# Subduction zone dynamics: role of $H_2O$ in generation of earthquakes and magmas

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Science as Method & Methodology 研究会@名古屋

**Title:**

- **Subduction zone dynamics: role of $H_2O$ in generation of earthquakes and magmas**

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- **Role of $H_2O$ in generation of earthquakes and magmas in subduction zones as inferred from seismic observations**

- ACROSS

**Content：**

1. **Subduction of oceanic plate**
2. **Slip pattern along plate interface**
3. **Earthquakes within subducted slab:**
   **Intermediate-depth intraslab earthquakes**
4. **Transportation of aqueous fluids from slab to arc crust and formation of volcanic front**
5. **Deformation of arc crust and shallow inland earthquakes**

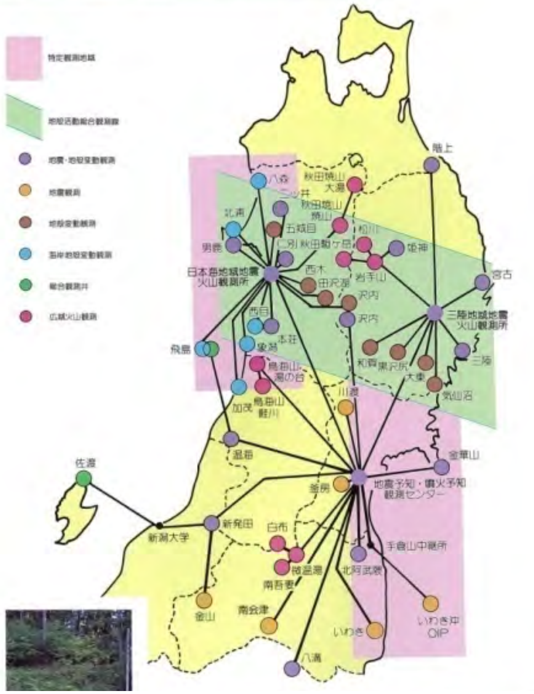
**Study area：**

- **Japan subduction zones / NE Japan subduction zone**

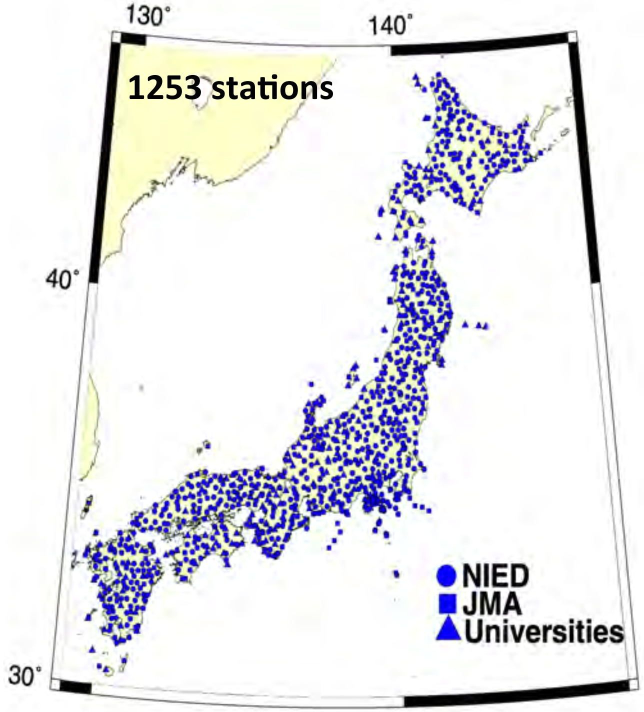
## Why Japan subduction zone? /NE Japan subduction zone?

