内陸地震の発生過程について

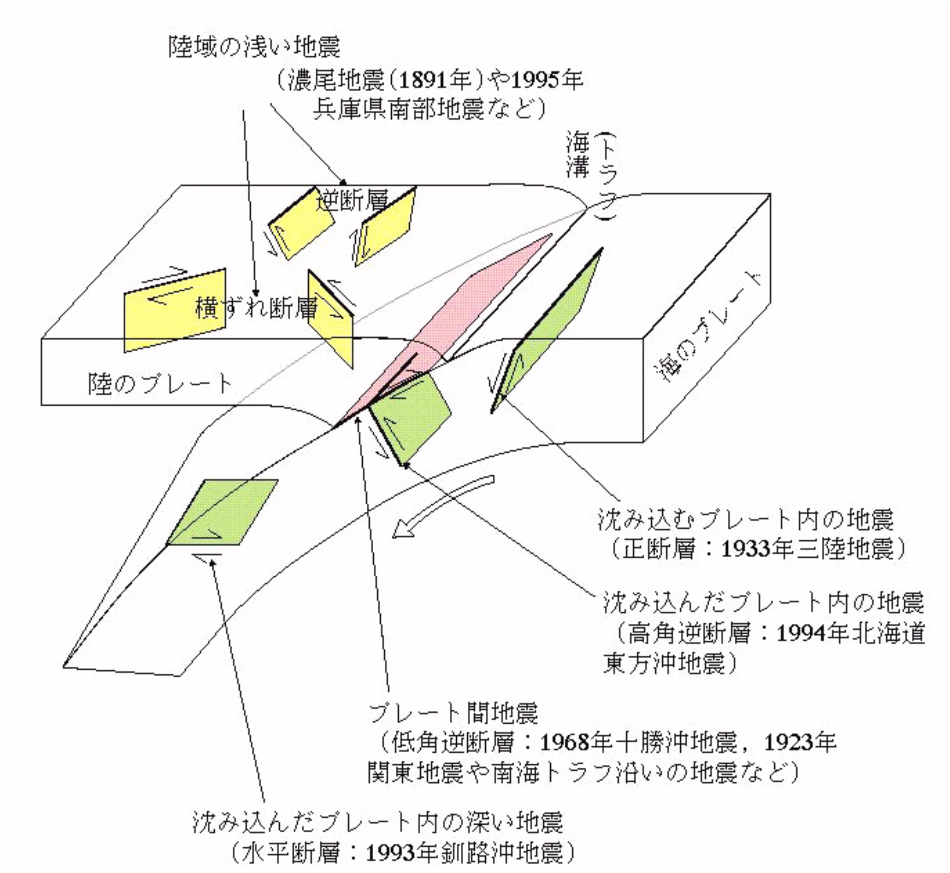
京都大学防災研究所　　飯尾能久

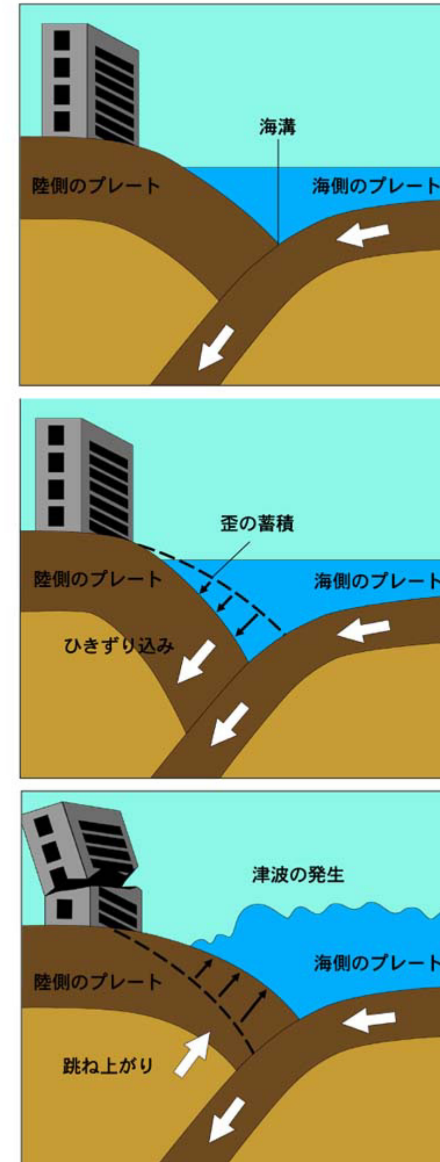
内陸地震の発生過程はよくわかっていない.

何が問題なのか？

- なぜプレート境界から遠くで起こる？
- なぜ発生間隔が長い？
- 何が発生間隔を決めるか？

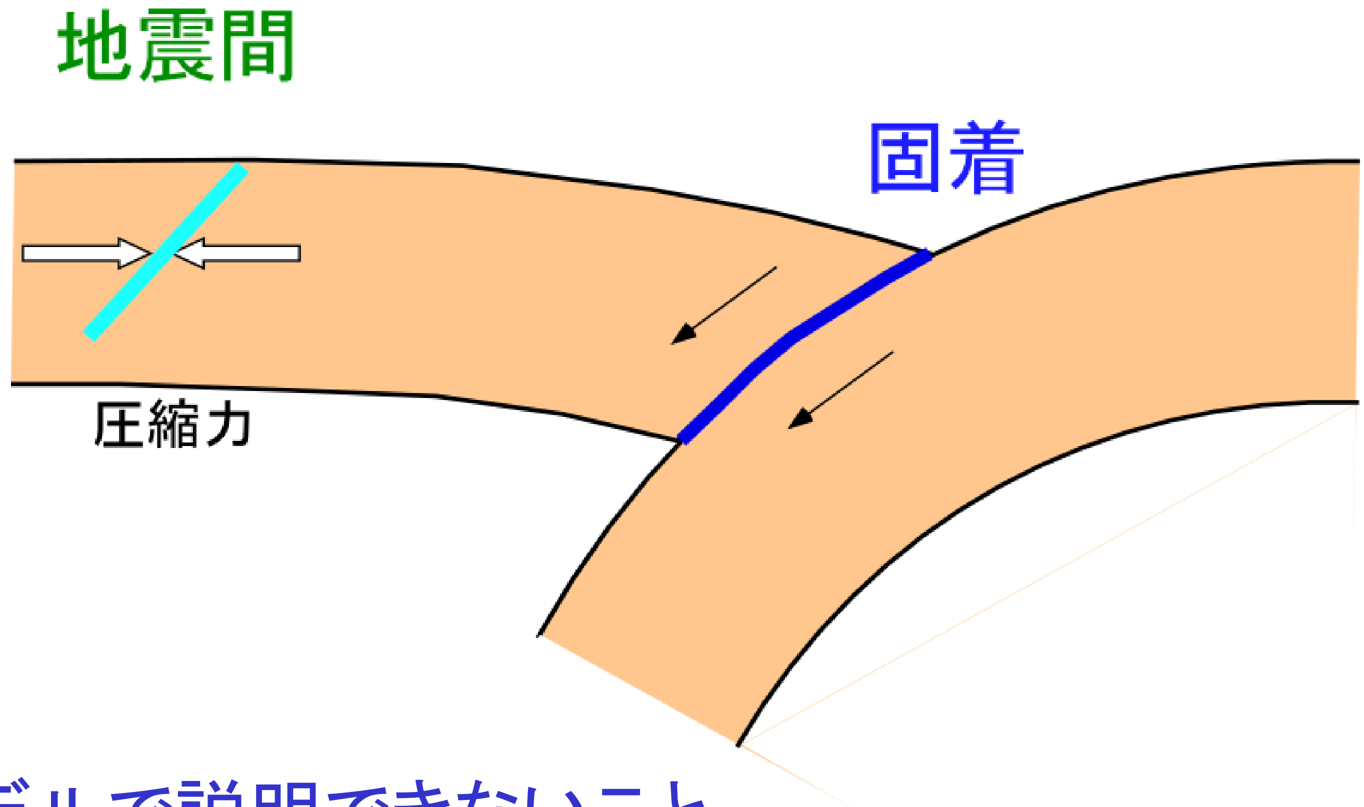
地震のメカニズム





地震調査委員会編「日本の地震活動」より

何となく信じられている内陸地震の発生の仕組み



<u>このモデルで説明できないこと</u>

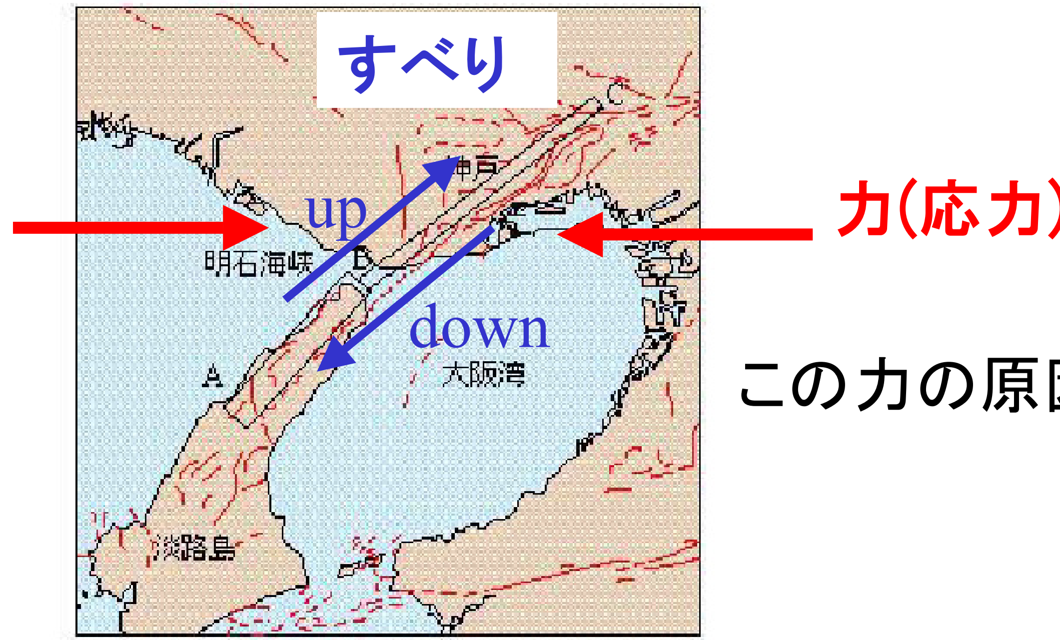
・なぜプレート境界から遠くで起こるのか？

・なぜプレート境界の大地震より発生間隔が長いのか？

・なぜ様々な発生間隔を持つのか？

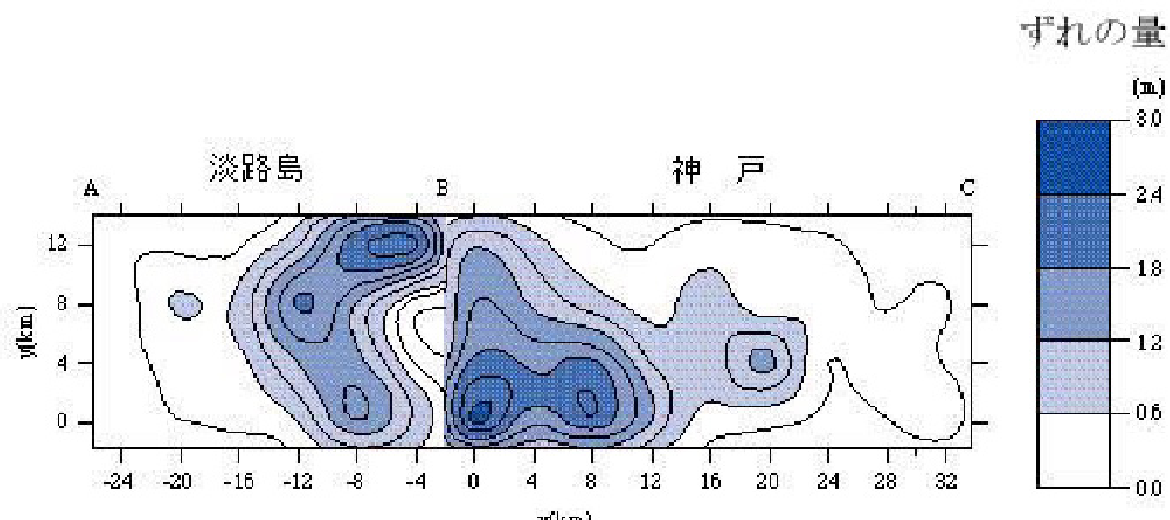
兵庫県南部地震のすべり分布と応力

「日本の地震活動」
地震調査推進本部より

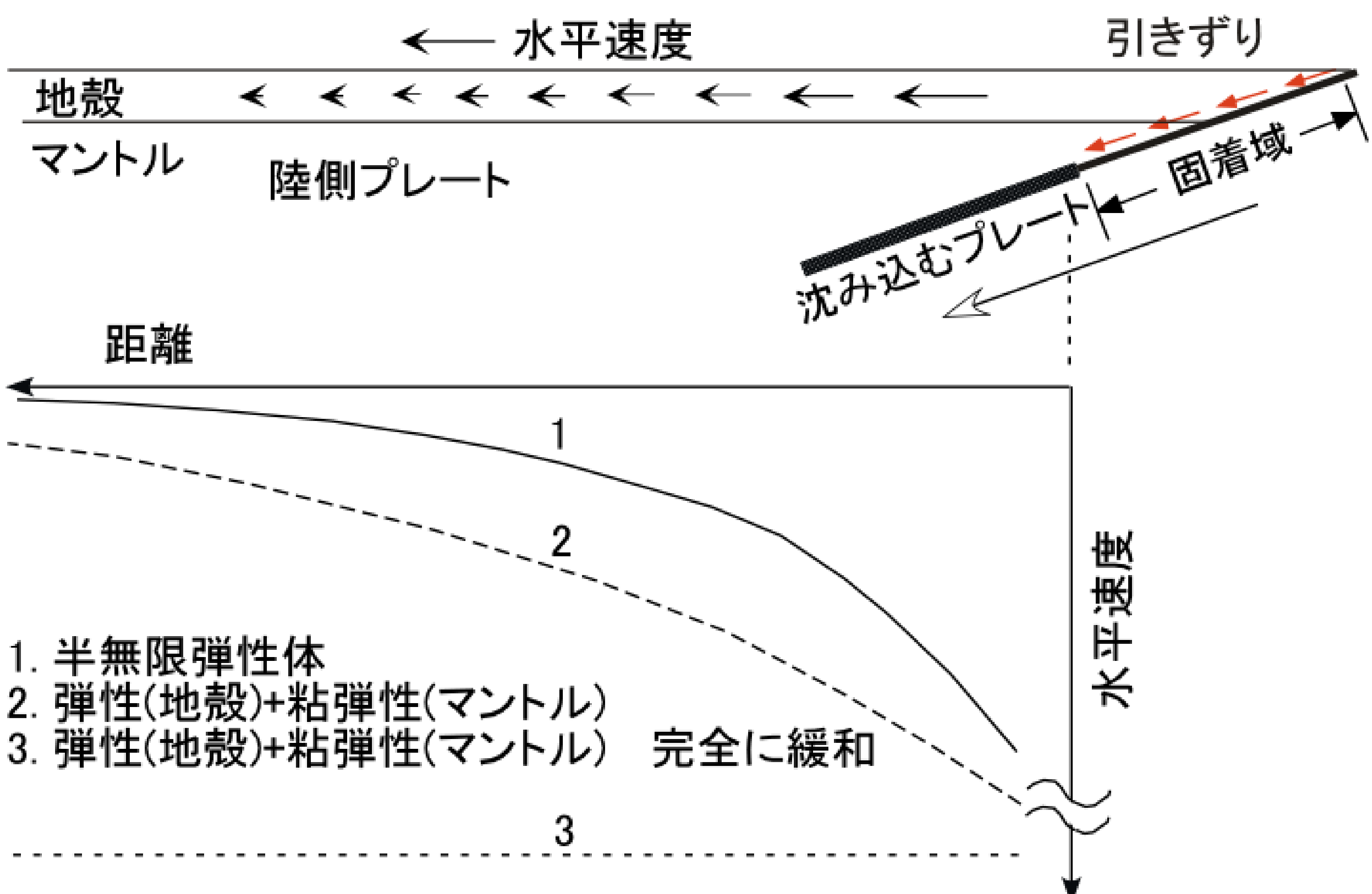


この力の原因は？

Yoshida et al. (199)

