Simulation of Earthquake Generation Process in a Complex System of Faults

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In this project, we aim to simulate generation processes of interplate and intraplate earthquakes in a complex system of interactive faults in northeast and southwest Japan, respectively, based on a laboratory derived rate- and state-dependent friction law.

In quasi-static earthquake cycle simulations which mainly deal with the long-term slow deformation process of earthquake cycle including a quasi-dynamic treatment of dynamic rupture process, we simulate simply in a homogeneous elastic medium before treating a viscoelastic one. For the Nankai trough earthquake cycle in southwest Japan, using a flat plate interface, we succeeded in reproducing the rupture segmentation and their complicated interactions similar to the actual historical earthquake sequences, which was already reported. By assigning the same heterogeneous frictional parameters, however, we can not reproduce the complicated earthquake cycle similar to the actual one, in the case for the realistic 3-D curved plate configuration. Including a comparison of the crustal deformation calculated for the simulated earthquake cycle with the observed one, we discuss the model parameters to be improved for reproducing the actual data. For a heterogeneous elastic FEM model in northeast Japan, we compute slip response functions with GeoFEM to estimate the afterslip distribution for the 2003 Tokachi-Oki earthquake.

As a simulation based on a viscoelastic FEM model in southwest Japan, we estimate the temporal stress change (ΔCFF: Coulomb failure function) on the active inland faults in the Nankai trough earthquake cycles, which is produced by the subduction of the Philippine Sea plate and the great earthquakes along the Nankai trough. Comparisons of the simulated temporal variations of ΔCFF with the occurrence times of old inland earthquakes suggest a possibility that we estimate the period with the high probability of earthquake occurrence on each fault within the Nankai trough earthquake cycle. Based on slip response functions calculated in the 2.5-dimensional viscoelastic FEM model in northeast Japan, we evaluate the resolving power of slip distribution along the Pacific plate.

For dynamic rupture simulation, we improved our scheme in the FEM calculation of dynamic rupture, as reported last year. Therefore, in a dip slip fault, we can obtain the same results of dynamic rupture as those in the previous studies by different techniques, indicating our code is well working in a dip slip fault in addition to the strike slip one which was reported last year.

Keywords: quasi-static earthquake cycle simulation, 3-D curved interface, Philippine Sea plate, Nankai trough, crustal deformation, Tokachi-Oki earthquake, slip response function,, temporal stress change, inland earthquake, stress dip slip fault

1. Introduction

A M 6.9 earthquake attacked the Noto peninsula in central Japan in March, 2007. This earthquake is classified to the inland or the intraplate earthquake occurring on an active inland fault whose recurrence time is larger than 1,000 years. In addition to this type of earthquakes, we have M8-class interplate earthquakes which repeatedly occur in 100 years. These earthquakes are caused by the subducting Pacific and Philippine Sea plates. The former is subducting beneath the northeast Japan along the Kuril and the Japan trenches, and the latter descends beneath the southwest Japan along the Nankai trough. The subduction of these plates produces the considerably heterogeneous structure beneath Japan Islands which causes complex interaction between interplate and inland earthquakes.

The main purpose in our project is to simulate earthquake generation cycles of both interplate and inland earthquakes to understand the complex sequences of earthquake occurrence and also to provide us basic information on past and future earthquakes. Constructing detailed regional heterogeneous FEM models in northeast and southwest Japan, respectively, we try to simulate earthquake generation cycle in a regional scale.

Our simulation of earthquake cycle consists of two processes; quasi-static and dynamic rupture ones. In the quasi-static earthquake cycle simulation, we simulate quasi-static slow stress accumulation and quasi-dynamic slip evolution on plate interfaces or inland faults due to relative plate motions based on a laboratory-derived rate- and state-dependent friction law. In this simulation, we employ the boundary integral equation method, and the final approach of simulation is the following. There, we divide the interface into cells with the sizes of around 1 km x 1 km, and calculate slip response functions for each cell in a 3-D viscoelastic FEM model, where the plate interface is further divided, using GeoFEM, a super-parallel FEM code (Iizuka et al., 2002). Then, using these slip response functions, we integrate a quasi-static equation of motion combined with a friction law with an adaptive time step Runge-Kutta algorithm. In dynamic earthquake cycle simulation, we simulate earthquake rupture propagation based on slip-dependent friction law as a contact problem and directly use the master-slave method for treating contact interfaces in GeoFEM.

Before simulation in complicated 3-D viscoelastic models, however, we first investigated the effect of frictional property reflecting the plate configuration on the earthquake cycle using a simple plane fault in a semi-infinite homogeneous elastic medium and successfully reproduced complicated earthquake cycle along the Nankai trough (Hori, 2006). Here, we extend this approach with heterogeneous frictional distribution to include the actual curved 3-D interfaces of the subducting plates. Further, we compare the crustal deformation calculated for the simulated earthquake cycle with the observed one. For laterally heterogeneous media, we evaluate slip response functions in a 3-D Hokkaido elastic model, and estimate the afterslip distribution of the 2003 Tokachi-Oki earthquake.