●高感度地震観測網

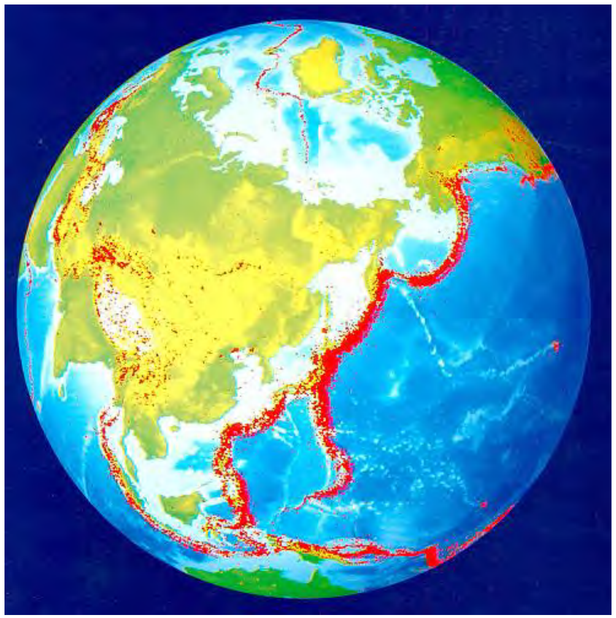
Tohoku University seismic network

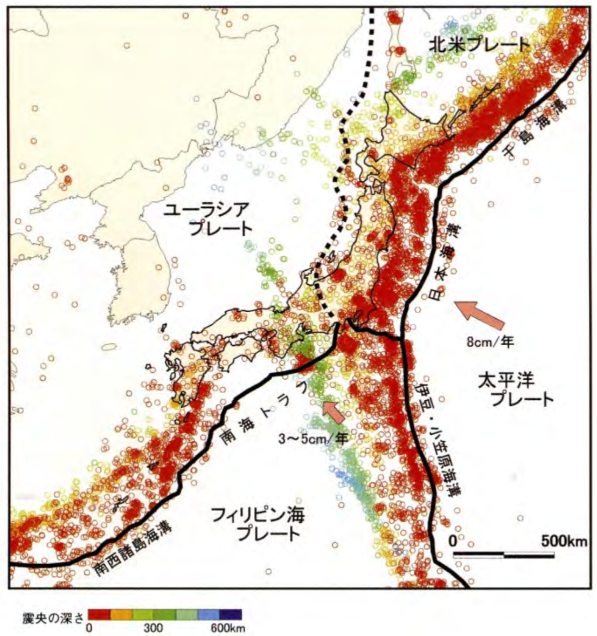


Nationwide Kiban seismic network




●地震活動：
震源分布



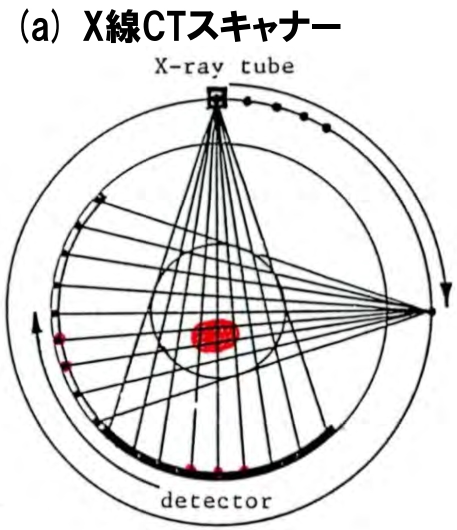


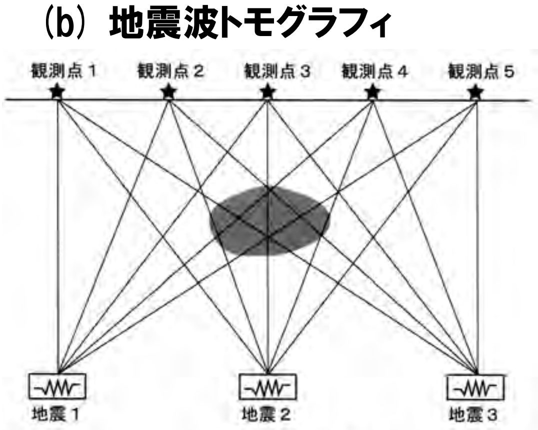
# 1. プレートの沈み込み

## 1. Subduction of oceanic plate

# Imaging subducting oceanic plate

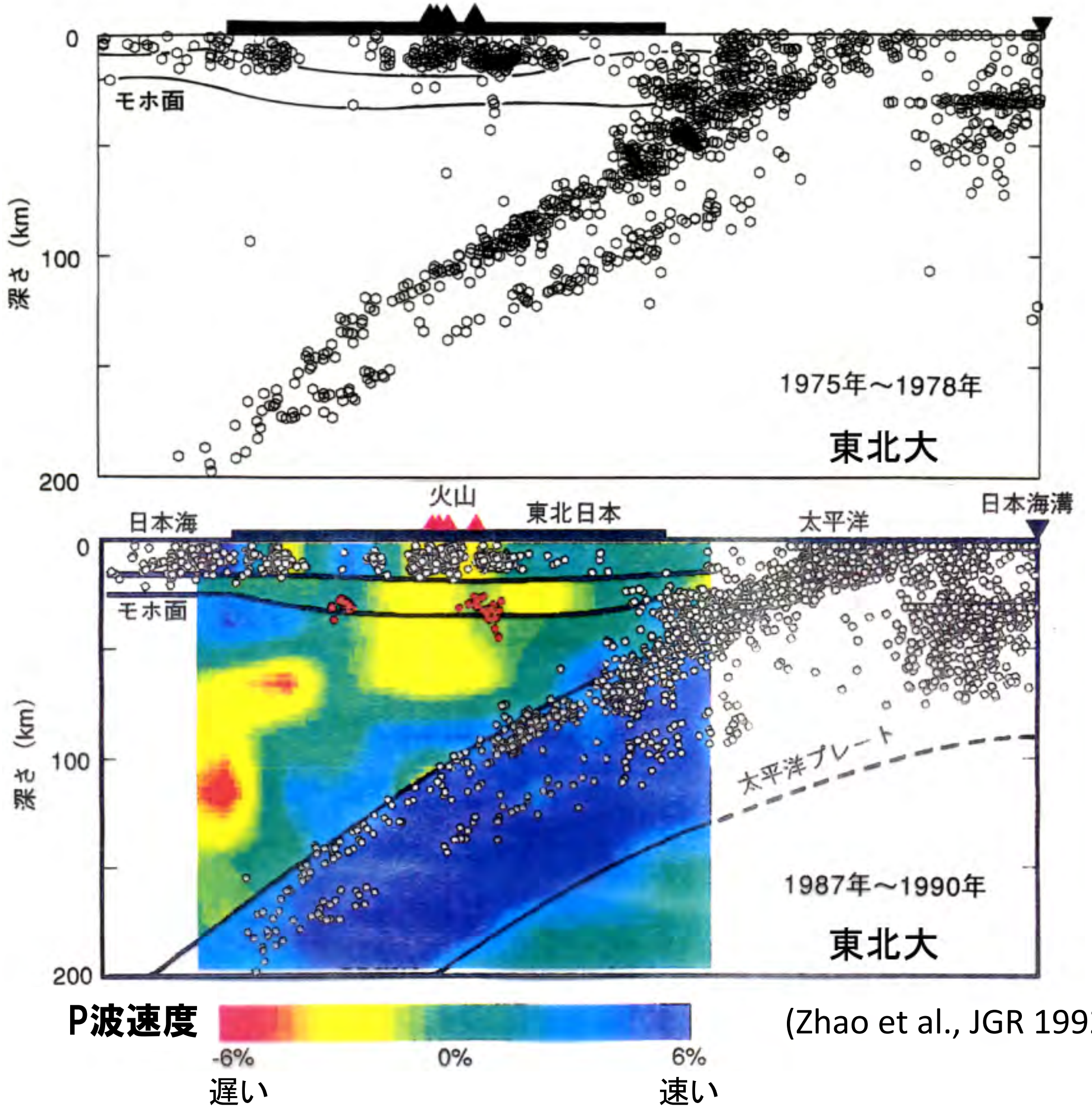
●X-ray CT & seismic tomography




・CT のように地震波で地球内部を覗く
・地球内部を見る最もpowerful　な手段
・地球全体～震源断層のスケールまで
・地震波速度構造(Vp, Vs)、地震波減衰構造(Qp, Qs)

●Across –arc vertical cross section of EQs




(Zhao et al., JGR 1992)

●Vertical cross section imaged by tomography

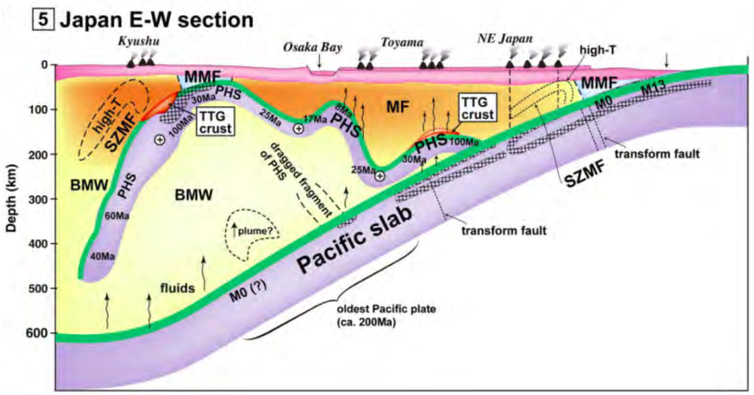
# Estimated configuration of PAC and PHS plates

コンター：プレート上面の等深線
青楕円：プレート境界大地震
▲：火山
黒点：深部低周波微動

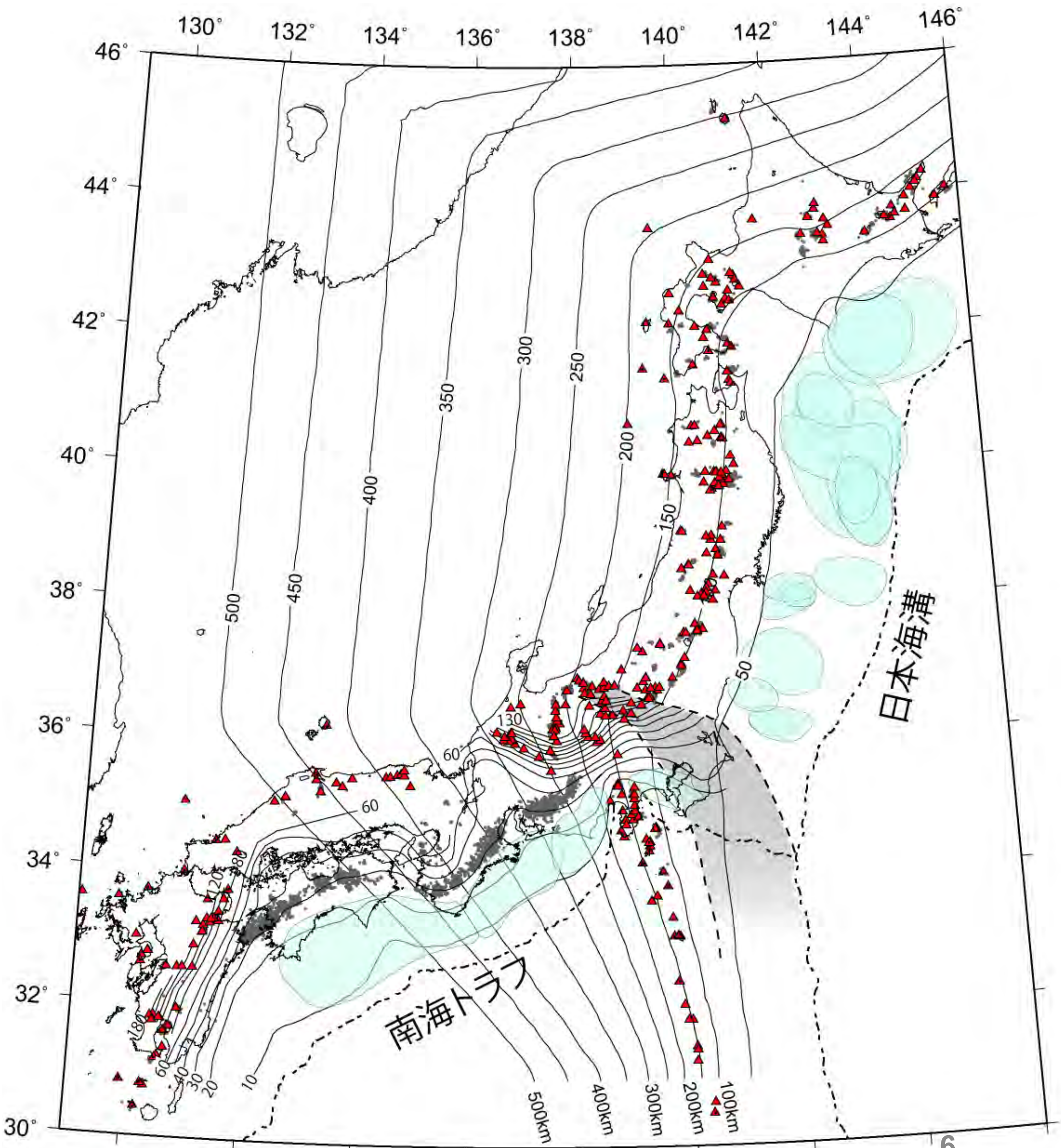
（Nakajima et al., 2009; Kita et al., 2010；Hirose et al., 2008; Nakajima & Hasegawa, 2007)

•Contact area between PAC & PHS plates is shaded; broad area nearly corresponds to Kanto Plain

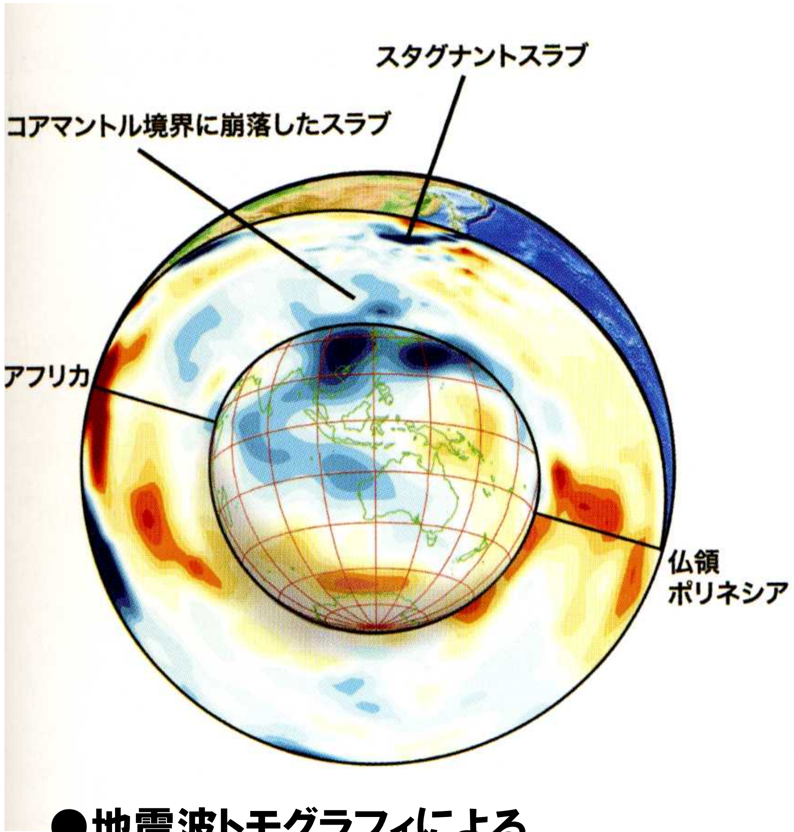
•PHS slab subducts beneath SW Japan being extremely contorted