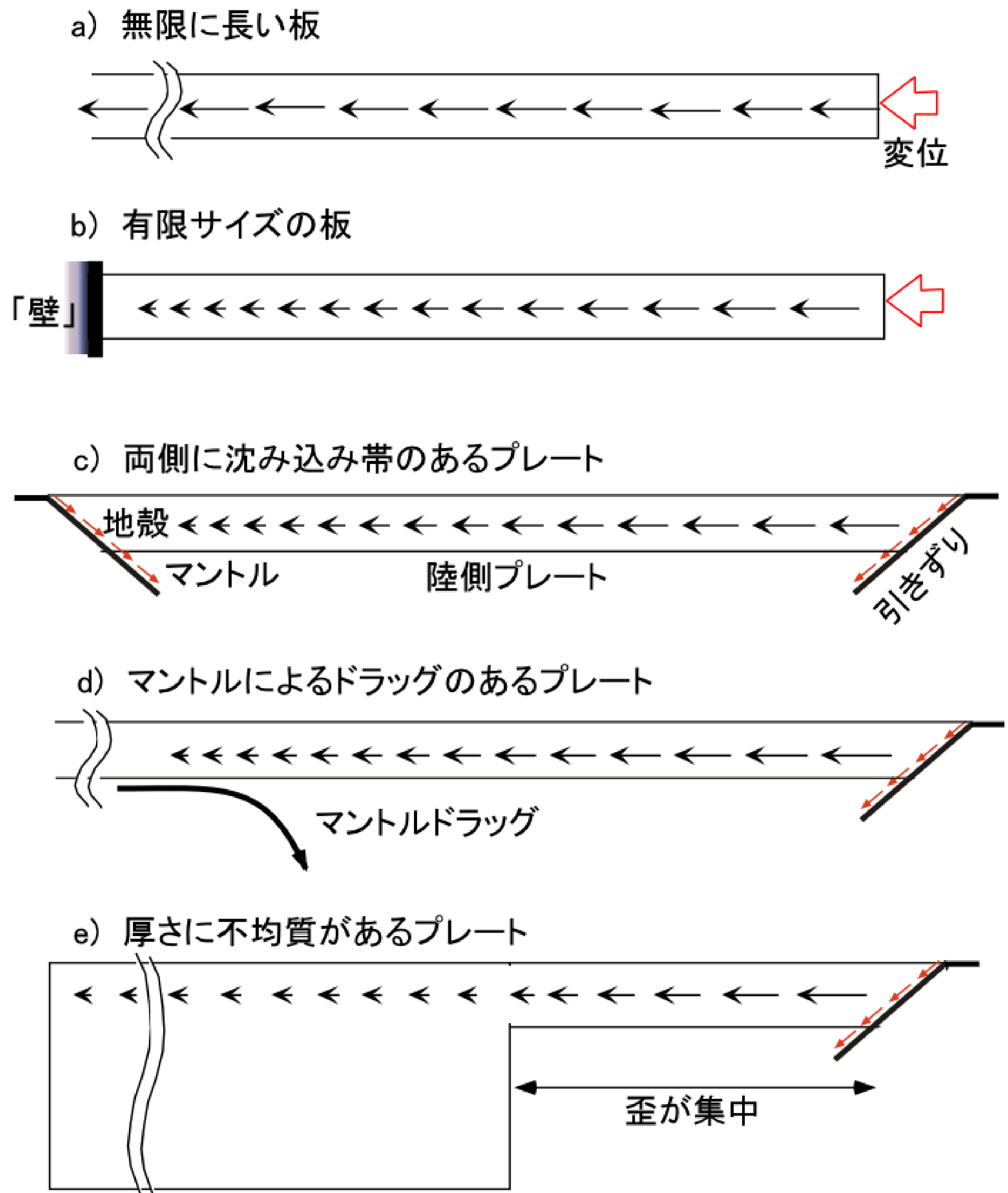


粘弾性と変位速度場
最上部マントルが緩和してしまうと地殻は無限に長い板となる



無限に長い板
は歪まない

領域は有限の
サイズを持っ
ているか？

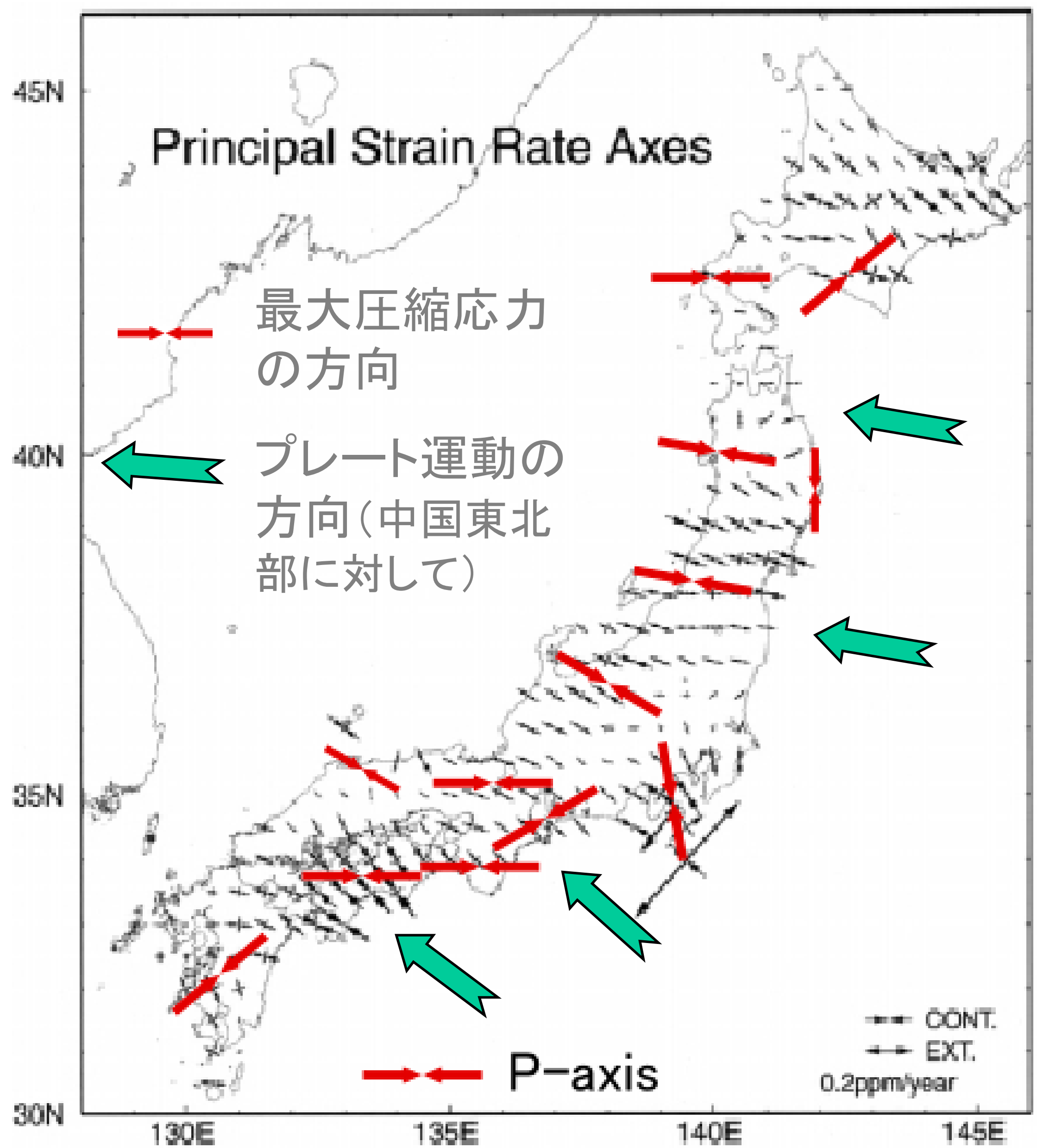


日本列島の応力場　Sagiya et al. (2000)に加筆

プレート相対運動の方向と必ずしも一致しない．

特に，西南日本で食い違いが顕著．

内陸地震はどんな力により発生するのか？



日本列島の応力場

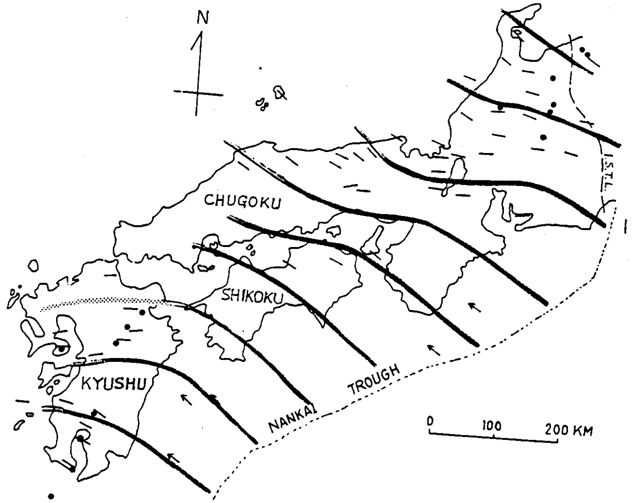


Fig. 6. A σH_{max} trajectory map of present southwest Japan. Drawn on the basis of data given by *Okada and Ando* [1979] and M. Ando et al. (manuscript in preparation, 1980). Arrows indicate slip vectors for low-angle thrust events. I.S.T.L.: Itoigawa-Shizuoka tectonic line. Nankai trough is the site where the Philippine Sea plate is consumed. Solid circles: active volcanoes after *Kuno* [1960]. Symbols for the trajectory lines are the same as in Figure 3.

(Nakamura and Uyeda,1980)

Ukawa: Lateral Stretching of Philippine Sea Plate

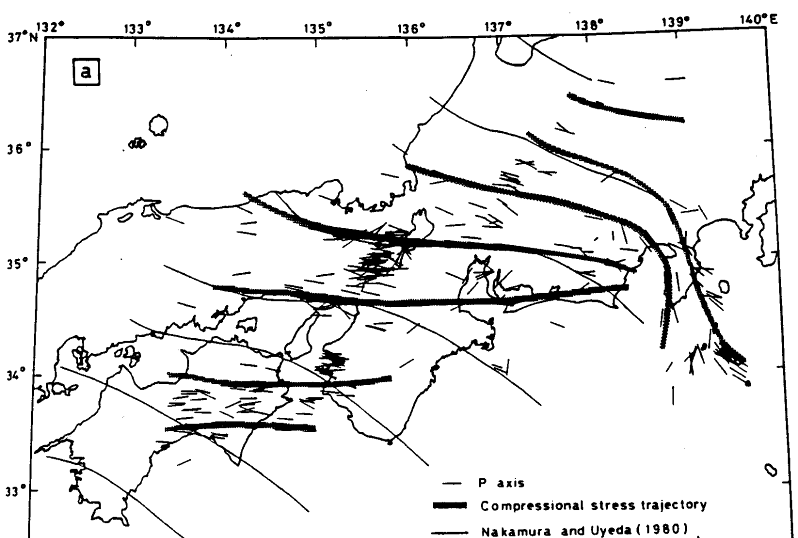
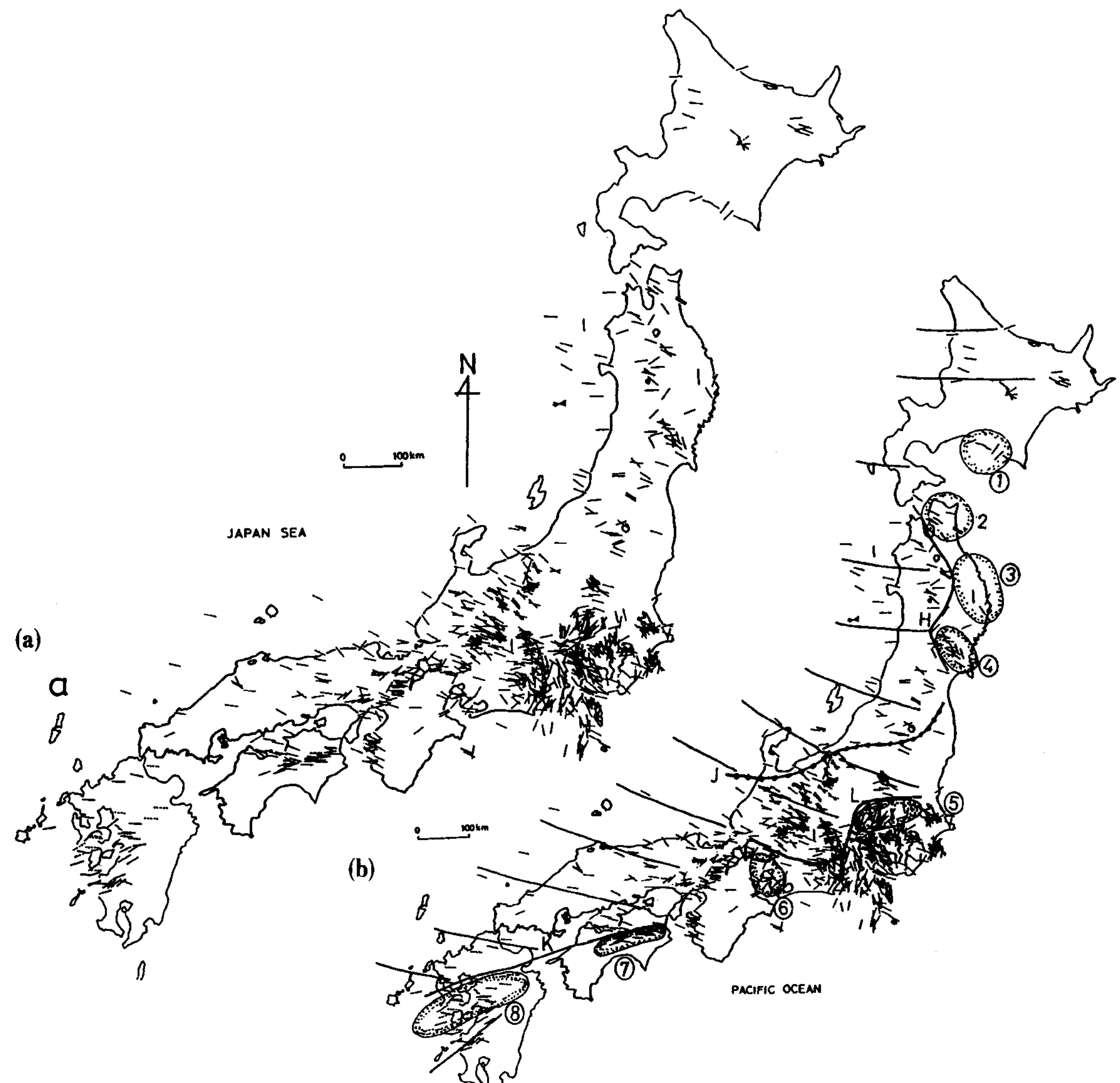


Fig. 15a. P axes of the upper crustal earthquakes and earthquakes in the Izu Peninsula. Compressional stress trajectory is drawn by thick lines. Thin lines indicate maximum horizontal stress trajectories estimated by Nakamura and Uyeda [1980].