In earthquake cycle simulation, it is important to assign frictional parameter distribution for reproducing the past earthquake cycle and for predicting the occurrence of future earthquake. For simple cell models in an elastic medium, we examine the estimation of frictional parameters from data assimilation, which is not described here because of still simple trails.

For viscoelastic simulation, we examine the temporal stress changes on inland active faults in southwest Japan due to the plate subduction and the earthquake slips, employing slip response functions calculated for the 3-D viscoelastic FEM model in southwest Japan. This simulation suggests that we possibly estimate the period with high probability of earthquake occurrence on inland faults. In northeast Japan, we examine the resolution power of slip distribution along the Pacific plate based on the data observed on land areas, employing slip response functions for a 2.5 dimensional viscoelastic FEM model. The results are skipped, however, in this report because of space limitation.

For simulation of dynamic rupture propagation, we continue the performance test of contact analysis code implemented in GeoFEM using simple plane models. Last year, we introduced an effective damping scheme to prevent some oscillations in slip velocity due to numerical dispersion. In this year, we execute dynamic rupture simulation on a dip slip fault and confirm that this damping scheme is well working also in the case of a dip slip fault as well as in the case of a strike slip fault which was reported last year. After simulating more realistic cases, we will report the results of dynamic rupture simulation in the near future.

2. Quasi-static simulation of earthquake cycle with actual curved 3-D interfaces of subducting Philippine Sea plate in a homogeneous elastic medium along the Nankai trough in southwest Japan, and the calculated crustal deformation

2.1 Simulated earthquake cycle

Last year, instead of the flat plane which we have so far used, we modeled the 3-D curved interface of the subducting Philippine Sea plate using triangles with sides of 1 km. As in our previous simulations, the convergence rate of the Philippine Sea plate varies along the Nankai trough, which is taken from Heki and Miyazaki (2001). The convergence rate is around 2 cm/yr in the Tokai region, and increases westwards and reaches 6 cm/yr around the west of Kii peninsula. Assuming the frictional properties depend only on the depth, we assign the distribution of frictional parameters, and we obtained the same result where the rupture always initiates off the Kii peninsula as in the case of flat plate interface (Hori et al., 2004).

In this year, we execute simulation by assigning the same frictional heterogeneities on the 3-D curved plate interface (Fig. 1) as in the case of flat plane where the actual historical sequences of the earthquake cycle along the Nankai trough have been well reproduced (Hori, 2006). Simulations do not, however, reproduce the historical complex sequences of segmented faulting in contrast to the case of flat plate interface. Namely, the simulations do not produce the time-predictable behaviors (Shimazaki and Nakata, 1980) in the rupture initiation areas off Kii peninsula which were seen in the flat case.

The high fracture energy area we put in the west of the rupture initiation area prevents the rupture from propagating westwards, and only the eastern segment, the Tonankai and/or the Tokai segment, is broken. In this case, the whole stress stored in the rupture initial area in the interseismic period is not released, but some amount remains, leading to the smaller earthquake. Then, in some time later, the rupture occurs and the western segment, the Nankai segment, is broken. The rupture of the Nankai earthquake does not extend to the eastern Tonankai area, because the strength is recovered there before the Nankai earthquake. Accordingly, at the rupture initiation area of the Tonankai earthquake, the unreleased stress remains, and causes the next earthquake to occur earlier. This is why the time-predictable behavior appears in the flat case.

However, in the curved plate interface case, the Nankai earthquake causes some amount of slip again in the Tonankai initiation area and the time-predictable behavior does not appear, because the time interval between the Tonankai and the Nankai earthquake is too short to recover the strength in the curved plate interface case. In the flat case, the area with the large characteristic length L we put in the deep portion makes effectively the time interval longer. In contrast, this does not work in the curved interface case. Accordingly, for reproducing the time-predictable behavior as seen in the flat case, we need to consider the faster healing process on the plate interface in the curved case. In fact, the time interval between the 1854 Tonankai and Nankai earthquakes is 32 hours and the strength would be recovered in this short time scale.

2.2 Comparison of crustal deformation calculated for the simulated slip evolution on the curved plate interface with the observed one

During an interseismic period, slip on the plate interface evolves from the deeper and the shallower stable sliding regions to the locked one, and the locked portion becomes narrower as approaching the occurrence of the earthquake as shown in Fig. 2. Such temporal changes of slip distribution on the plate interface in the interseismic period produce the corresponding crustal deformation at the surface. We compare the simulated and the observed crustal deformations to examine whether our model explain the observations or not.