（Maruyama et al., Gond. Res. 2009)

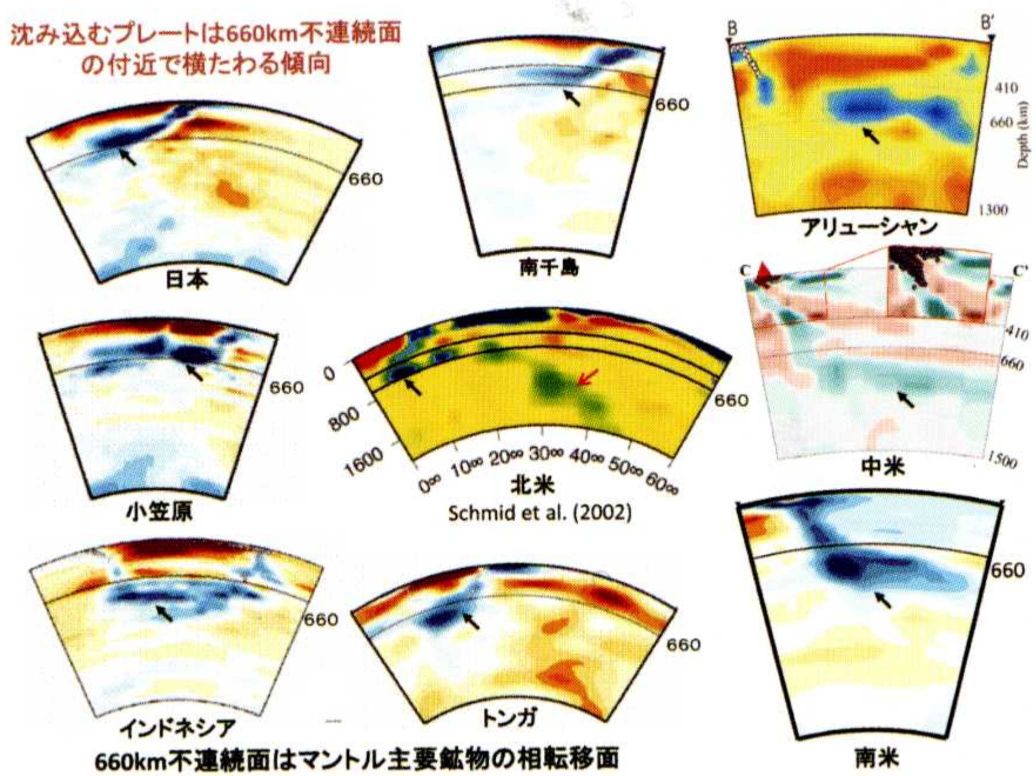


# Slabs stagnate in the mantle transition zone




●地震波トモグラフィによる
マントルのイメージング

(Fukao et al., Ann. Rev. Earth Planet. Sci. 2009)

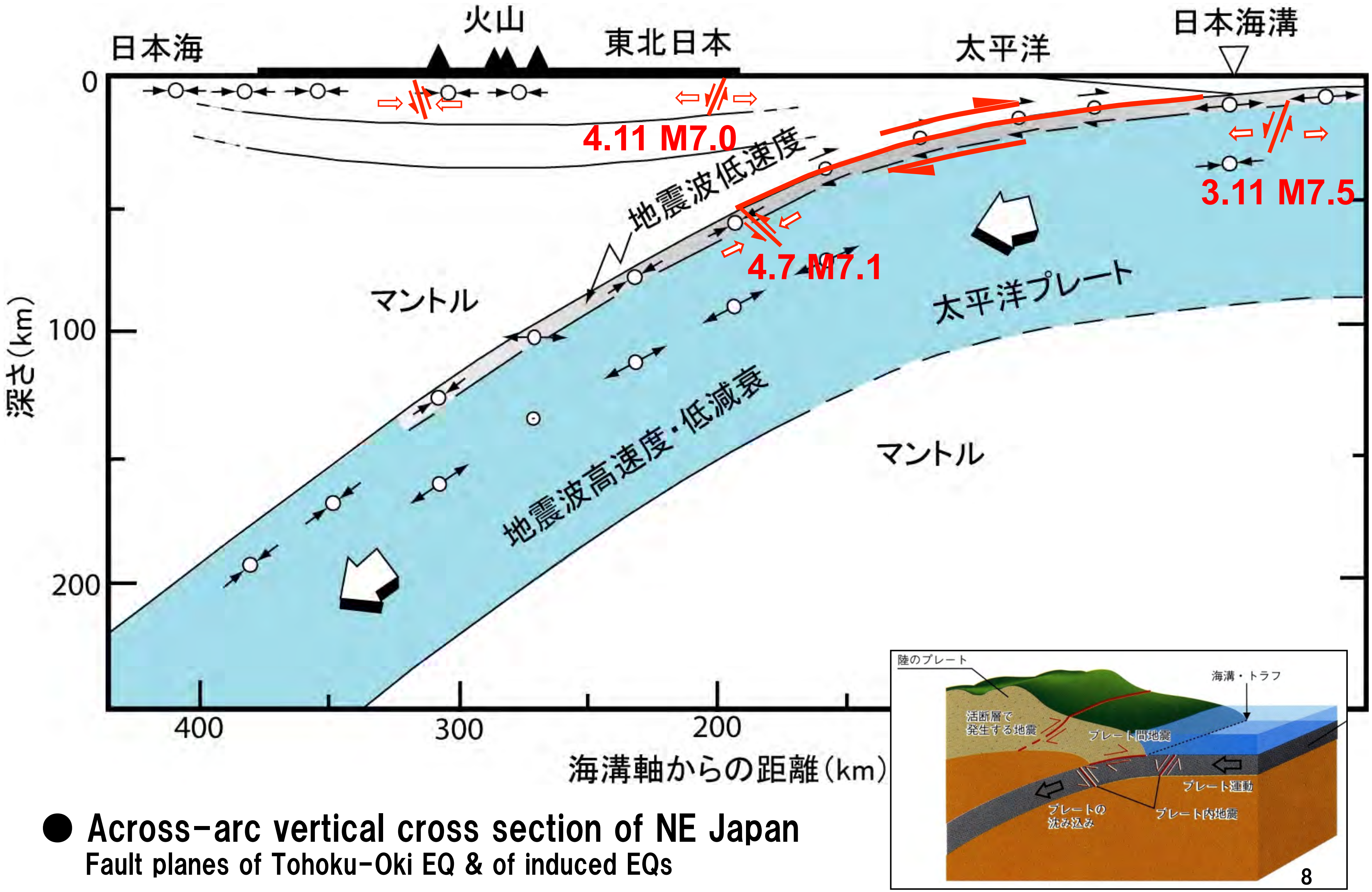



●さまざまな場所で見つかった滞留 (スタグナント) スラブ

マントル遷移層で滞留しているものや，それより深いところで滞留しているもの，あるいは下部マントルに崩落しかけているものもあり，滞留スラブの姿は多様である．

（深尾，2010）

# Three main types of EQs in subduction zones:
# 1) Interplate, 2) Intraslab, 3) Inland crustal EQs



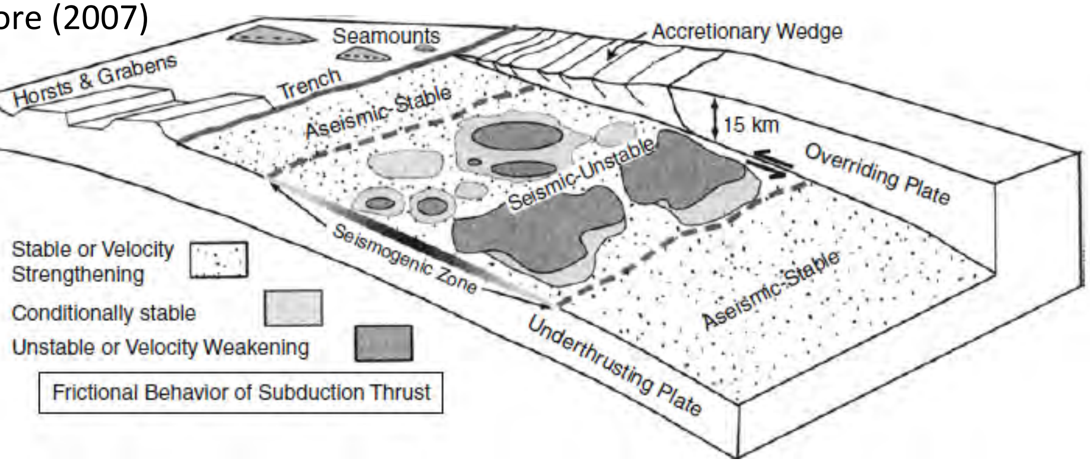

- Across-arc vertical cross section of NE Japan

Fault planes of Tohoku-Oki EQ & of induced EQs

# 2. プレート境界での
# すべり様式
## 2. Slip pattern along plate interface

# Frictional behavior of fault ー Asperity model

Bilek & Lay (2002),
Dixon & Moore (2007)