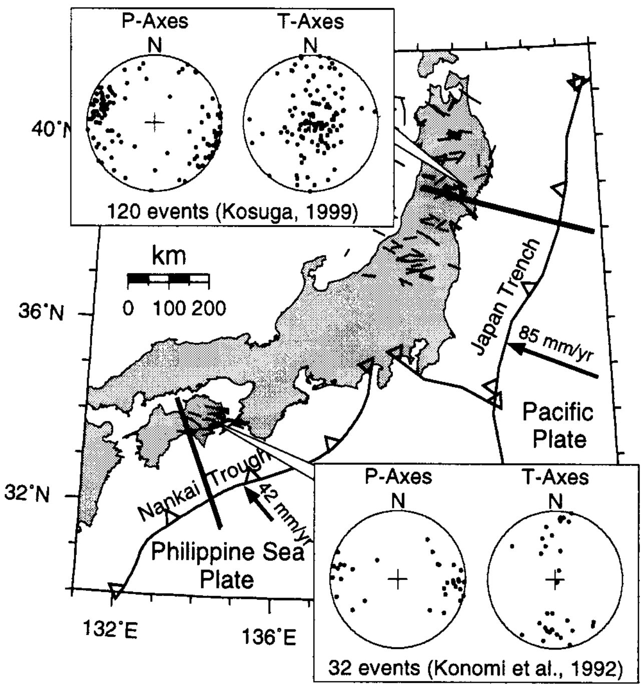
(Ukawa,198)

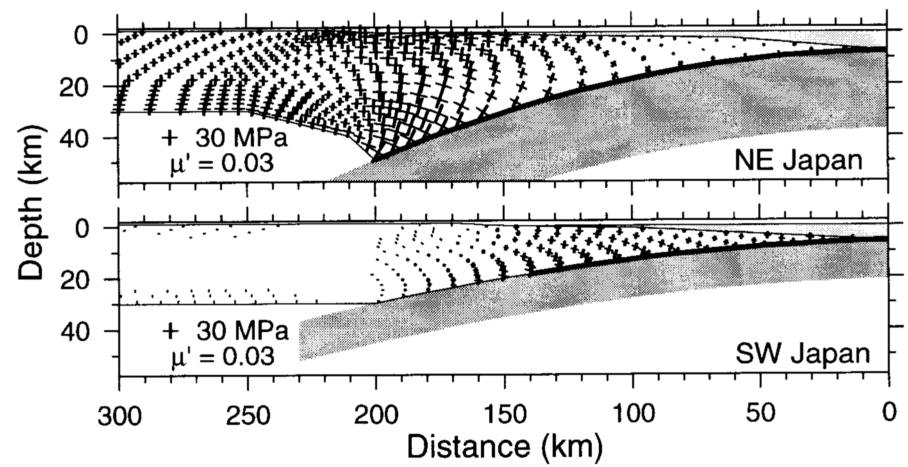
日本列島の応力場



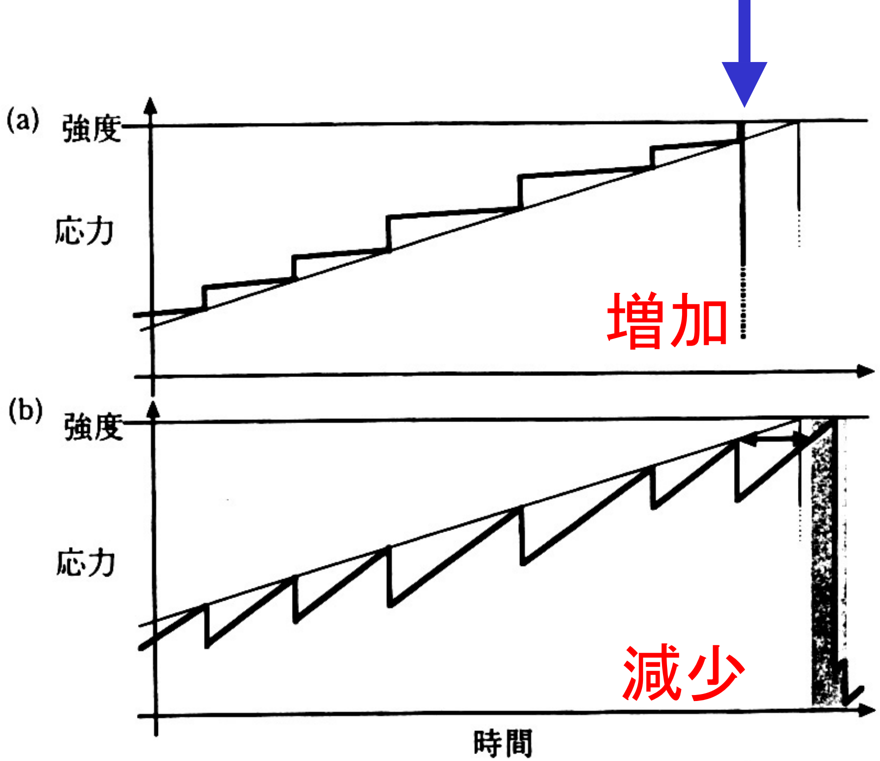
塚原(1999)

日本列島の応力場





Wang and Suyehiro(1999)

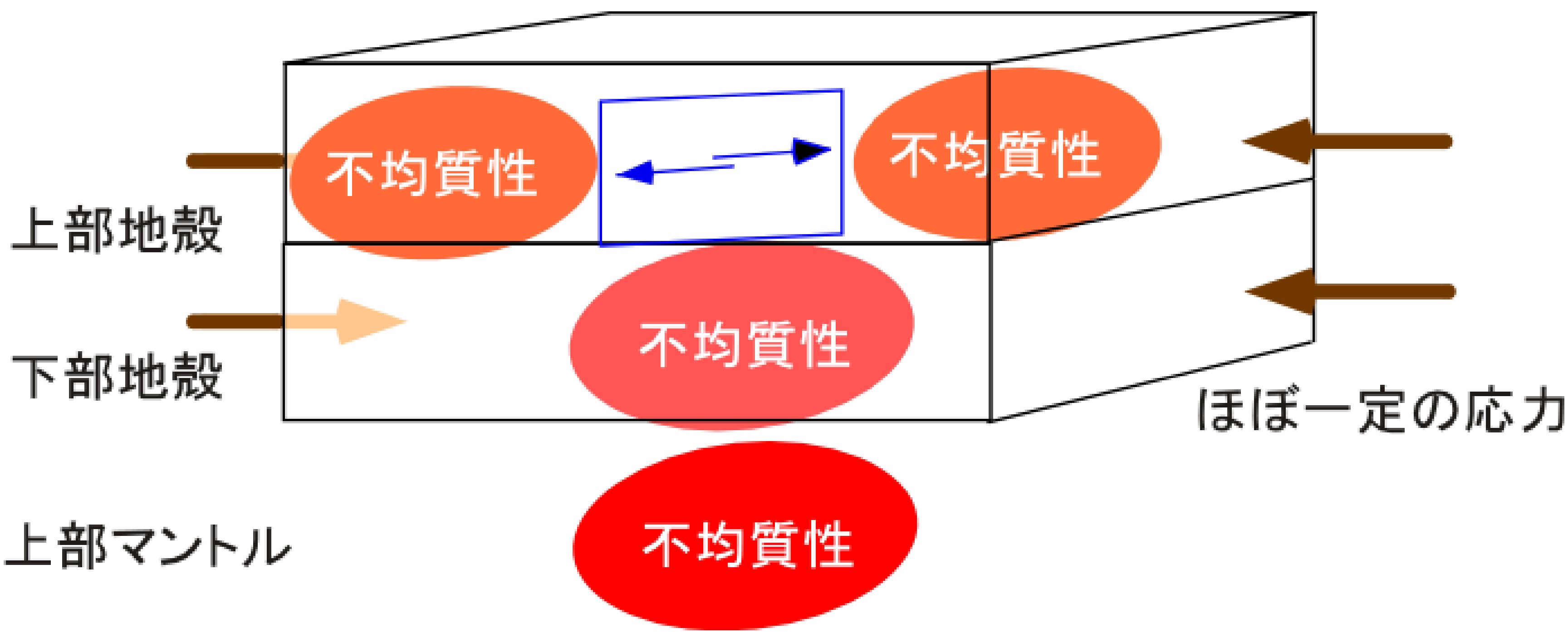


西南日本内陸の断層に固有な応力増加と南海トラフの地震による応力変化の模式図(堀・尾池, 1999). ↓が南海トラフの地震.

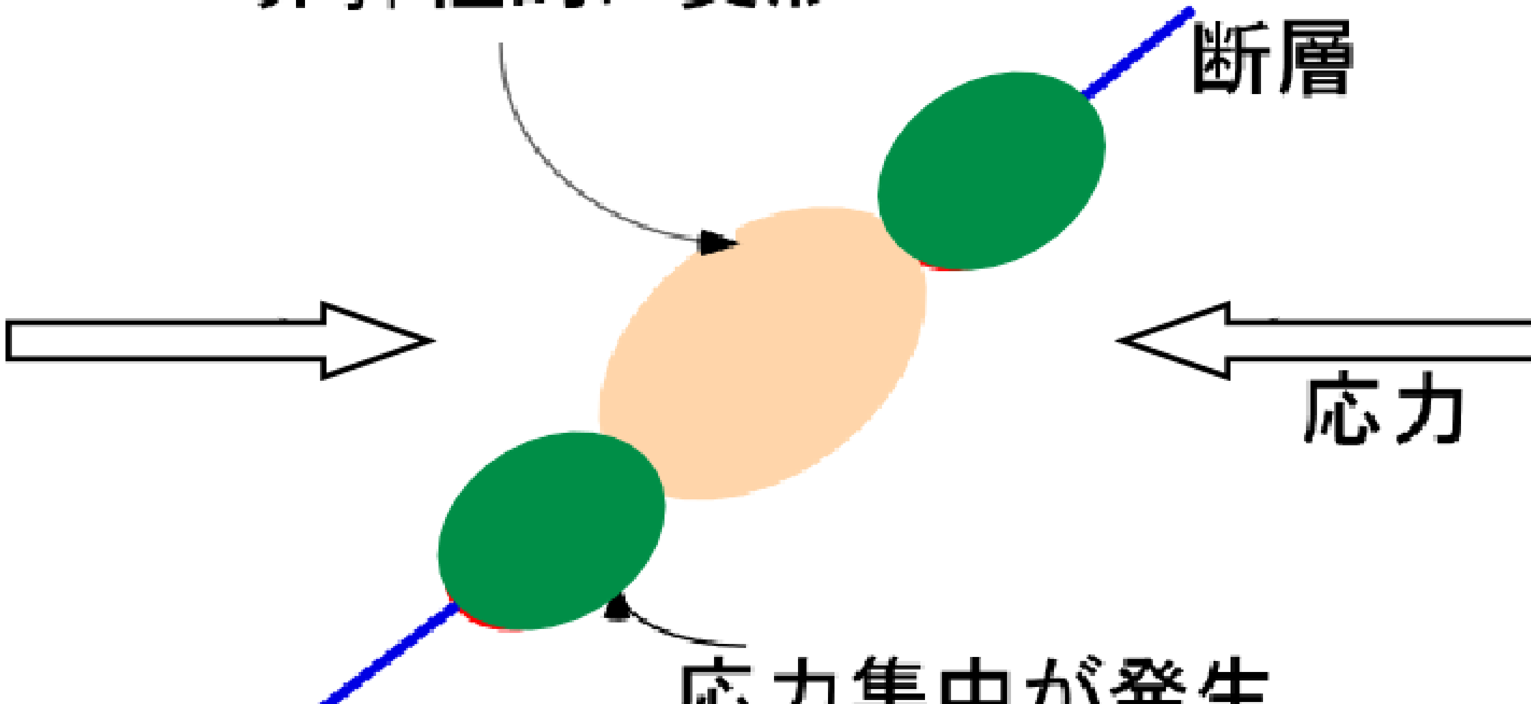
1944年東南海,1946年南海道地震の前後の内陸大地震の発生時期と応力変化

地震名	発生時期[年]	応力変化
濃尾地震	-53 (+37*)	増加
姉川地震	-35	減少
北但馬地震	-20	?
北丹後地震	-18	減少
鳥取地震	- 1	減少
福井地震	+ 4	増加
北美濃地震	+17	増加
越前岬沖地震	+18	増加
兵庫県南部地震	+49	?