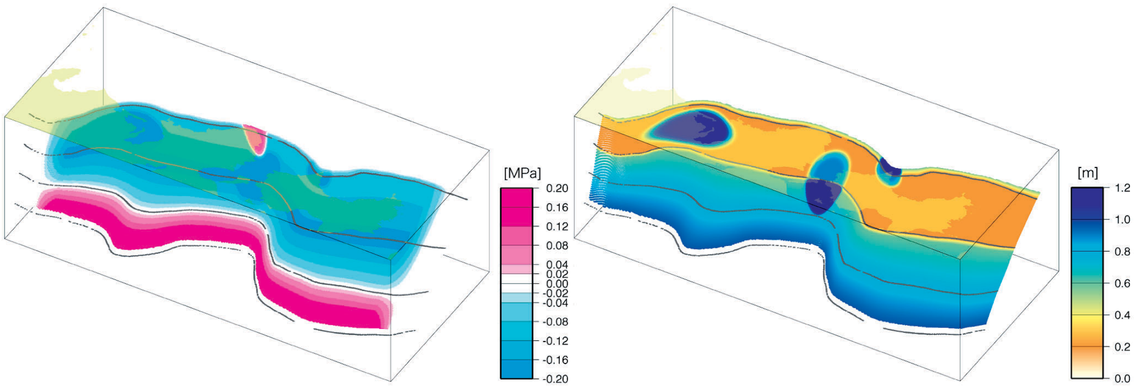

Fig. 1 Heterogeneous frictional parameter distribution on the 3-D curved plate boundary for (a-b)s (left) and L (right) values. Contour lines indicate the depth with 10 km interval.

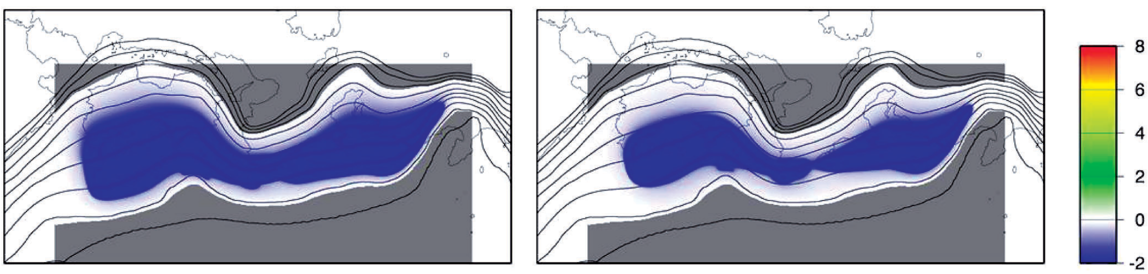

Fig. 2 Distribution of simulated slip rate (left: 60 years and right: 15 years before the occurrence of the Tonankai earthquake). The locked (blue) portion becomes narrower before the occurrence of the Tonankai and Nankai earthquakes.

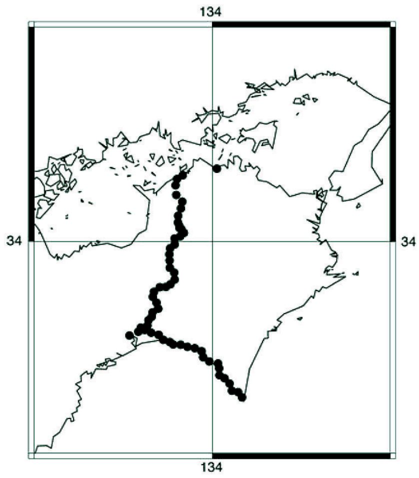

Fig. 3 Leveling route in the Shikoku.

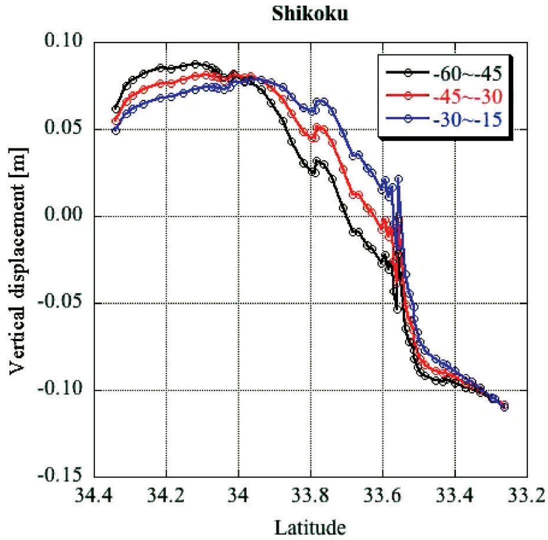

Fig. 4 Calculated vertical displacements along the leveling route in Fig.3. Black, red and blue lines represent the vertical displacements for the times of 60-45, 45-30 and 30-15 years before the occurrence of the Nankai earthquake, respectively.