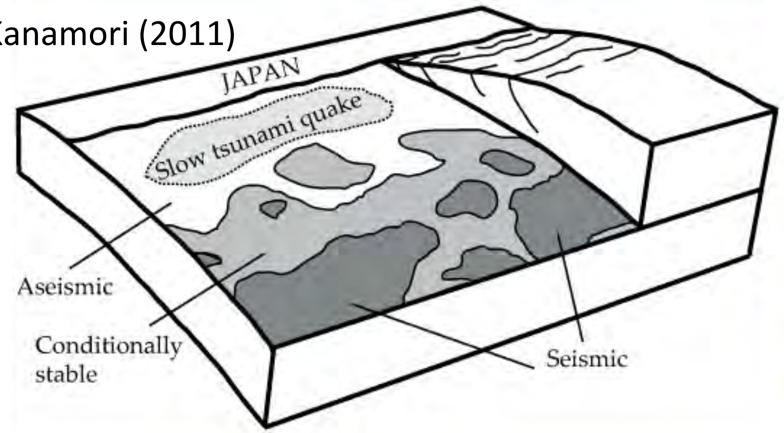



**Stably sliding: a-b>0**
**a-b〜0**
**Asperity: a-b<0**

**●Asperity model**

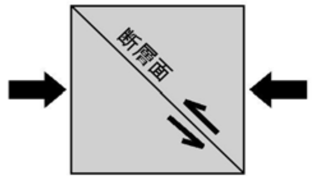
1) Asperity (locked area): a-b<0
   Interseismic period: locked
   At the time of EQ: dynamic slip
   (Seismic slip/unstable sliding)
2) Conditionally stable area: a-b〜0
   Normally slip aseismically but can also slip seismically when loaded abruptly during the failure of neighboring seismic patches
3) Stably sliding area: a-b>0
   Interseismic period: stably sliding
   (Aseismic slip/stably sliding)
   At the time of EQ: works as barrier

Lay & Kanamori (2011)

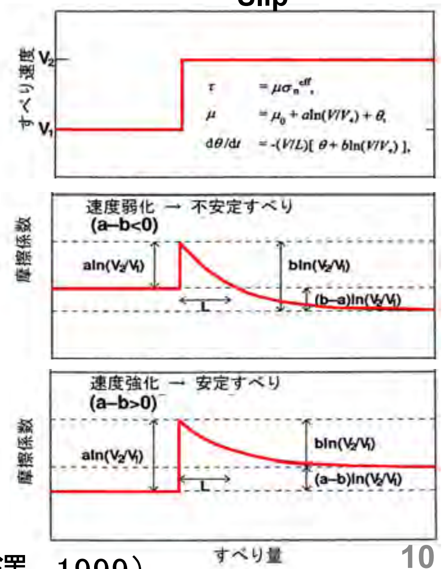



**●The megathrust off the coast of Tohoku**

**●Rate- and state-dependent friction law**




**Slip**




**Slip velocity**

**Friction coefficient**

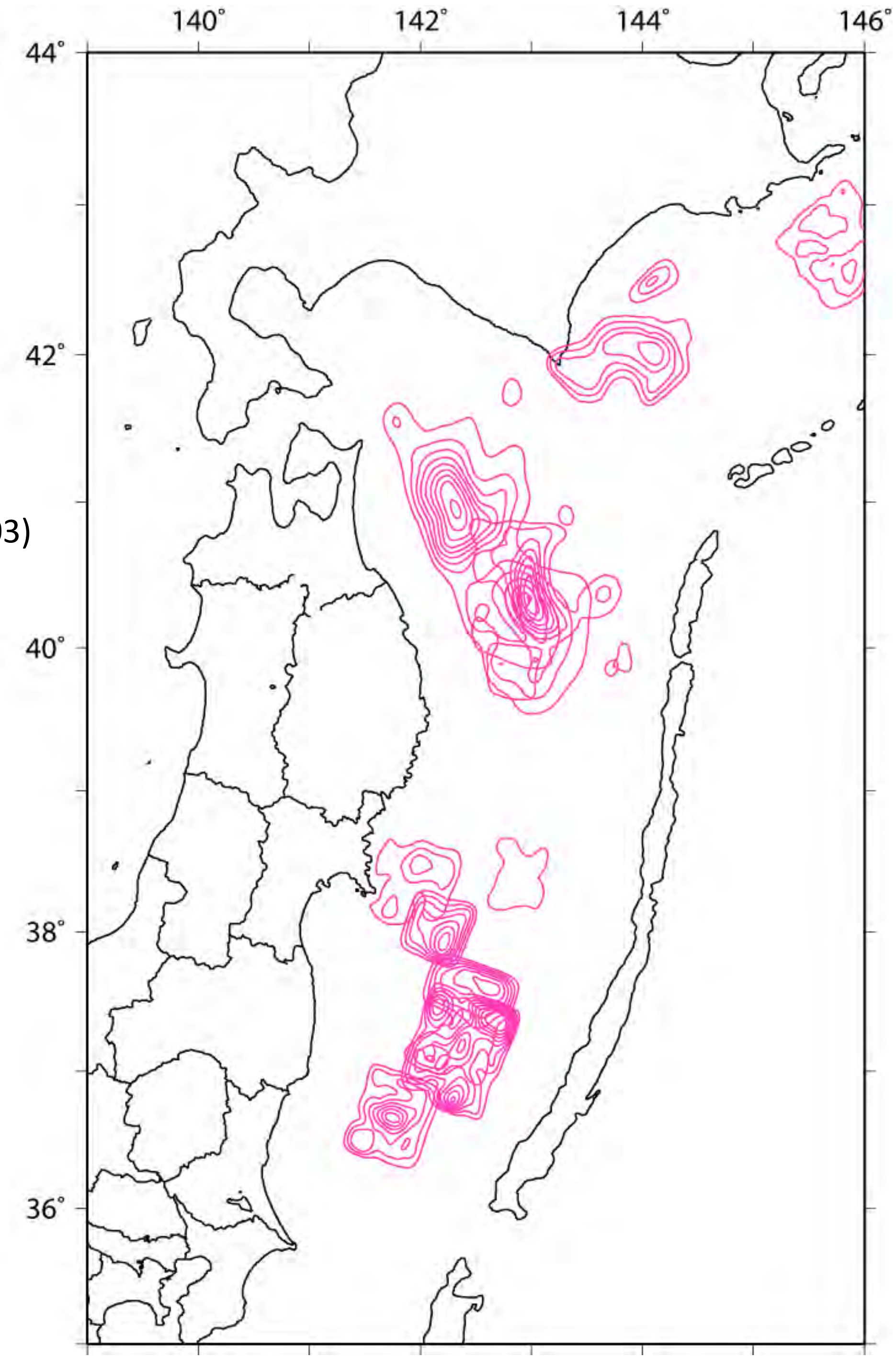
（平澤，1999）

# Asperity map

Pink contour: slip distribution of

EQs for the last ~70 yr with M>7

Yamanaka & Kikuchi (2004), Murotani et al. (2003)




アスペリティマップ

(過去70年間のM7以上の地震の滑り分布:

Yamanaka & Kikuchi (2004), Murotani et al. (2003) )

に重ねて示す

# Asperity map & Tohoku-Oki EQ

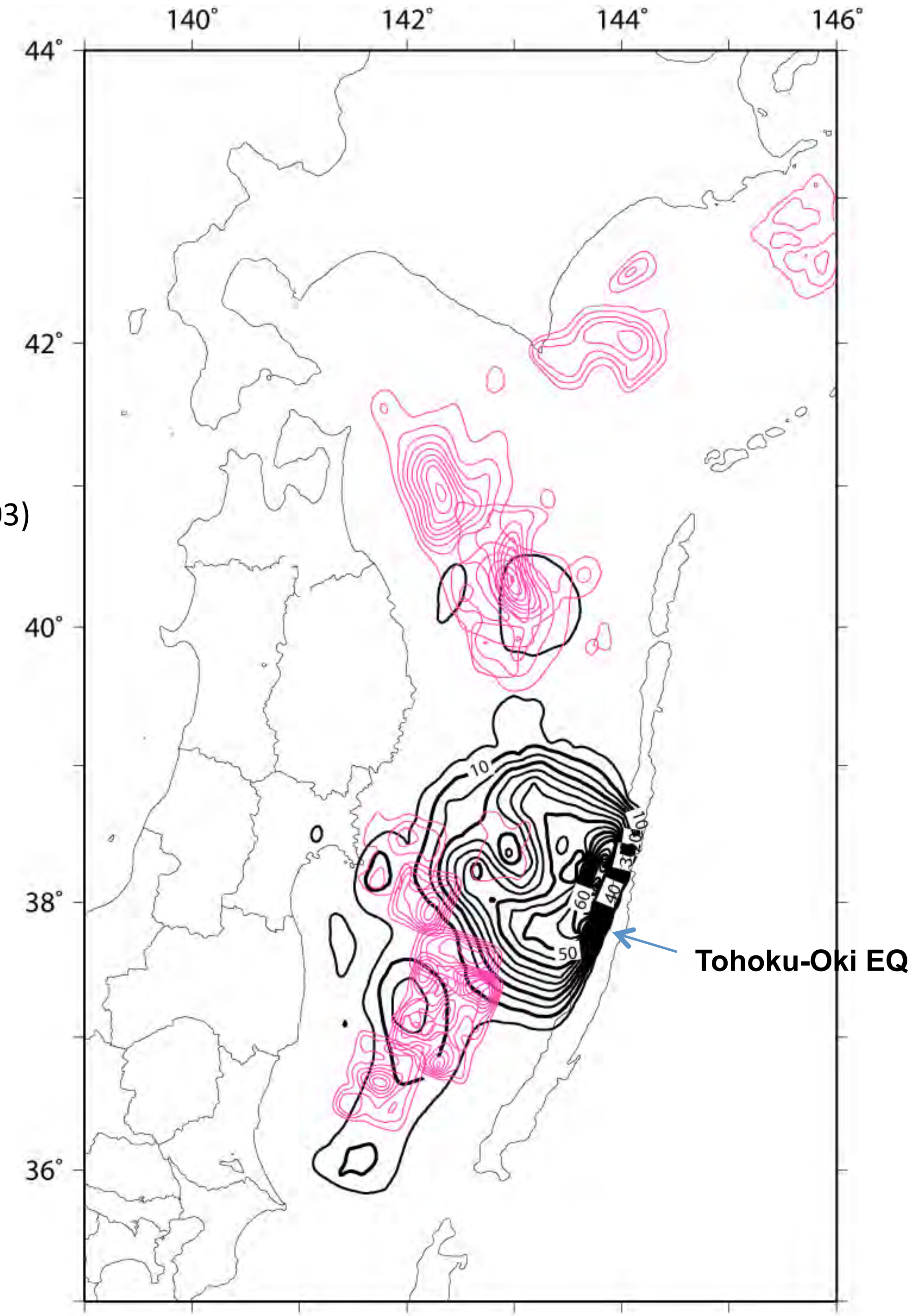
Pink contour: slip distribution of EQs for the last ~70 yr with M>7