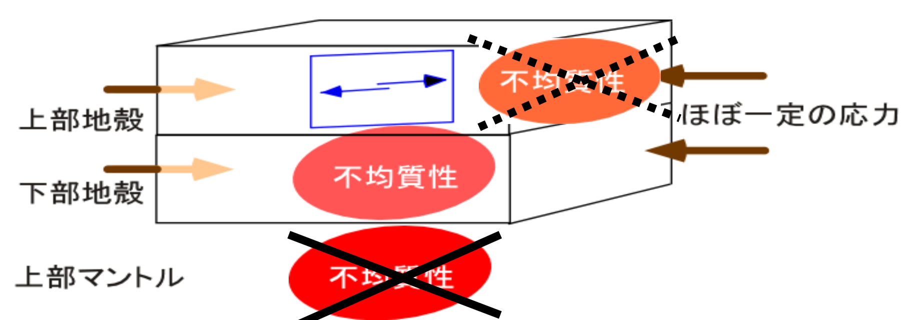
下部地殻･上部マントル･上部地殻の不均質により
上部地殻に応力集中が発生



不均質により応力集中が発生

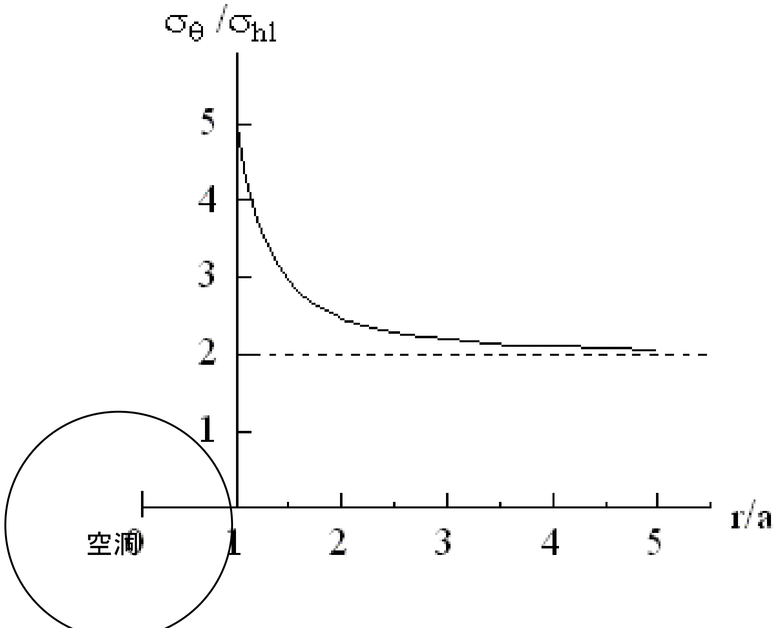


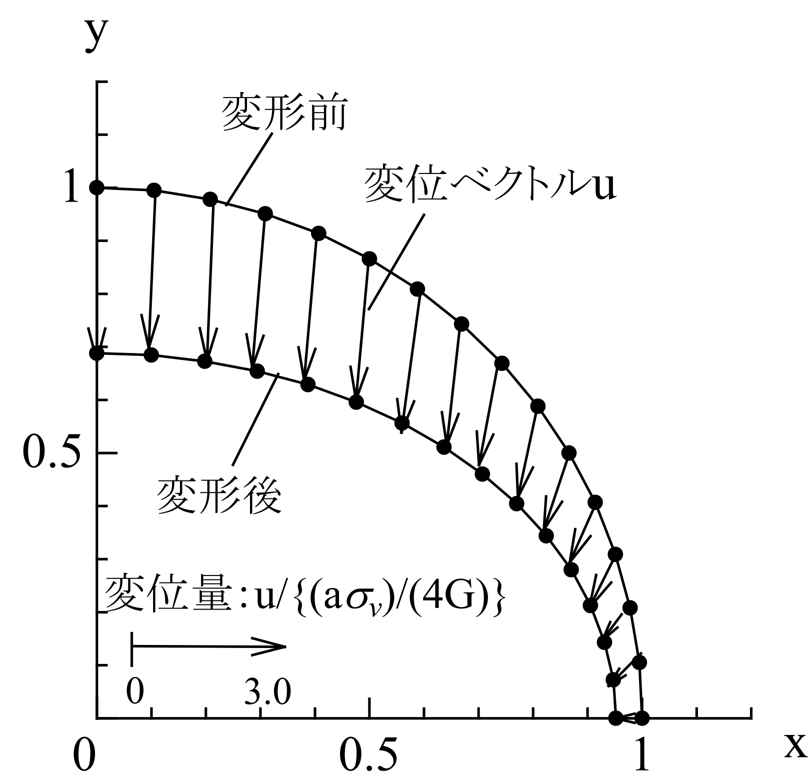
トンネルを掘ると側壁に応力集中が発生する



空洞のまわりの変形

北海道大学岩盤力学研究室のHP　http://rock.eng.hokudai.ac.jp/japanese.html より





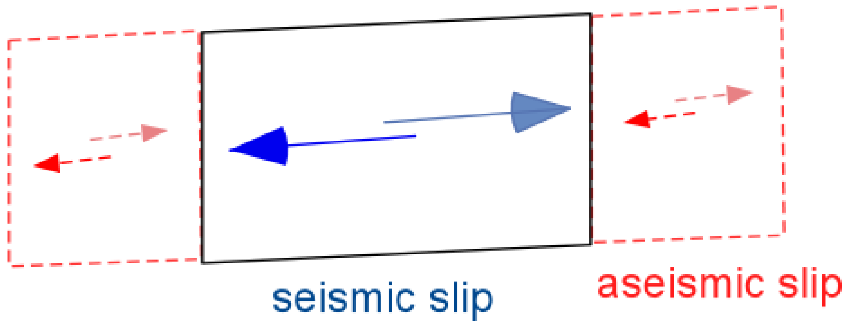
円形断面空洞周囲の $\theta=0$ 上の $\sigma\theta$ の分布。
初期地圧は　$\sigma v = 2\sigma h1$ を仮定

活断層の端はどうなっているか？

端で非弾性変形する必要がある.

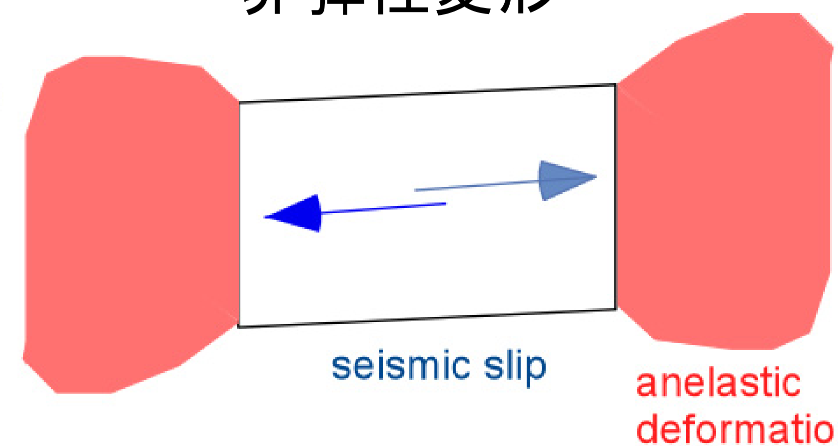
非地震性すべり

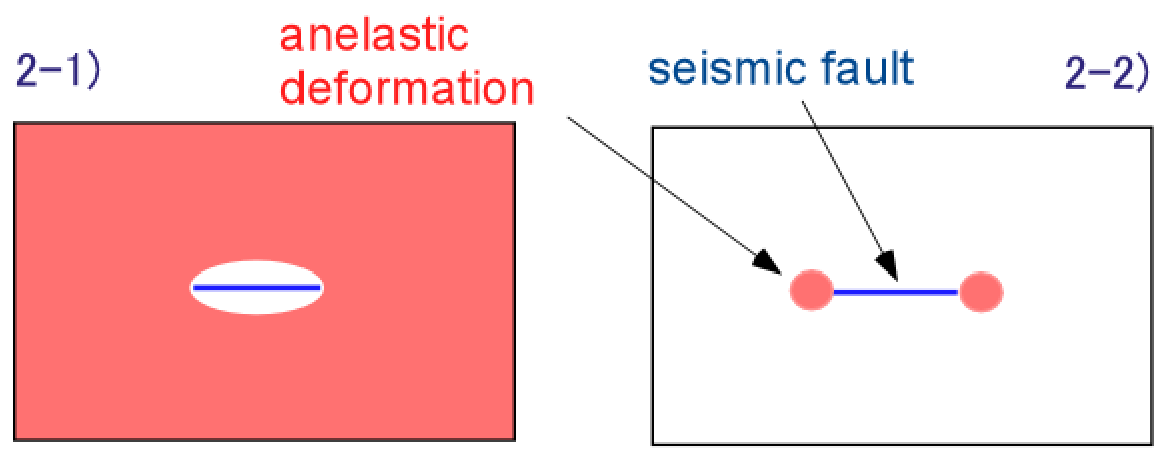
1)



非弾性変形

2)

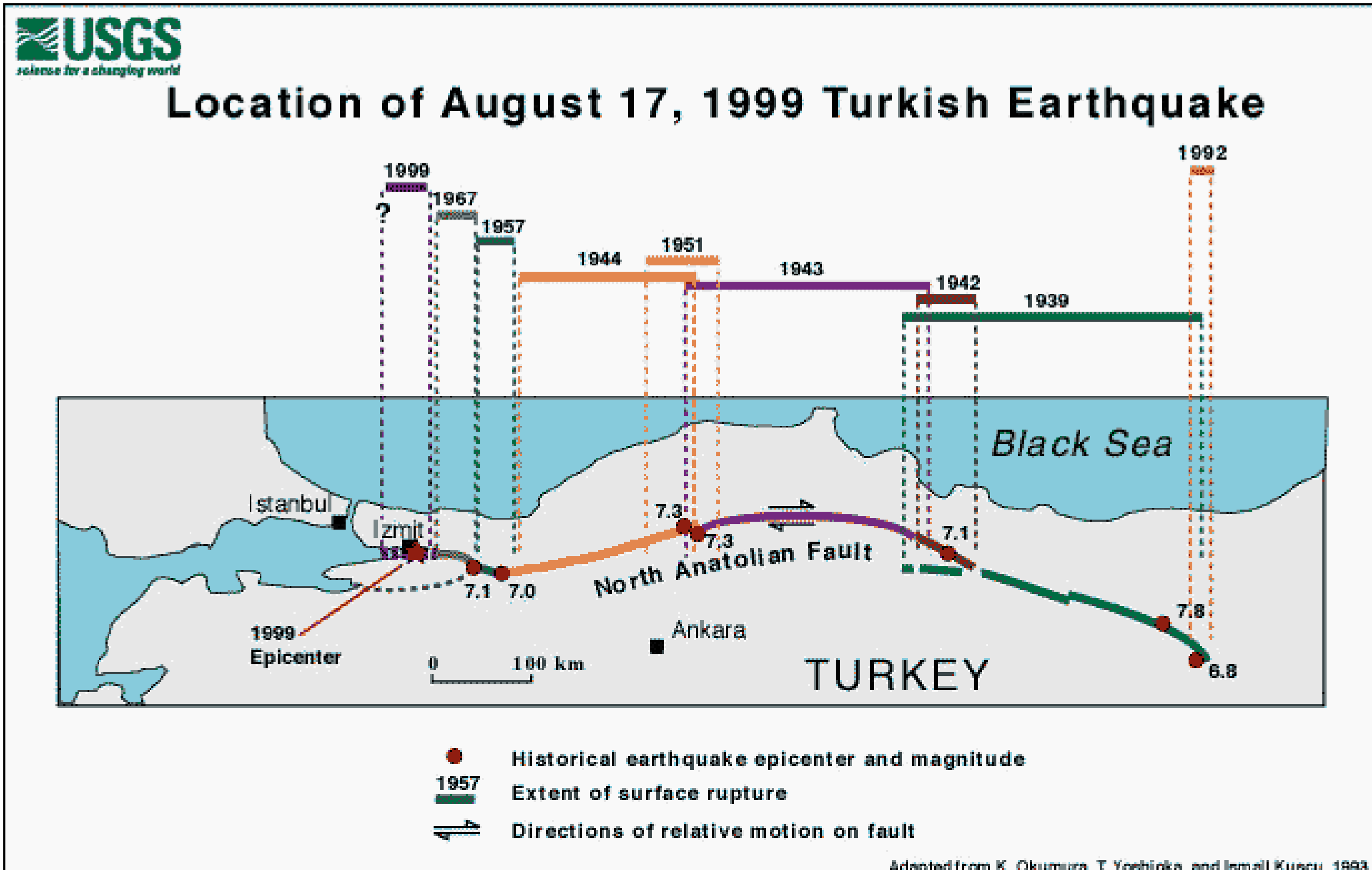




上から見た平面図

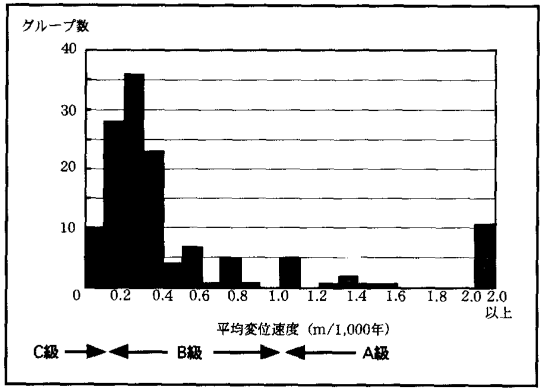
トルコ　北アナトリア断層における震源移動

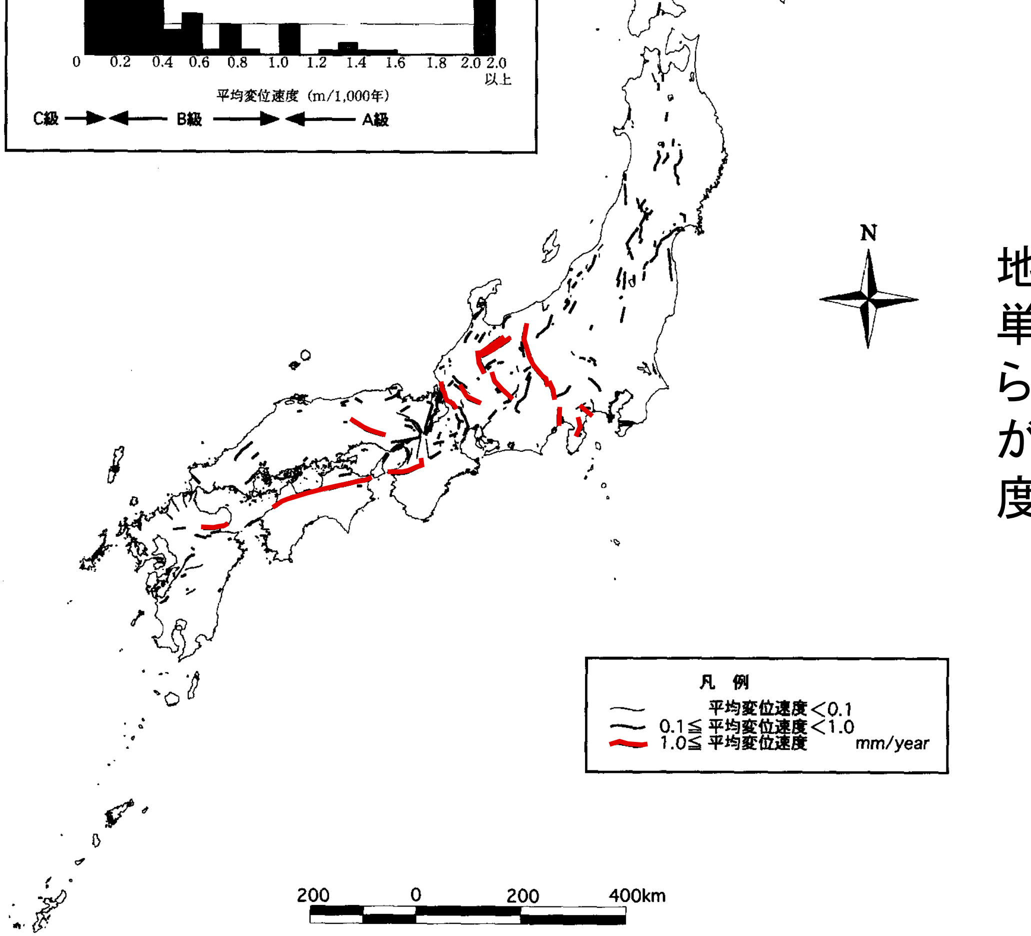
USGSのホームページ http://ghtmaps01.cr.usgs.gov/turkey/turkey.html より引用



