro Yoshida1,3,4, Vitali C. Mamets3 & Satoshi Miki1,2,4,5

Our study shows that the fluid release in the mantle wedge is a key mechanism for the dual subduction of the Pacific plate beneath Japan. The fluid release is controlled by the generation of seismicity in the mantle wedge, which is driven by the interaction between the subducting slab and the mantle wedge. The fluid release is also controlled by the geodynamic settings of the subduction zone, which is characterized by the presence of a high-temperature mantle wedge and a low-temperature slab. The fluid release plays a crucial role in the generation of seismicity in the mantle wedge, and it is a key mechanism for the dual subduction of the Pacific plate beneath Japan.

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