Yamanaka & Kikuchi (2004), Murotani et al. (2003)

Black contour: slip distribution of 2011 Tohoku-Oki EQ

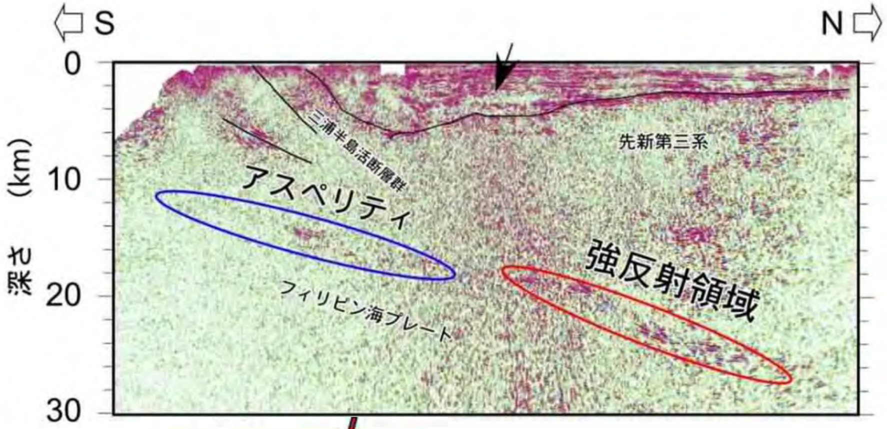
Iinuma et al. (2012)

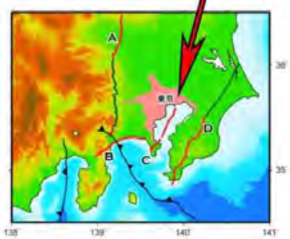
アスペリティマップ
(過去70年間のM7以上の地震の滑り分布：
Yamanaka & Kikuchi (2004), Murotani et al. (2003) )
に重ねて示す



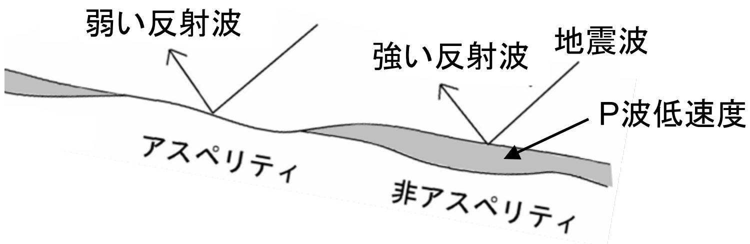
# Cause of asperity?

● Seismic section along a line crossing Tokyo Bay



・フィリピン海プレート上面の反射強度が，1923年関東地震のアスペリティ部分で小さい



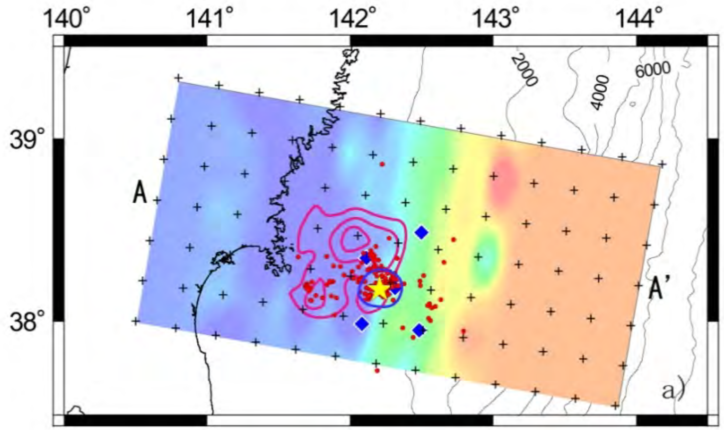

・固い岩盤同士が噛み合っている場所がアスペリティ？

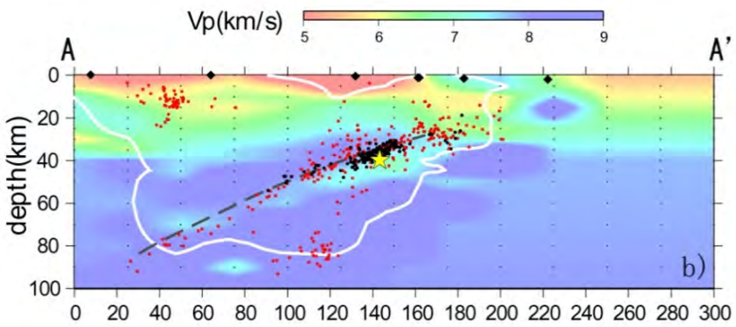
・非アスペリティ領域：P波低速度 (fluid が存在？)

（Sato et al., Science 2005）

● Vp along a plane just above plate interface off Miyagi

・プレート境界直上の面に沿うP波速度




・A－A'に沿うP波速度の鉛直断面

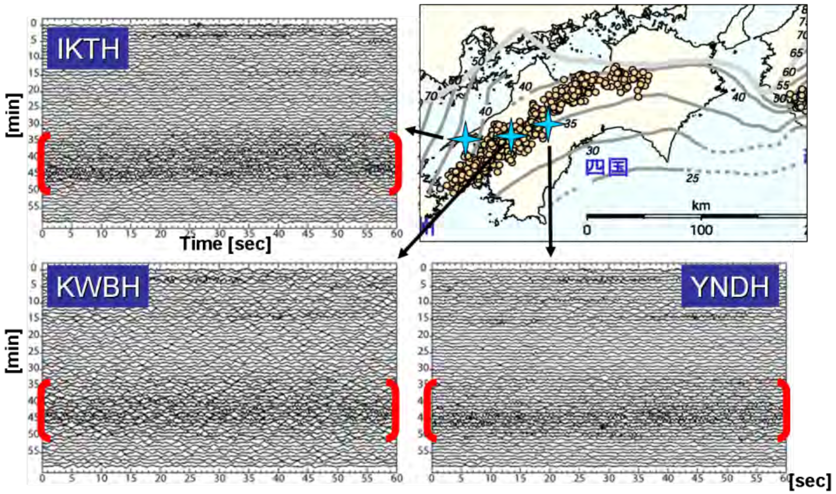
・非アスペリティの直上は低Vp
　→ マントルウェッジの蛇紋岩化（安定すべり）
・アスペリティ直上のマントルウェッジは高Vp
　→ マントルウェッジは蛇紋岩化してない（不安定すべり）