活断層帯の活動度ごとの分布図

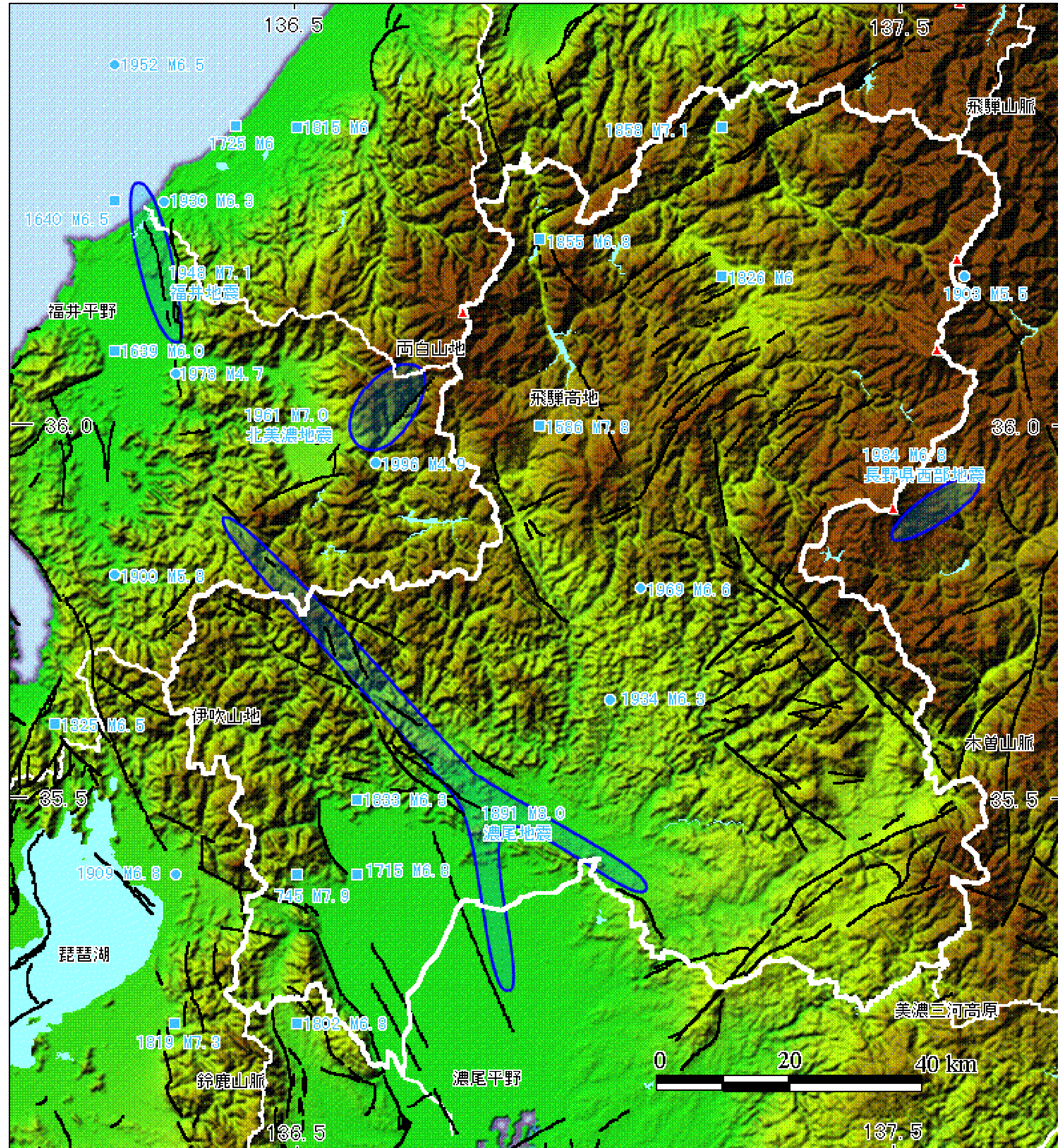
200万分の1活断層ワーキンググループ(2000)





地震時の変位量（断層の単位変位量）が断層によらず一定なら、発生間隔が短いほど平均変位速度が大きくなる。

中部地方の活断層と被害地震「日本の地震活動」より



Strain rates estimated by the nationwide GPS network in Japan (Sagiya et al., 2000)

Large strain rates along the Pacific ocean are mainly due to the subductions of oceanic plates.

A concentrated deformation zone is detected along the Japan Sea coast.

NKTZ: Niigata-Kobe Tectonic Zone(Sagiya et al. ,2000)

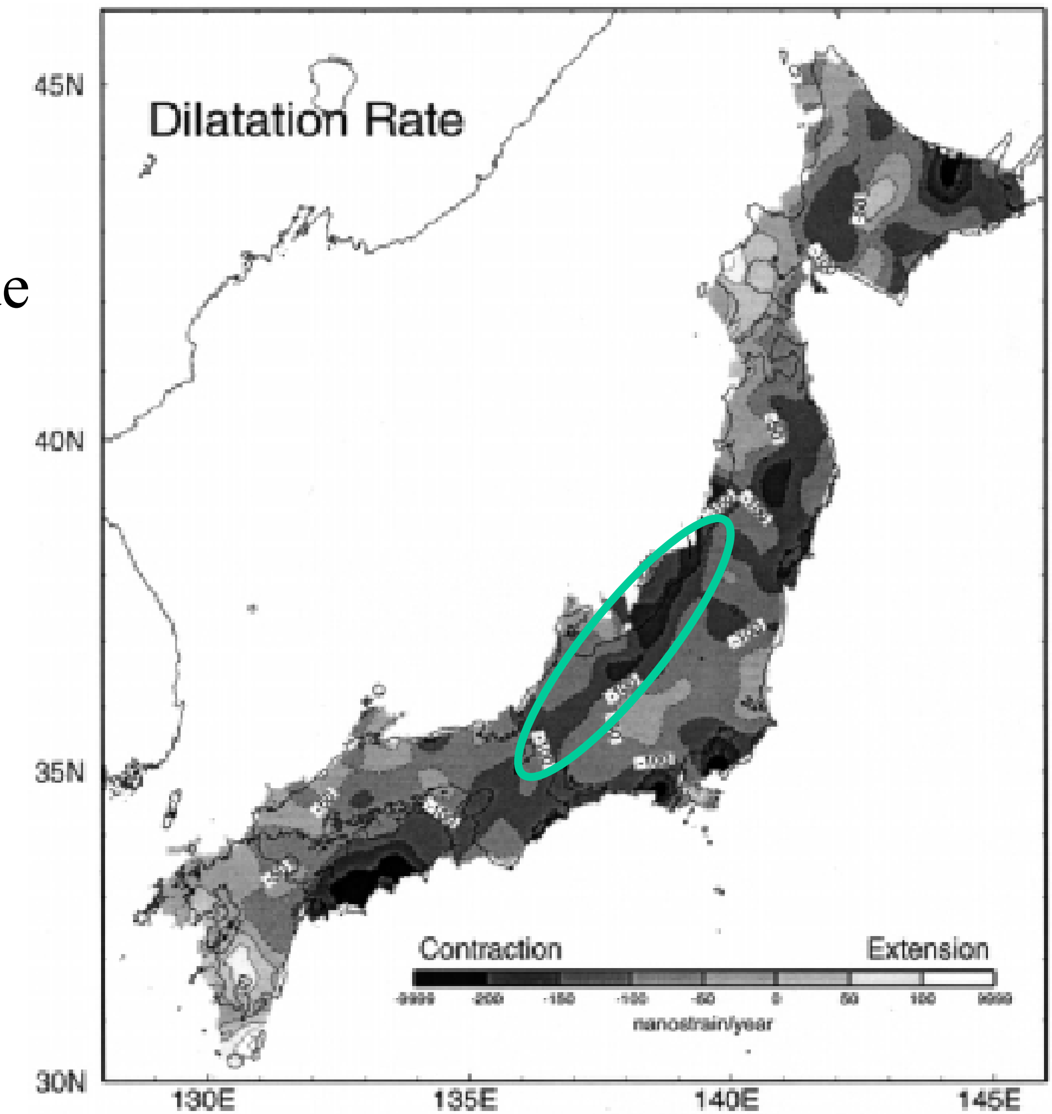
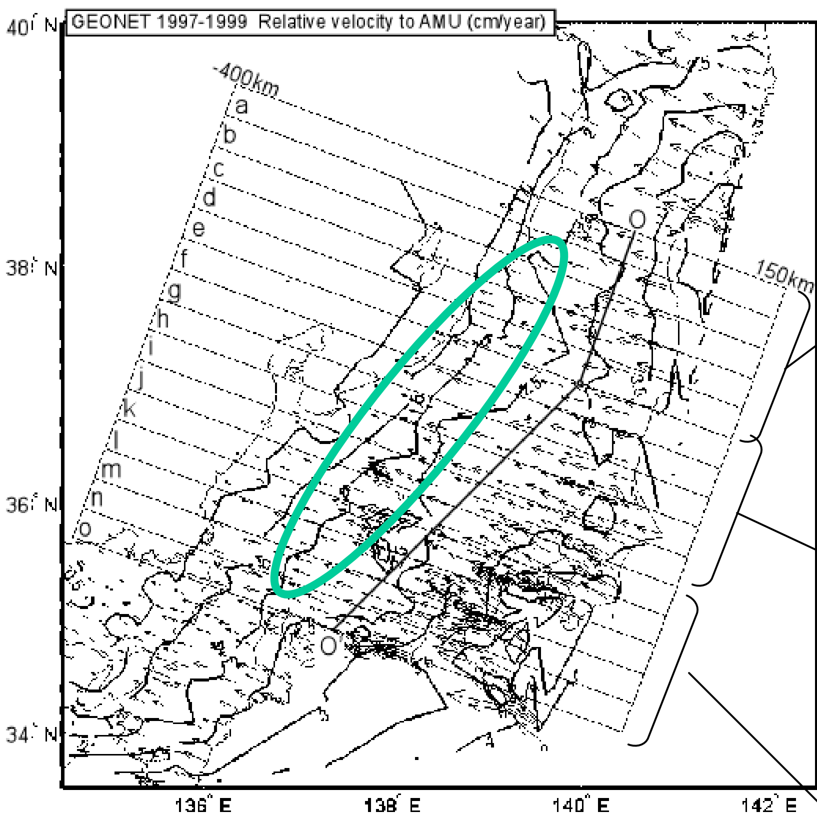
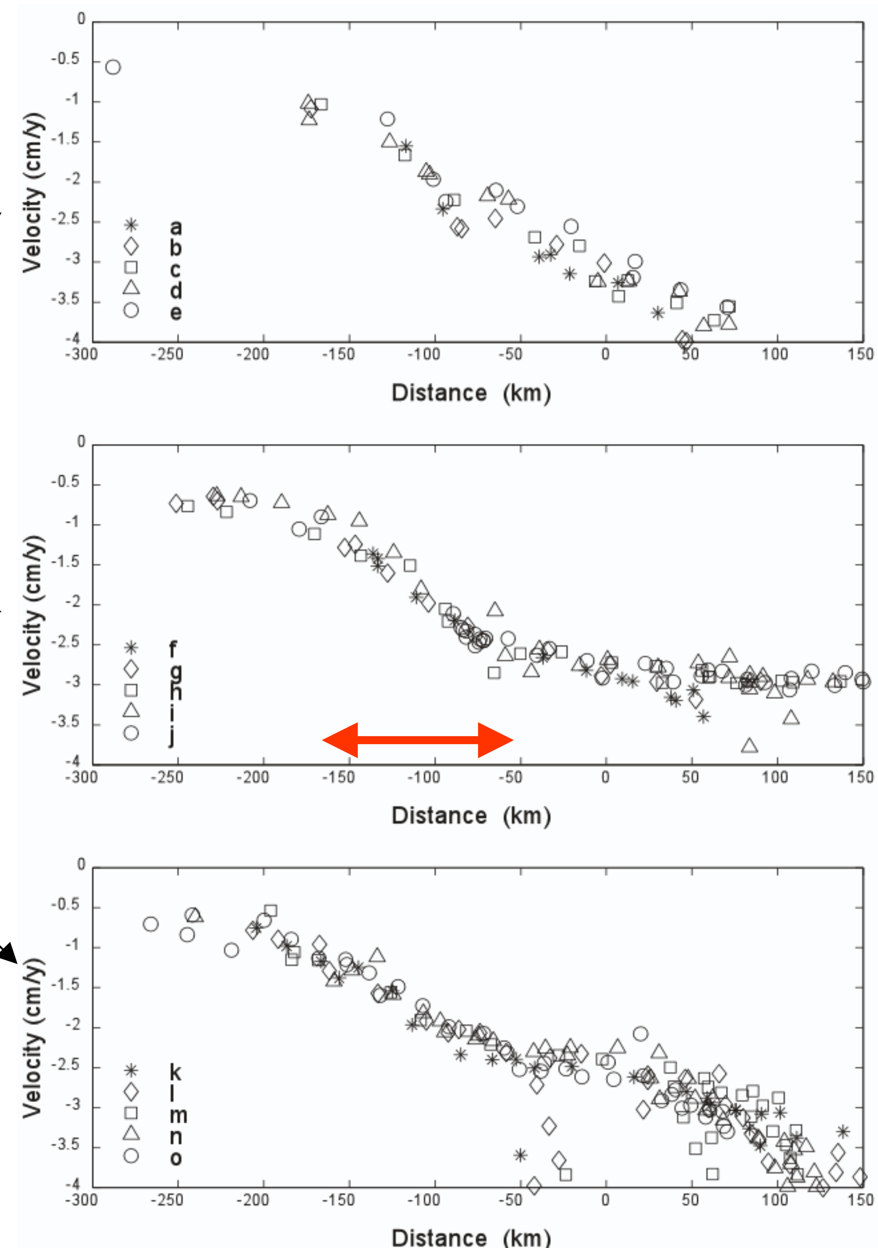


Figure 4
Estimated distribution of dilatational strain rate.

Concentrated deformation zone along the Japan Sea coast, NKTZ: Niigata-Kobe Tectonic Zone(Sagiya et al. ,2000)



Horizontal velocity vectors relative to AMU in and around NKTZ.