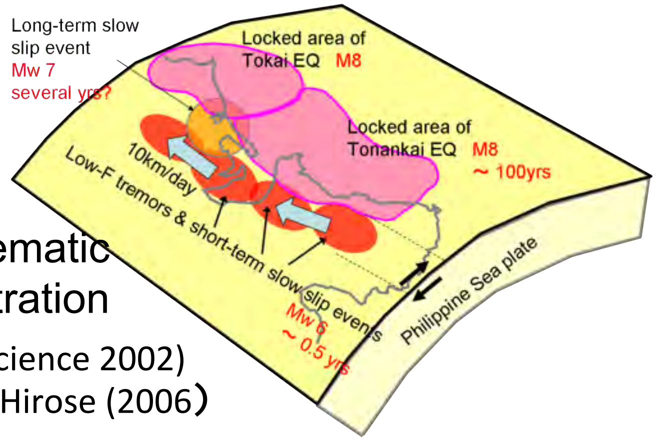
（Yamamoto et al., GRL 2007）

# Slow slip event & deep low-frequency EQs

●Seismogram showing deep low-F EQs

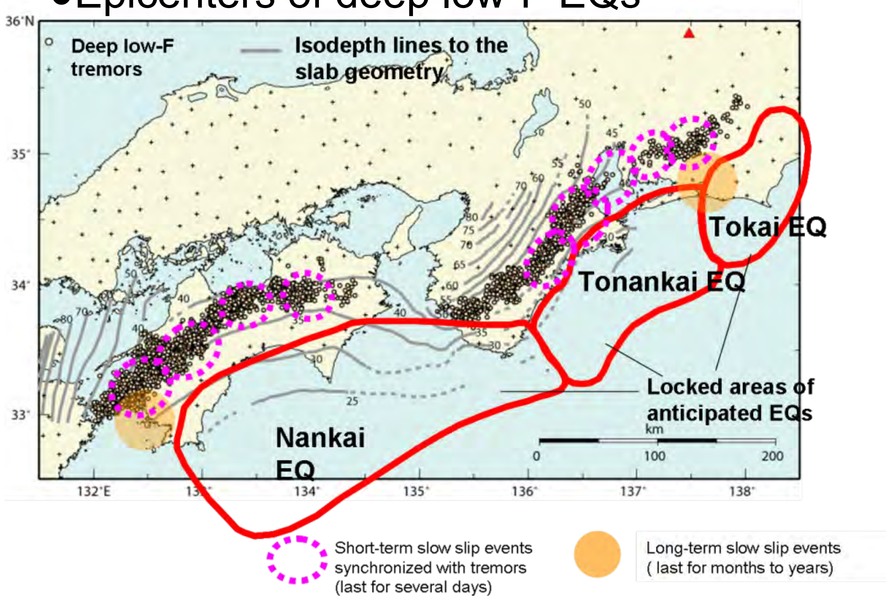



●Schematic illustration

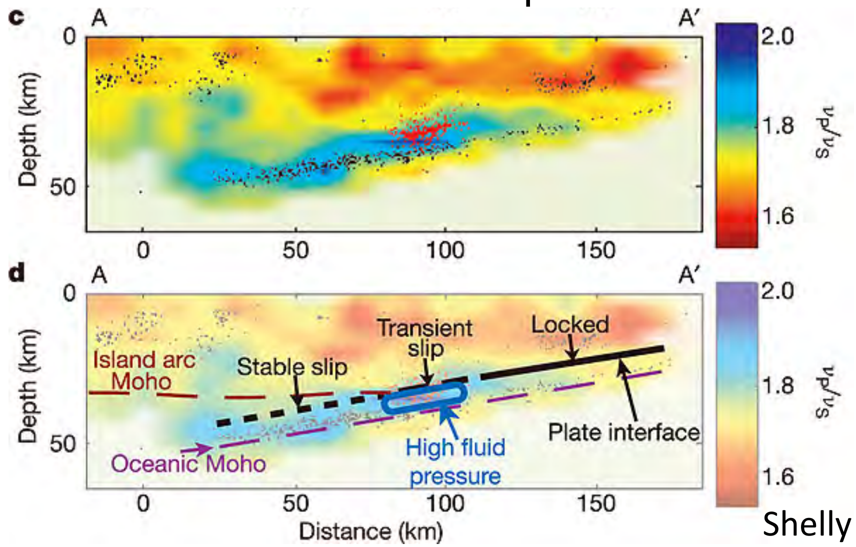



Obara (Science 2002)
Obara & Hirose (2006)

●Epicenters of deep low-F EQs




●Vertical cross section of Vp/Vs in Shikoku



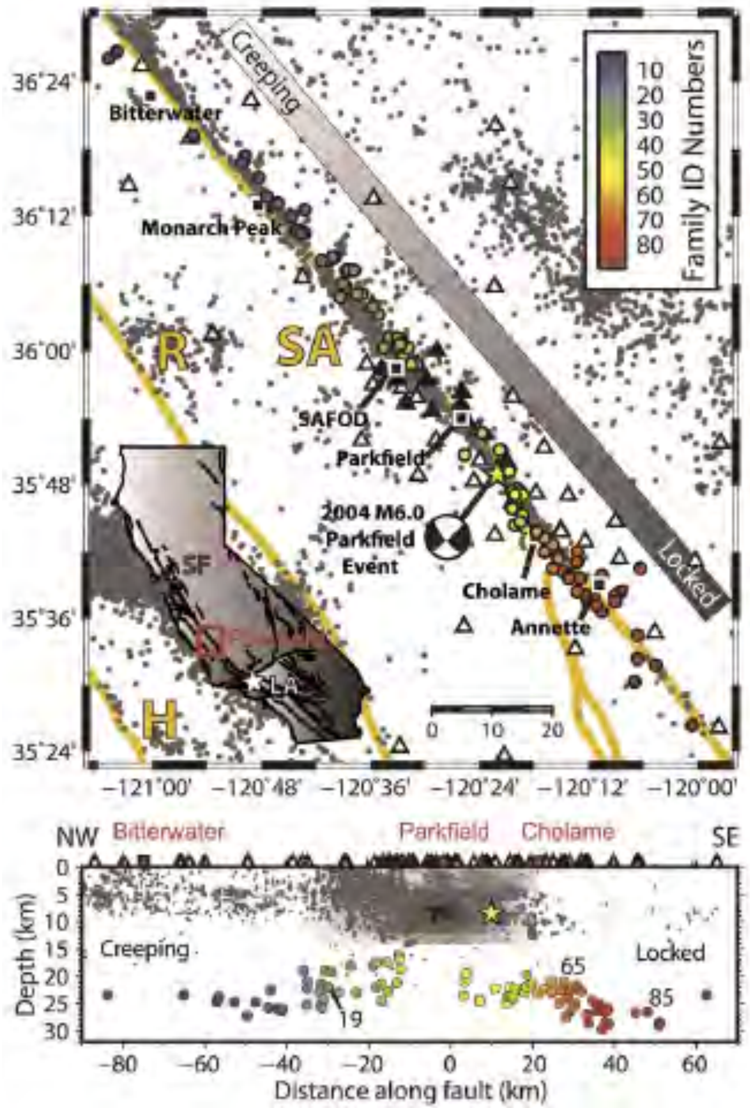

Shelly et al. (2006)

•Oceanic crust just below SSE has anomalously high Vp/Vs → High pore fluid pressure

# Effective normal stress along fault plane of deep low-F EQs

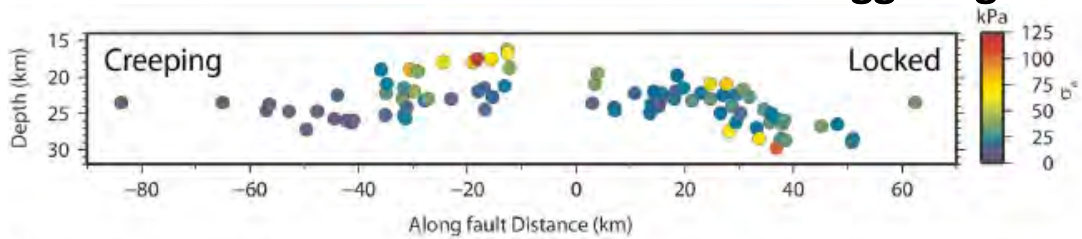
●Hypocenter distribution of low-F EQ families in the lower crust along deeper extension of SAF

Thomas et al. (2012 JGR)




・サンアンドレアス断層の深部延長面上の下部地殻内に分布
→ サンアンドレアス断層はモホ面まで鉛直に伸びている
・低周波地震は流体が関わって発生
→ 断層下部に地殻流体が存在. それが断層に沿って上昇、地震発生を規定

●Estimated effective stress from tidal triggering




・Effective normal stress estimated from tidal triggering of low-F EQs

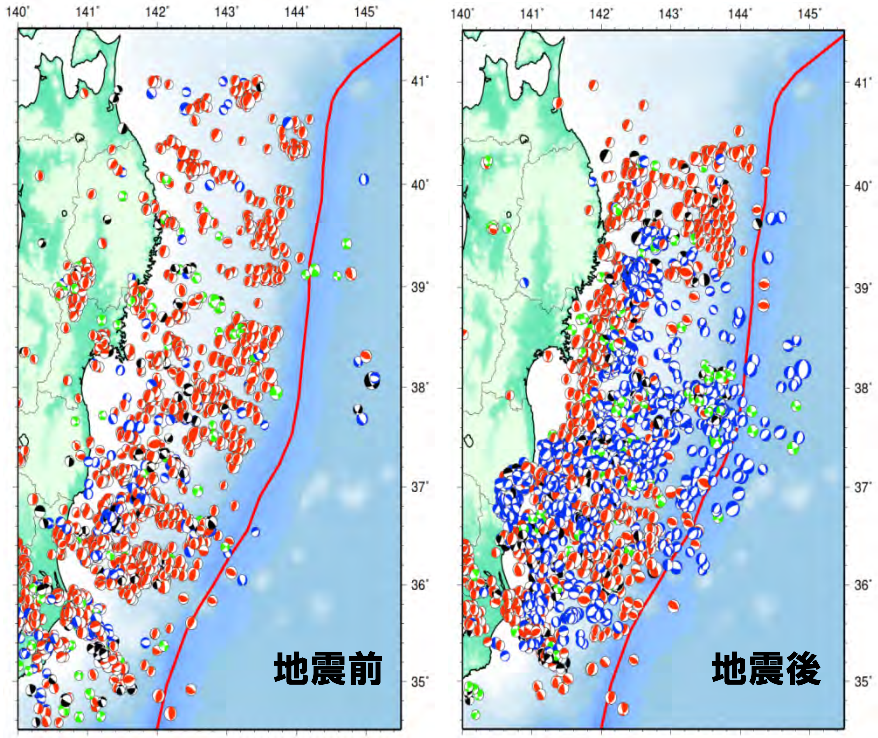
$\sigma_n$ = 10 – 100 kPa average 30 kPa

→ Very close to lithostatic pore fluid pressure

# Focal mechanism of EQs before & after Tohoku-Oki EQ

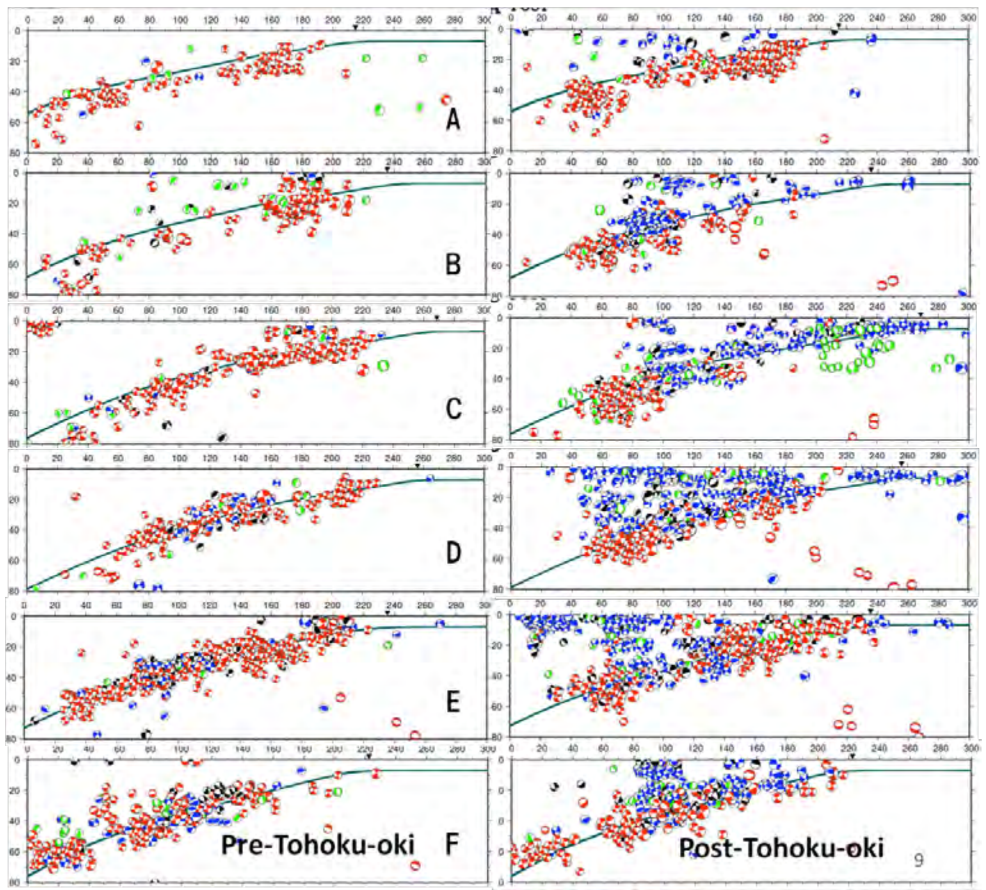
Asano et al. (2011 EPS)
Hasegawa et al. (2012 EPSL)

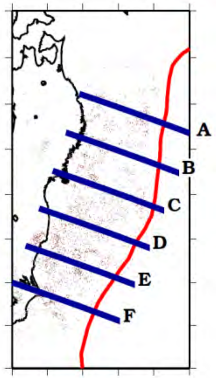
赤：逆断層
青：正断層
緑：横ずれ断層




●平面

●鉛直断面



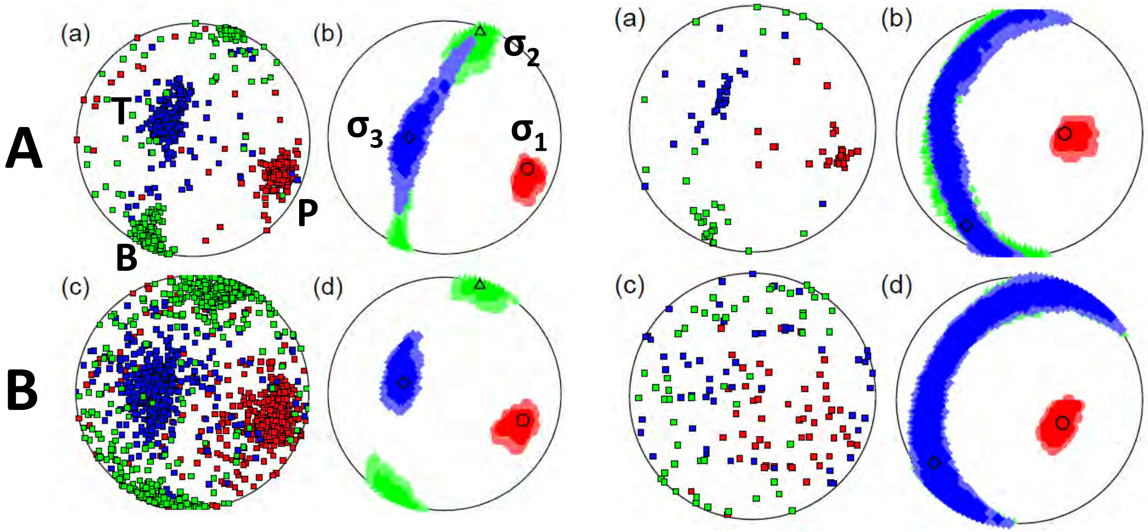



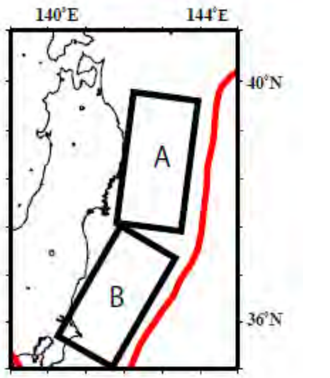

・ Normal fault EQs significantly increased after Tohoku-Oki EQ

# Change in stress field by Tohoku-Oki EQ – Rotation of $\sigma_1$ axis

●Distribution of P, T, B axes (left) & that of $\sigma_1$, $\sigma_2$, $\sigma_3$ axes (right)

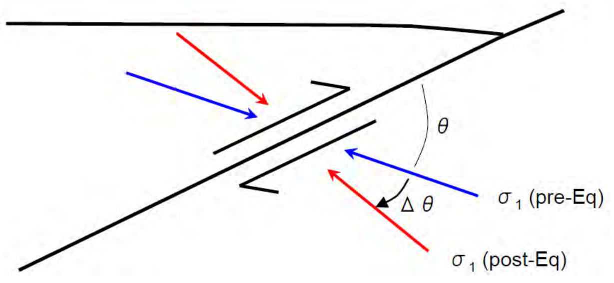
Hasegawa et al. (EPS 2011)



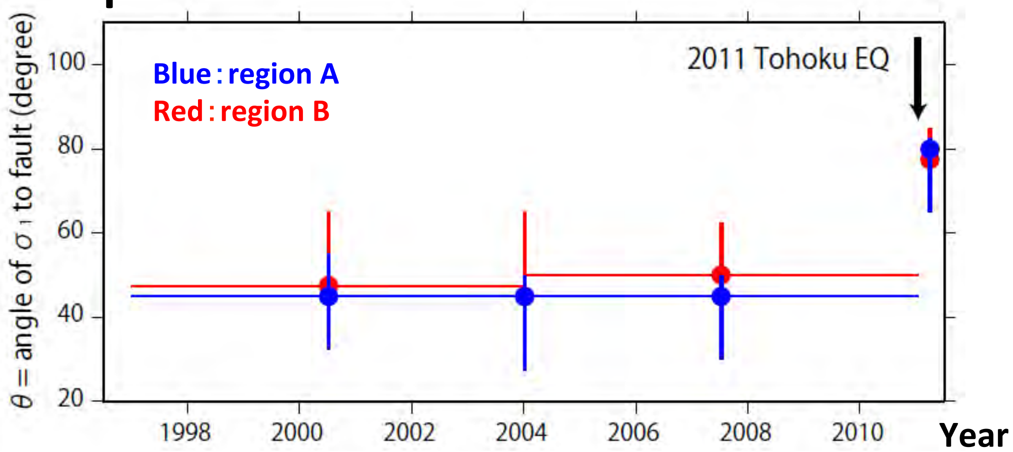




$\sigma_1$: max. compression (red)
$\sigma_3$: min. compression (blue)

●Temporal change in angle of $\sigma_1$ axis to plate interface




~45 degree before the earthquake
~80 degree after the earthquake

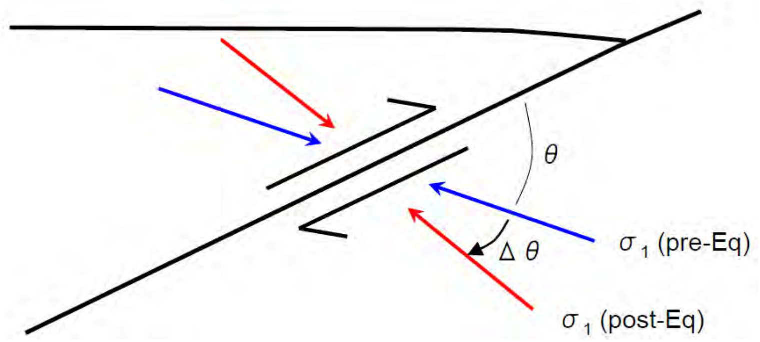



# Angle between $\sigma_1$ axis & plate interface clearly increased from about 45 degree to about 80 degree after Tohoku-Oki EQ. This stress rotation is due to slip on plate interface by Tohoku-Oki EQ.