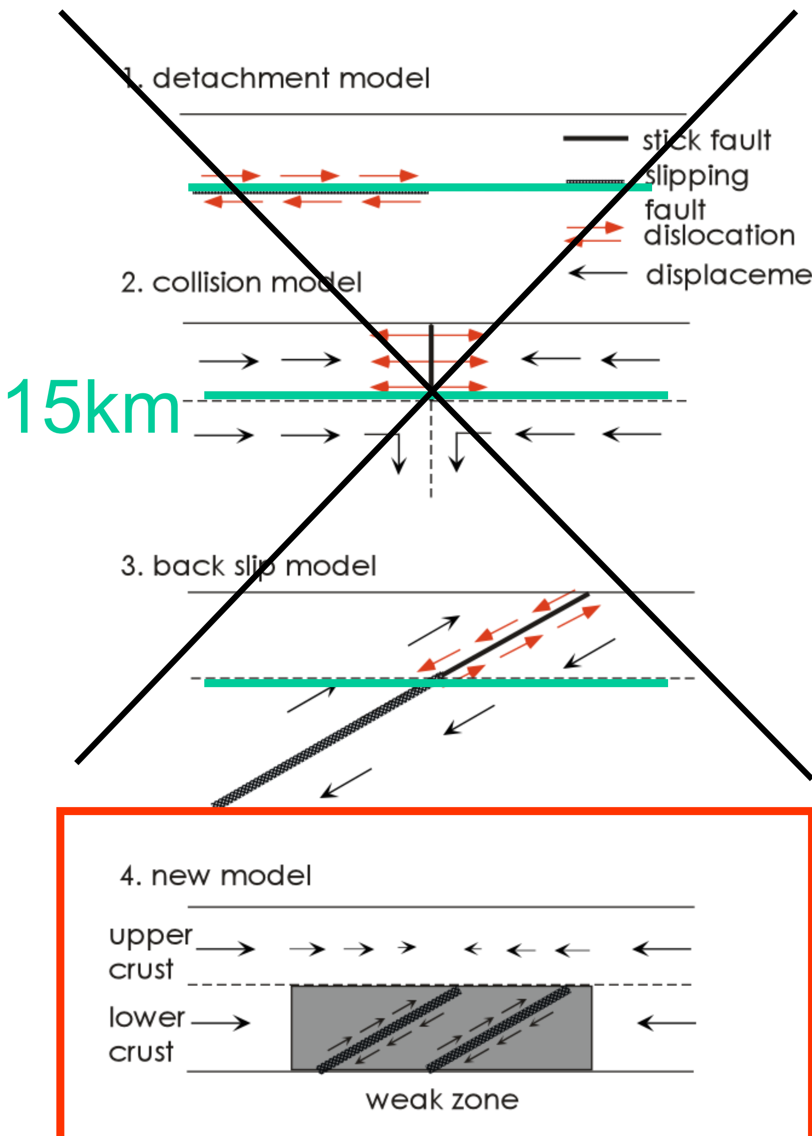


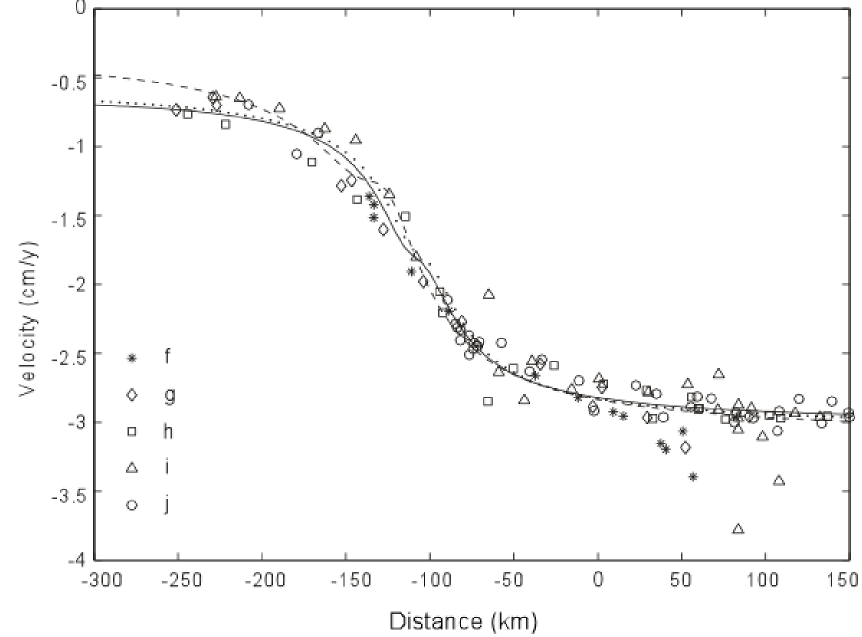
Distance vs. velocity plots for three different regions are displayed in the right panel.

It is clear that deformation is concentrated in a narrow zone having a width of about 100 km in the middle panel.

Velocities are almost constant in region except for NKTZ, even near the subduction zone of the Pacific plate.

A weak zone (heterogeneity) is needed by a model fitting (Iio et al., 2002)





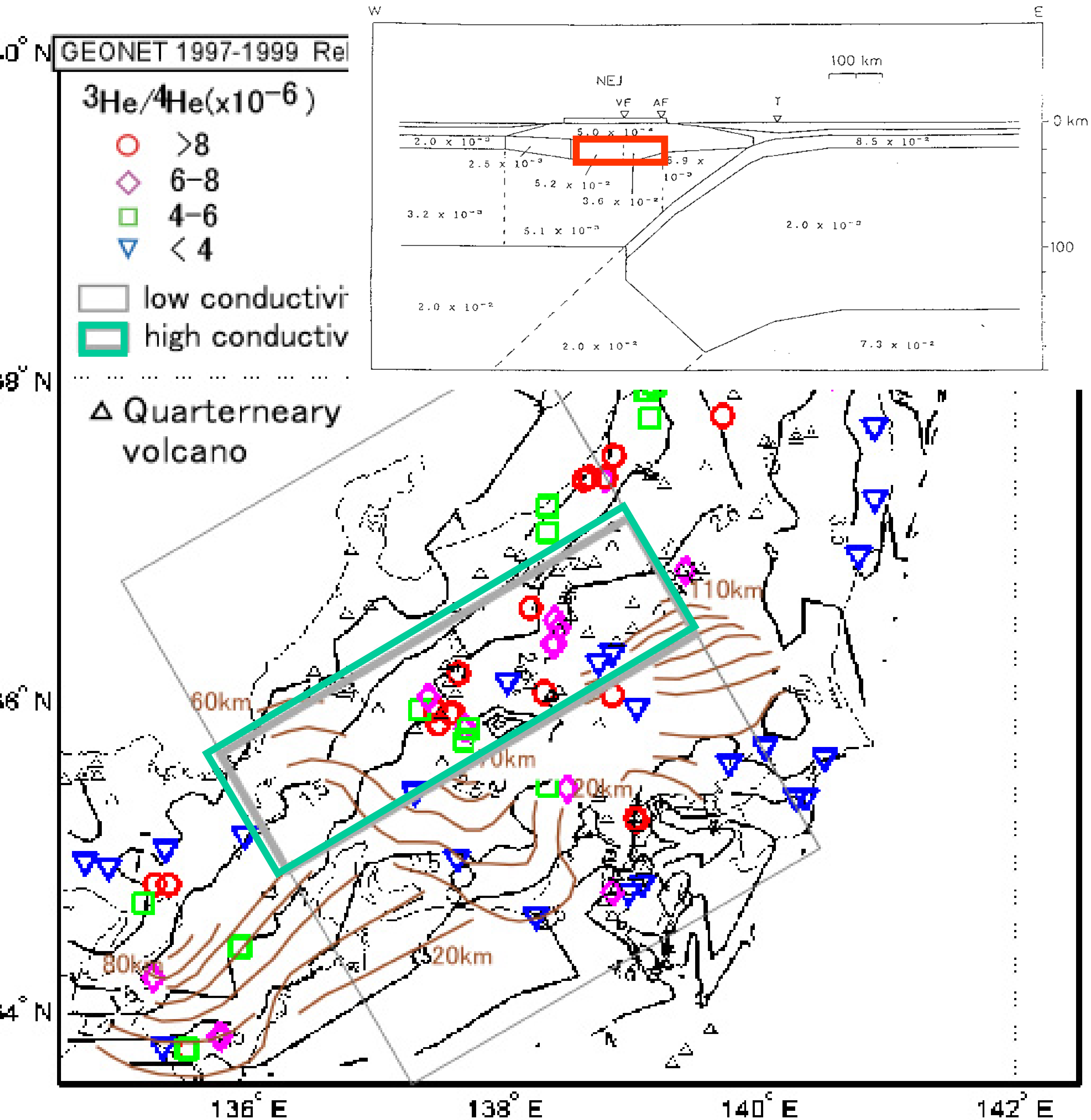
The typical velocity profile was fitted by these three kinematic models. For all of the models, the boundaries between the upper and lower layers are determined at a depth of 15 km by fitting the data.

In the upper two models, this result implies that the lower crust drags the upper crust. → This is strange.

The third model contradicts the fact that strike-slip faults dominated in the zone.

Thus, we will choose a model with a weak zone in the crust. Here, we assume it in the lower crust, since it is inferred from various observations that there exists a heterogeneity in the lower crust .

Conductivity anomaly and $^3He/^4He$ ratios plotted on the GPS velocity contour map



The center rectangle shows a high conductivity anomaly in the lower crust estimated by the 2D modeling in this region (Utada, 1987).

The region of high conductivity is roughly consistent with the concentrated deformation zone.

The locations of the high 3He/4He ratios (Sano & Wakita, 1985) also tend to align along the zone .

It is inferred from these observations that the lower crust in the zone has a higher water content than the surrounding region.

Heterogeneity in the upper crust?

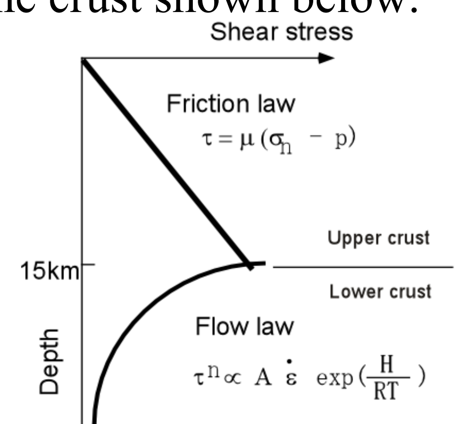
First, we will investigate where is the weak zone.

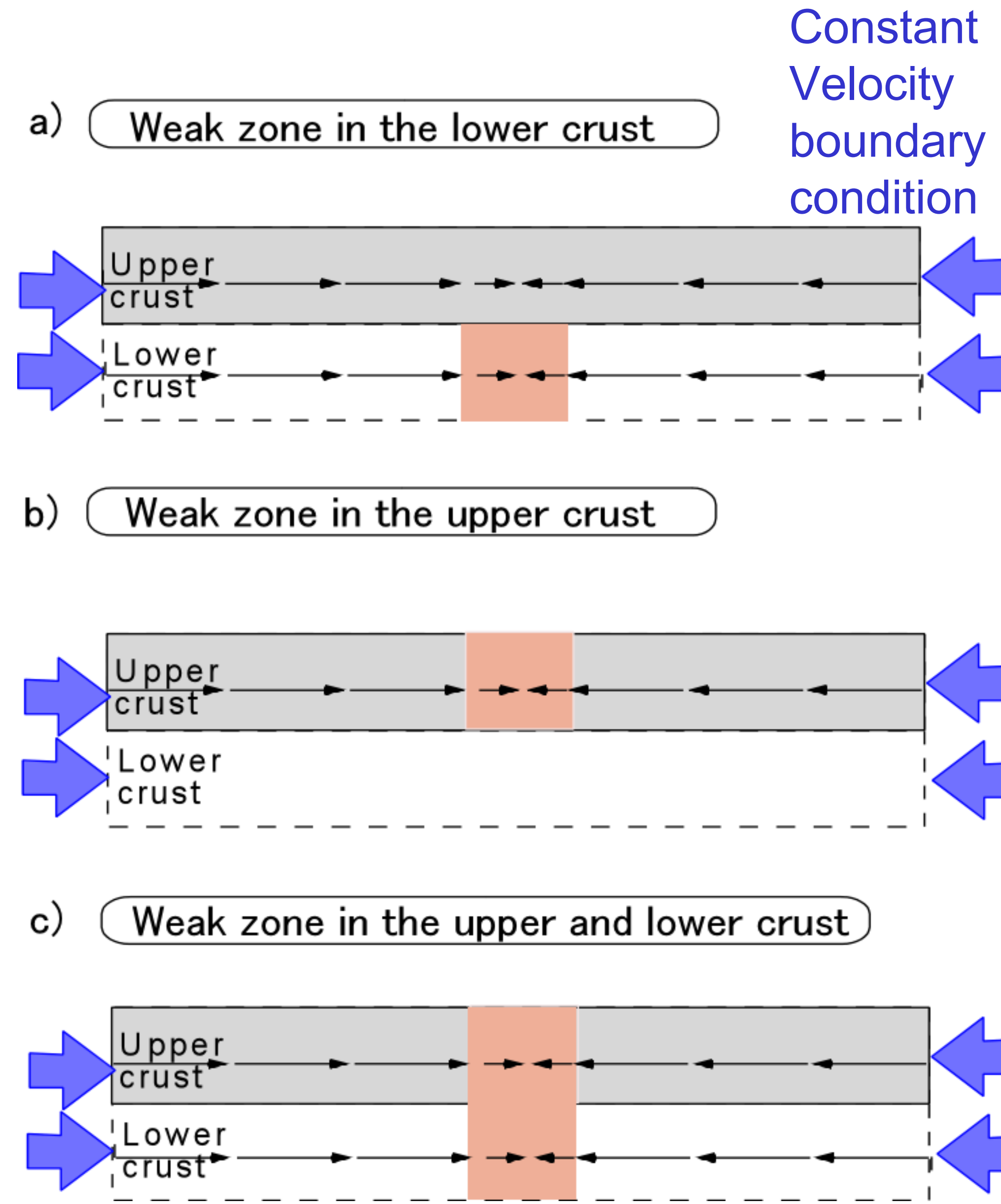
There are three possibilities, the weak zone

a) in the lower crust,
b) in the upper crust, or
c) in the upper and lower crust.

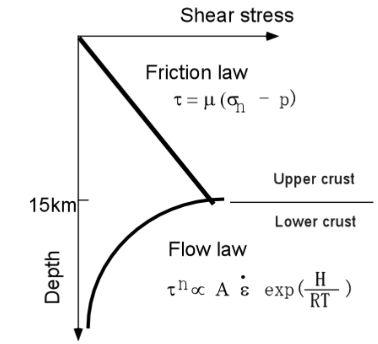
We will examine whether each case can produce the concentrated deformation zone.