# Estimation of deviatoric stress magnitude

Hasegawa et al. (EPS 2011)

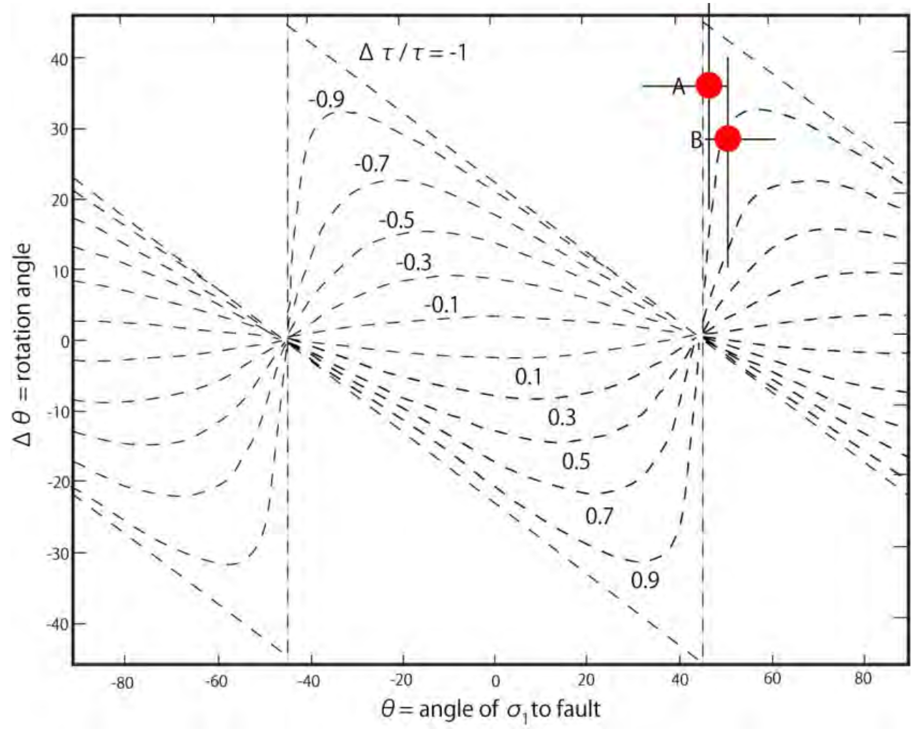
●Stress rotation due to slip on fault




**τ** : background deviatoric stress

**Δτ** : stress drop

● Δθ as a function of θ for various Δτ/τ




(Hardebeck and Hauksson, 2001)

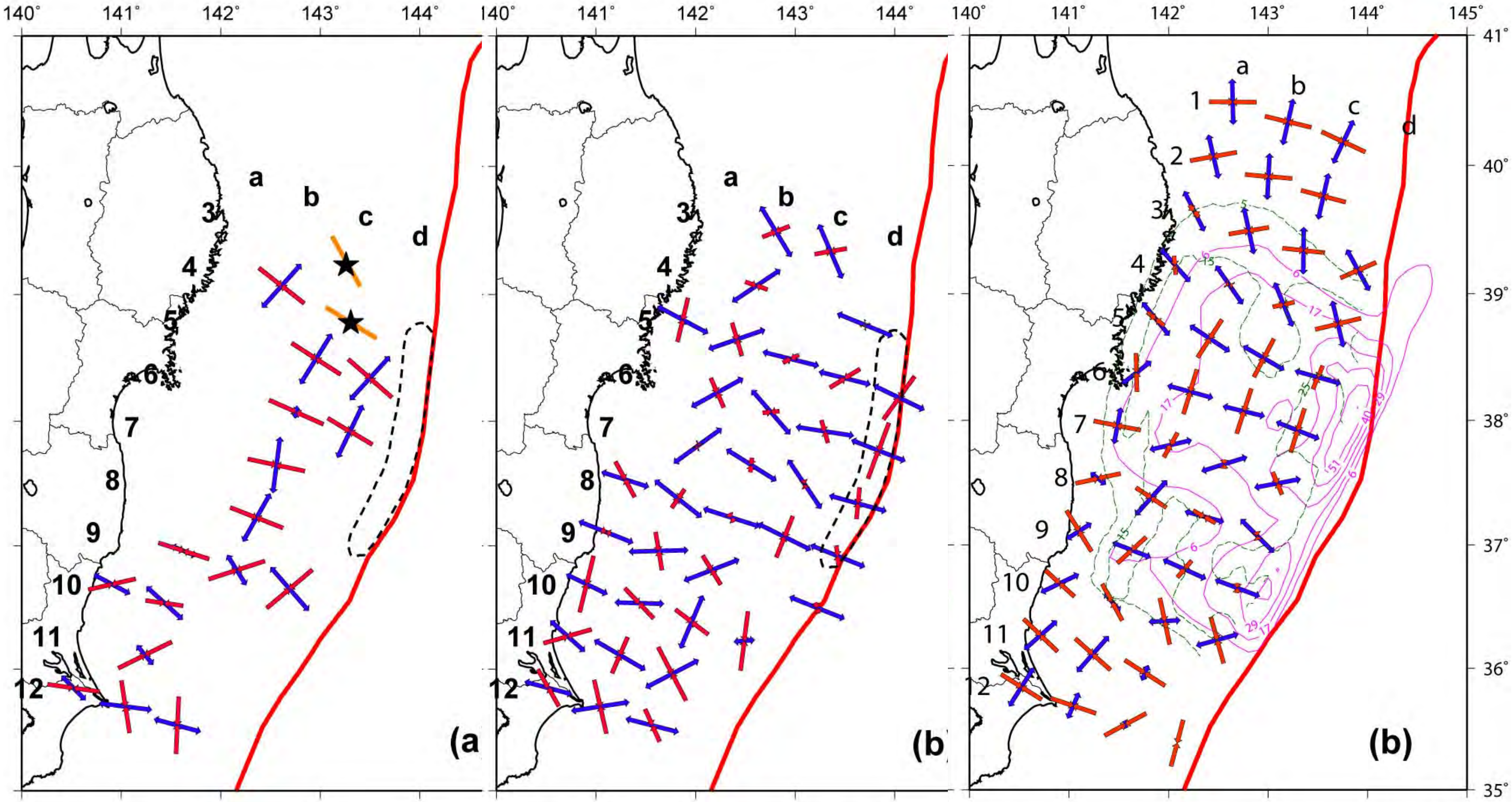
# θ vs Δθ relation in 2 dimensional case is given by Hardebeck & Hauksson (2001) for various <u>Δτ/τ</u>
# <u>Δτ/τ ~ 0.7 – 1.0</u>
# Background deviatoric stress, which caused Tohoku-Oki EQ, almost released
or <u>stress drop nearly complete</u>
# Average stress drop for areas with slip>10 m is Δτ ~8 MPa (Iinuma et al., 2011) → τ = 8 - 13 MPa
This means that <u>fault strength is 8 - 13 MPa</u> → weak fault
# Assuming weak fault is caused by over-pressured fluids, we obtain
pore pressure ratio <u>$\lambda = P_f / \sigma_n$</u> (ratio of pore pressure to normal stress) <u>= 0.97 – 0.98.</u>

Hasegawa et al. (EPSL 2012)

# Stress field before & after Tohoku-Oki EQ & static stress change

red : $\sigma_1$ blue : $\sigma_3$

● Pre-Tohoku-Oki ● Post-Tohoku-Oki ● Static stress change




Red contours: slip amount green contours: differential stress

# Stress field in the area enclosed by ∼15 MPa contour line completely reversed after Tohoku-Oki, which indicates differential stress magnitude before the EQ is less than static stress change, i.e. < 15 – 25 MPa ➞ <u>$\lambda$ > ∼0.95-0.97</u>

# Other observation: pore pressure ratio estimated based on force balance

- Force balance between shear stress at plate boundary & lithostatic pressure in the fore-arc wedge

- Estimated **shear stress** $\bar{\tau}$ and **pore pressure ratio** λ (pore fluid pressure/normal stress) @ plate interface

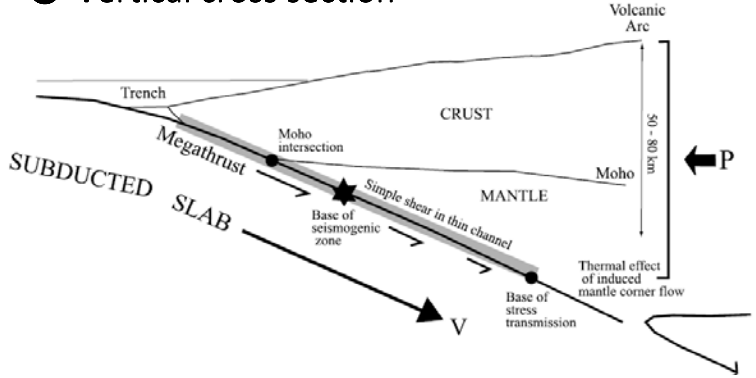
| | $\bar{\tau}$ | λ |
|---|---|---|
| Shikoku | 4.8±1.9 MPa | 0.980±0.008 |
| N Chile | 15.1±7.6 | 0.97±0.015 |
| S Chile | 16.1±4.0 | 0.96±0.01 |
| **Miyagi** | 20.1±5.7 | **0.965±0.010** |
| Peru | 14.2±9.0 | 0.948±0.033 |
| Washington | 7.8±3.4 | 0.93±0.03 |
| S Vancouver Island | 18.0±2.6 | 0.895±0.015 |

(Seno, 2009 JGR)

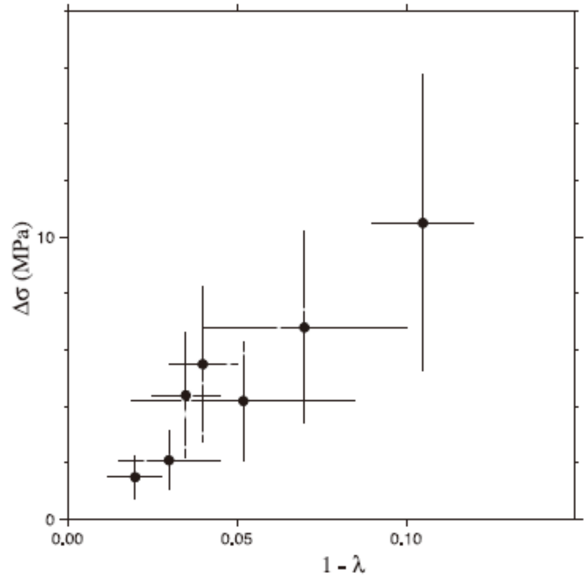
- Estimated λ from stress field change
  λ **= ∼0.97-98** or **> ∼0.95-0.97**
  **Almost consistent with each other**

- (1 – λ) seems to be proportional to average stress drop Δσ (right figure)

● Vertical cross section




● Plot of (1-λ) against Δσ



# 3. 沈み込んだプレート内で起こる地震：スラブ内地震

## 3. Earthquakes within subducted slab: Intermediate-depth intraslab earthquakes