Here, we assume the standard strength profile model of the crust shown below.



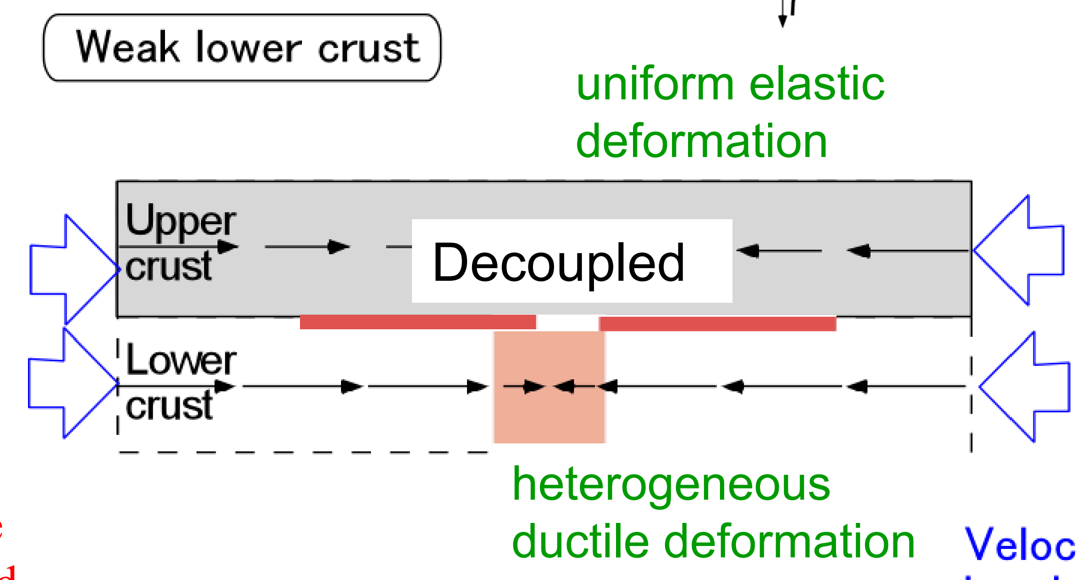


A weak zone in the lower crust can produce a concentrated deformation zone?



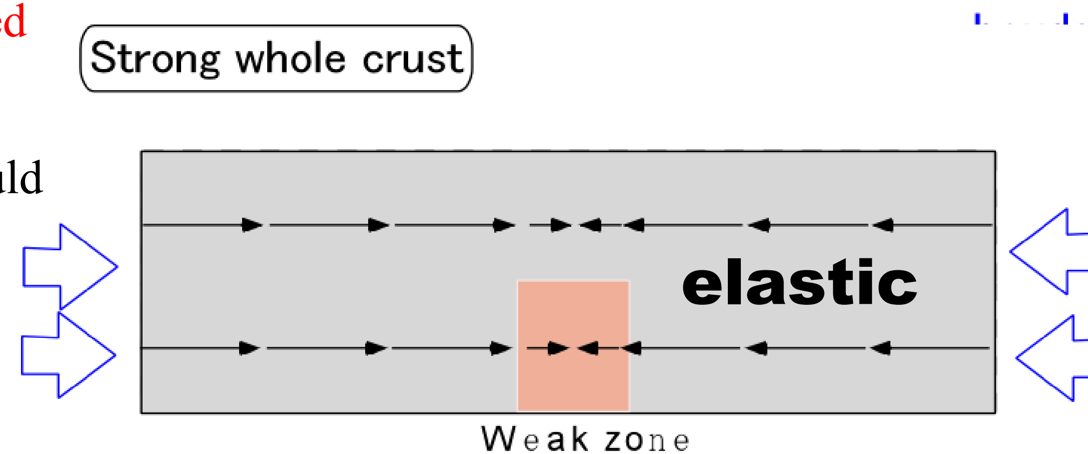
In the case of a weak zone in the lower crust, deformation is concentrated in the zone.

In the upper crust, however, an uniform elastic deformation tends to be generated because of no heterogeneity there.



Then, the upper crust is thought to be decoupled to below under the assumed strength profile.

It is necessary that the upper crust is not decoupled for the sake that the weak zone in the lower crust generates a concentrated deformation zone in the upper crust.



Thus, the strength of the lower crust should not decrease rapidly with depth and the whole crust should be rather strong. The whole crust except for the weak zone is regarded as elastic.

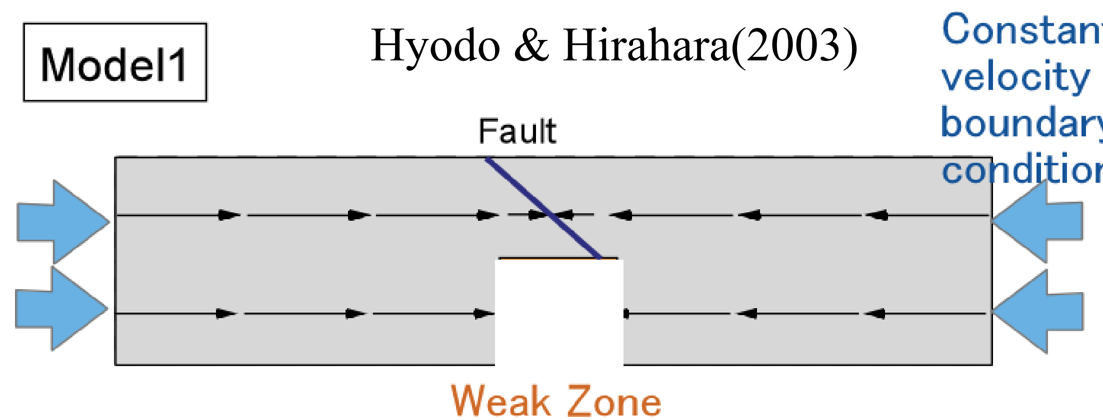
The crust in an equilibrium state or not ?

Model1 assumes a static force balance and a constant velocity boundary condition in the crust.

The concentrated deformation directly reflects a thinner elastic thickness.

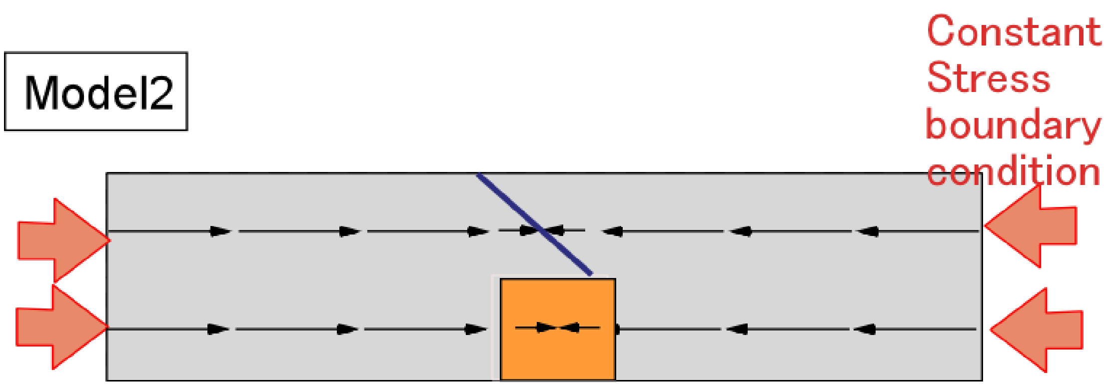
Model1

Hyodo & Hirahara(2003)



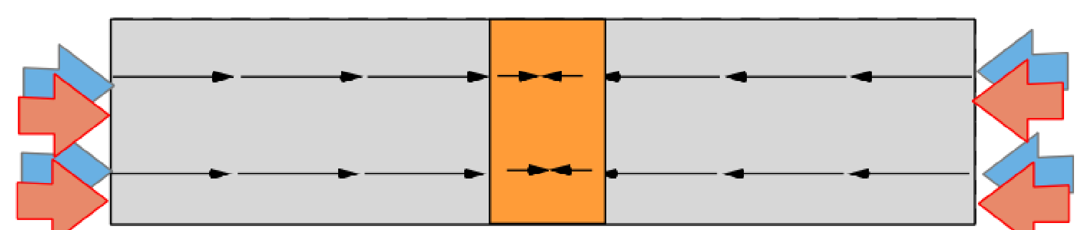
Model2 assumes a constant stress boundary condition and that a transient deformation is generated until static force balance is accomplished after the fault breaks, or the next earthquake occurs.

Model2



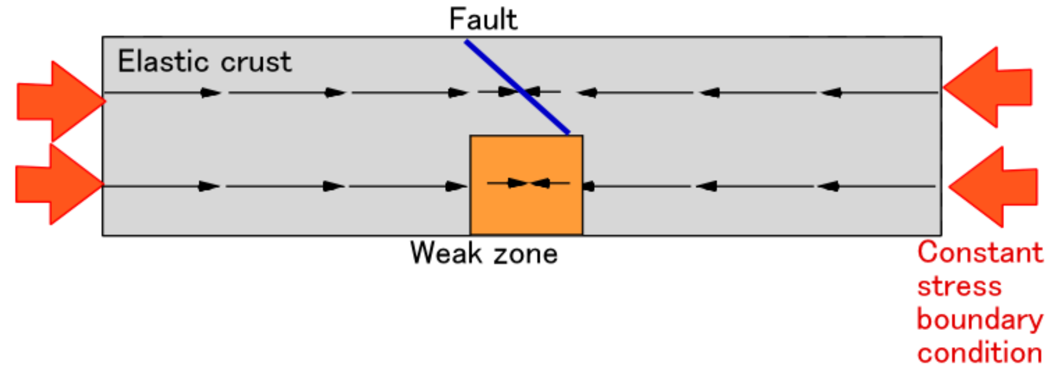
Model3 assumes a weak zone in the upper and lower crust.

Model3

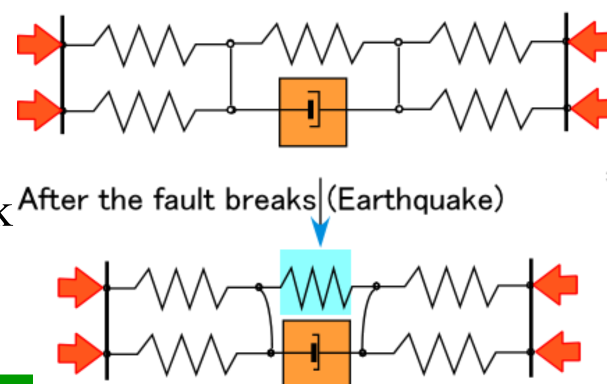


Detailed description of Model2 (transient deformation model)

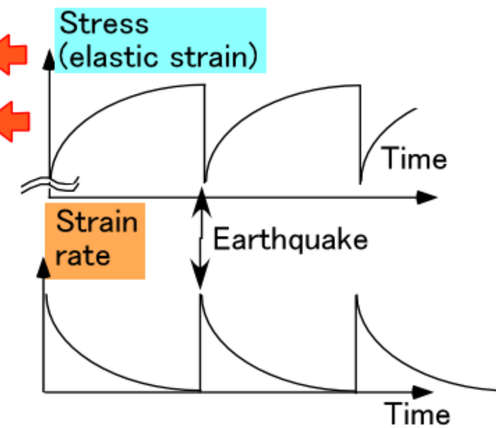
The region except for the concentrated deformation zone is not deformed under a constant stress.



The region above the weak zone is deformed after the fault breaks, since the weak zone is deformed by stress concentration.

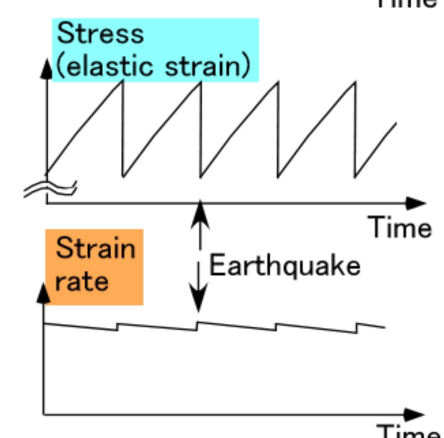


Strain rate in the weak zone decreases with time, as stress (elastic strain) is accumulated in the region above the weak zone, if the strength of the fault nearly equals to a static equilibrium stress state.



Model2a

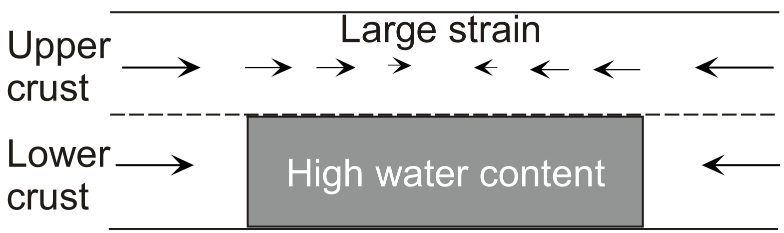
If the strength of the fault is smaller than the equilibrium stress state, strain rate does not decrease rapidly. In this case, the stress state above the weak zone can take a wide variety according to the strength of the fault.



Model2b

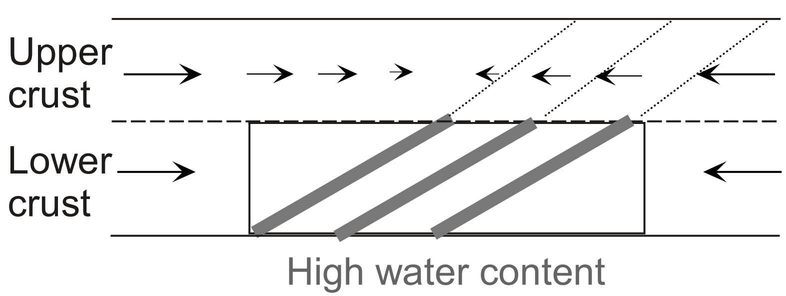
Weak zone in the lower crust and its internal structure

1. Water is distributed in the lower crust?



or

2. Water is localized in the lower crust?



Both reverse and strike-slip faults

The lower crust in NKTZ can be weakened by the water.

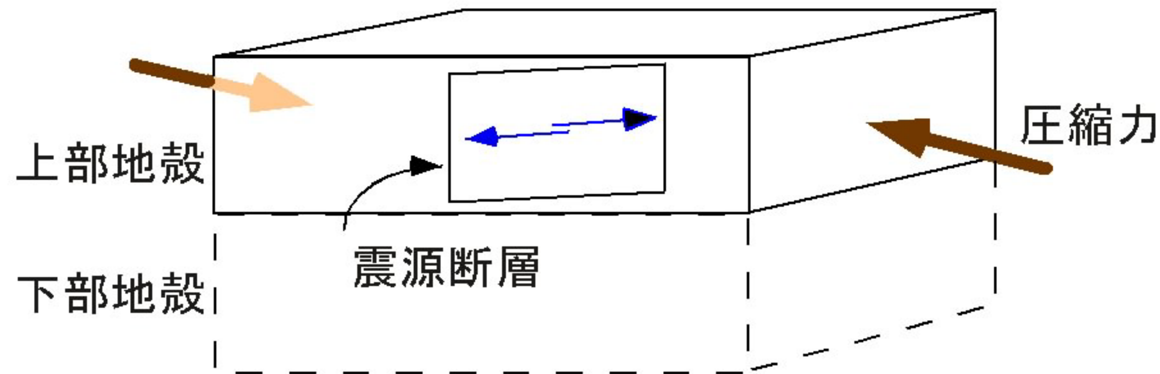
The water-weakened lower crust may be the origin of the concentrated deformation zone.

Although it is not resolved by these observations whether the water is localized or distributed in the lower crust, it is inferred from geological and experimental results that water is localized in fault zones in the lower crust .

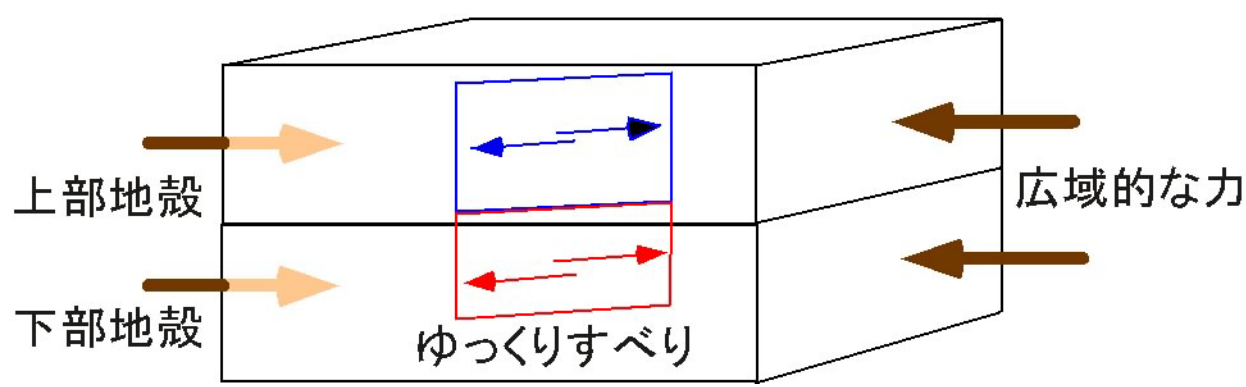
Thus, it is likely that the weak zone consists of fault zones in the lower crust. It includes not only reverse faults but also strike-slip faults.

内陸地震を起こす力についての新しい考え方

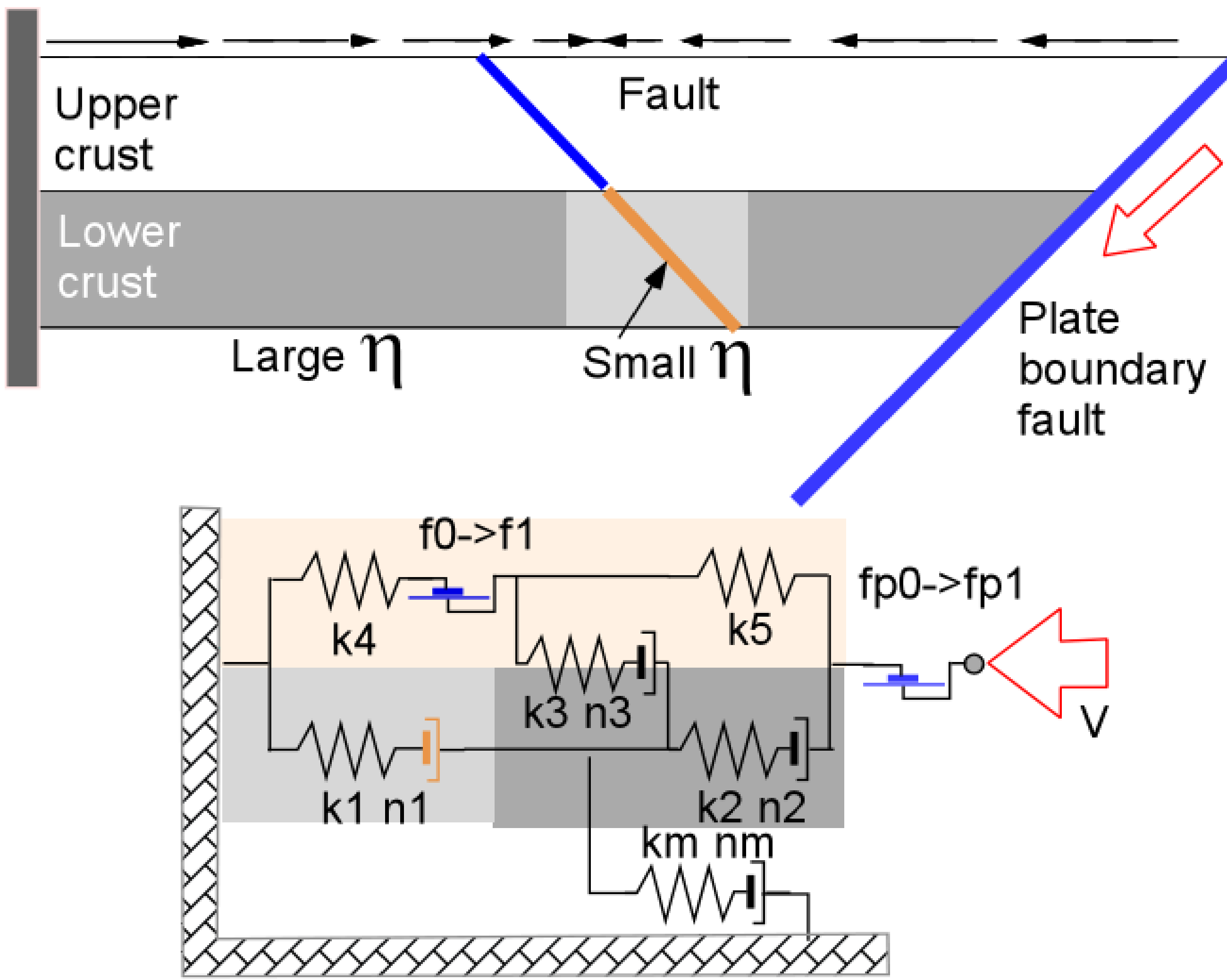
1. 沈み込むプレートによる圧縮力（従来の考え方）



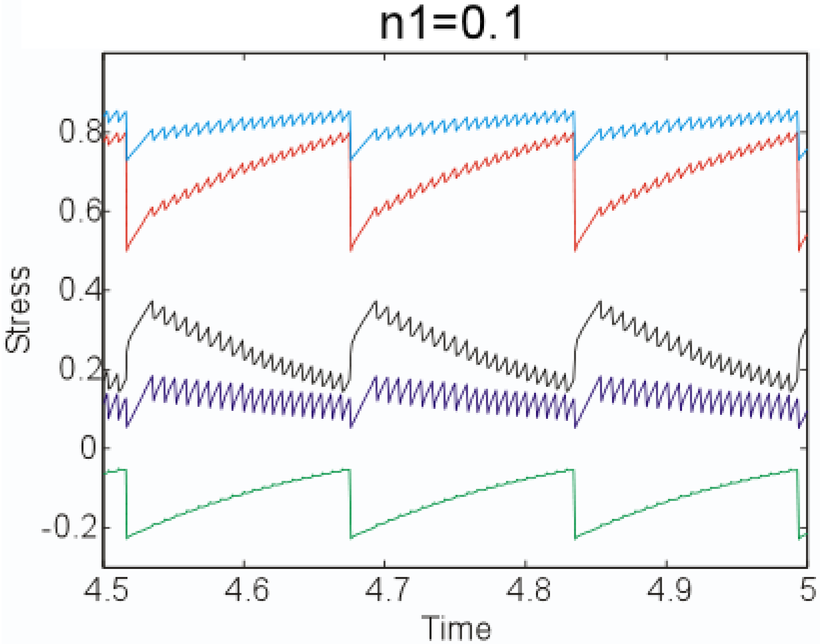
2. 陸側プレート内に広域的に働く力+
震源断層の深部延長のゆっくりすべりによる力

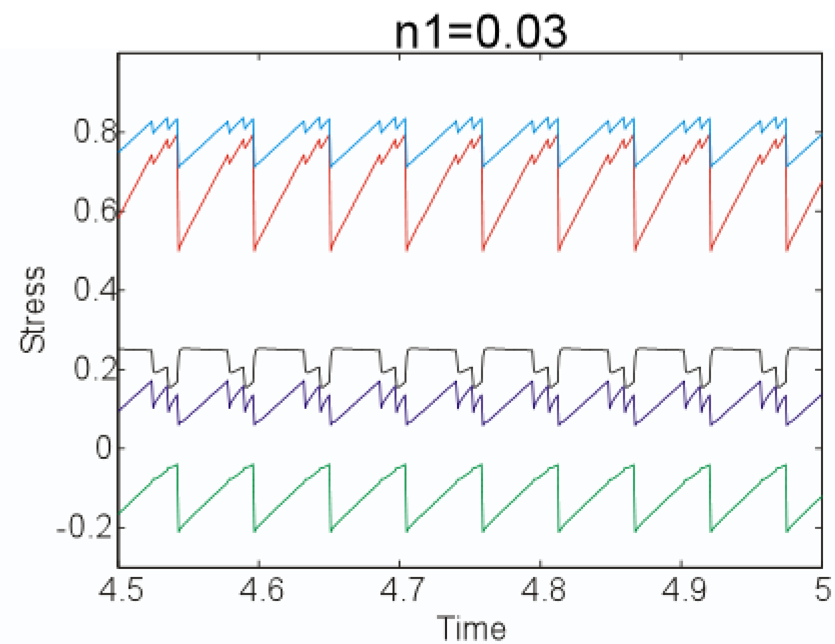


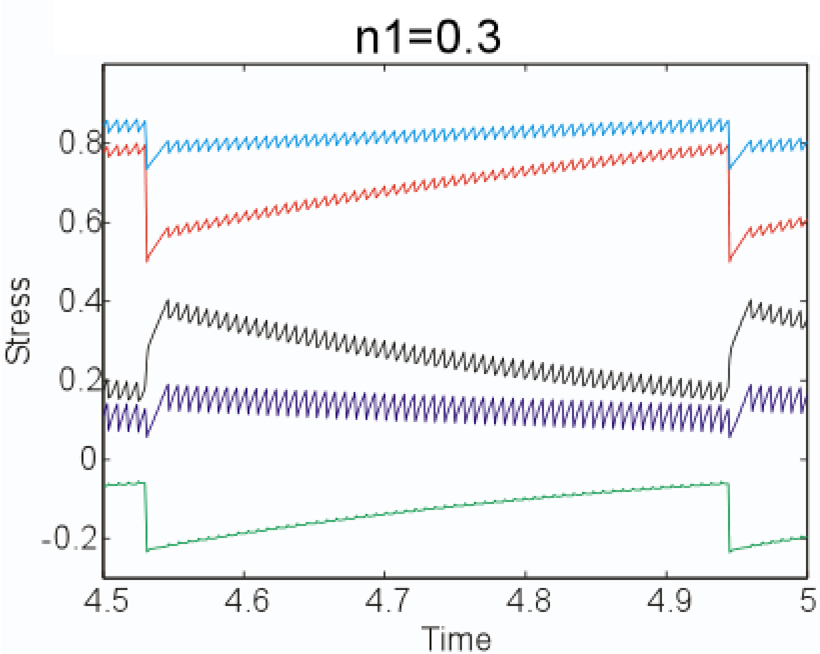
内陸地震の定量的概念モデル
―沈み込むプレートを考慮―



Weak zoneの粘性を変える

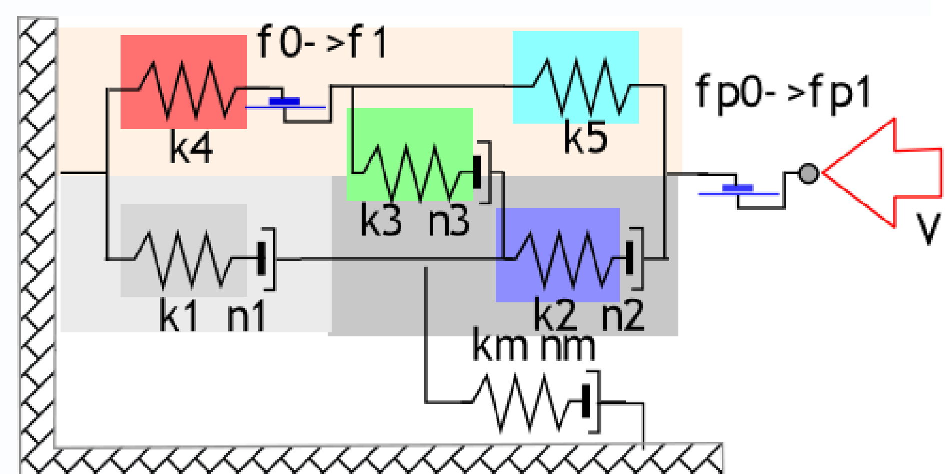




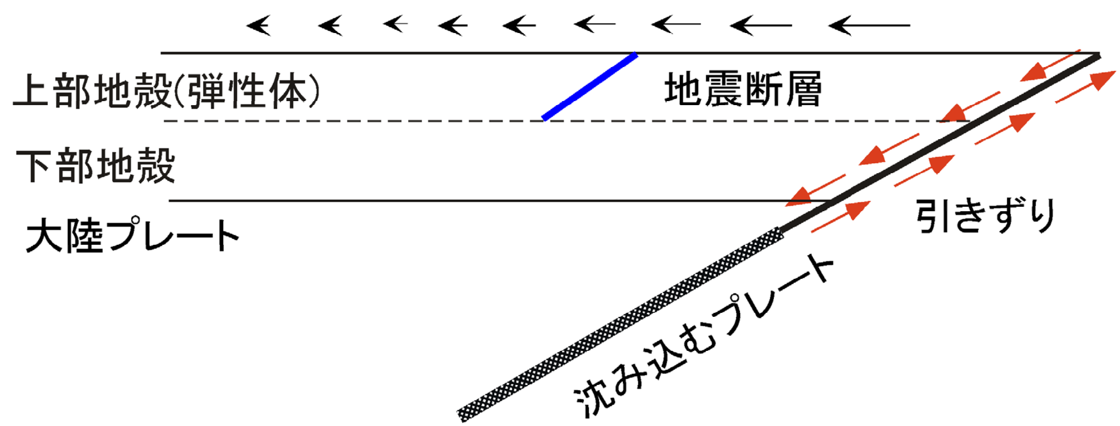


n2= 1 n3= 1

f0= 0.8 f1= 0.5 fp0= 1 fp1= 0.9 v= 10



仮説1.　プレートの相対運動に起因する応力蓄積



仮説2.　プレートの相対運動に起因する応力蓄積　+ 深部延長の非地震性すべりによる局所的な応力蓄積