The leveling observations have been repeatedly executed by Geographical Survey Institute along a route in the Shikoku as indicated in Fig. 3. Figure 4 shows the vertical crustal displacements for three different interseismic periods. As seen in Fig. 4, the zero displacement portions in the calculated vertical displacement move seawards as the locked portion on the plate interface becomes narrower.

Figures 5 and 6 compare the calculated and the observed vertical displacements for different periods. The peak and bottom portion in the simulated vertical displacements for the periods before and between the occurrence of the Nankai earthquake, respectively, are located landwards compared with those in the observed ones. The separate examinations of the simulated deformations before and after the occurrence of the earthquake indicate that our model produces the subsidence region in landwards compared with the observed one. And the prominent afterslip in the deep portion occurs soon after the earthquake, which shifts the subsidence region further northwards.

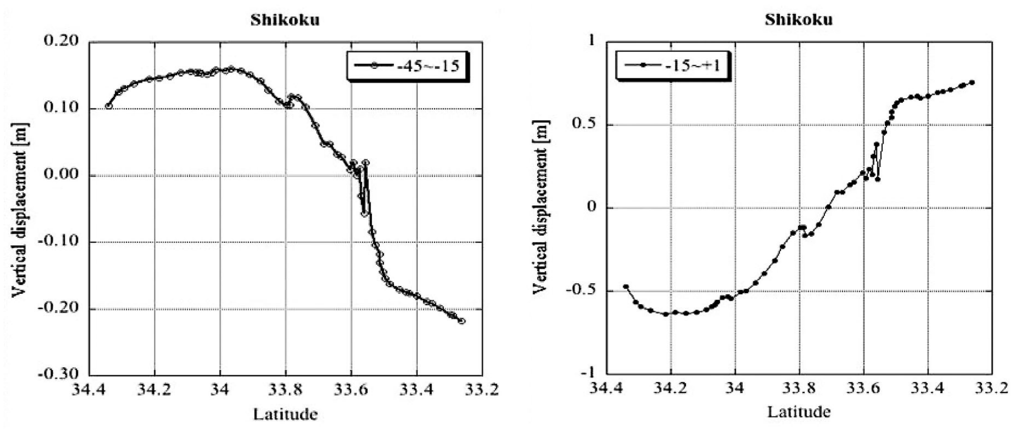

Fig. 5 Simulated vertical displacements for two different periods: (left) before the Tonankai type earthquake, (right) before and after the earthquake. Note the different vertical scale.

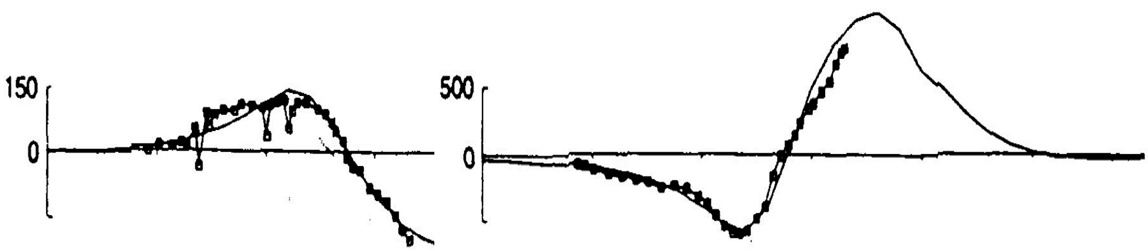

Fig. 6 Observed vertical displacements along the leveling route for two periods of 1897–1939 (left) and of 1939–1947 (right). The dotted points represent the observations, which are compared with the points in Fig. 5. These figures are taken from Sato and Matsu'ura (1992). Note the different vertical scales.

In summary, we need to improve our simulation model in the followings. First, the healing or the strength recovery should occur in a considerably short time for reproducing a variety of earthquake sizes and intervals which appear in the actual historical Nankai trough earthquake cycles. Second, comparisons of the simulated and the observed crustal deformations show that the coseismic slip region seems to be deeper than the observed one, and the afterslip has different time constants from the observed one. These should be improved together with the model extension from the elastic to the viscoelastic medium.

3. Effect of elastic heterogeneity on the estimation of afterslip distribution of the 2003 Tokachi-Oki earthquake in north Japan

We calculated the crustal deformation at the surface for the 3-D heterogeneous elastic FEM model in north Japan to examine the effect of elastic heterogeneity on the estimation of afterslip distribution of the 2003 Tokachi-Oki earthquake in north Japan. Figure 7 shows the observed horizontal and vertical postseismic displacements. Figure 8 compares the estimated afterslip distribution for homogeneous and heterogeneous elastic models. The estimated moment is 30 % larger in the heterogeneous elastic model than that in the homogeneous one.

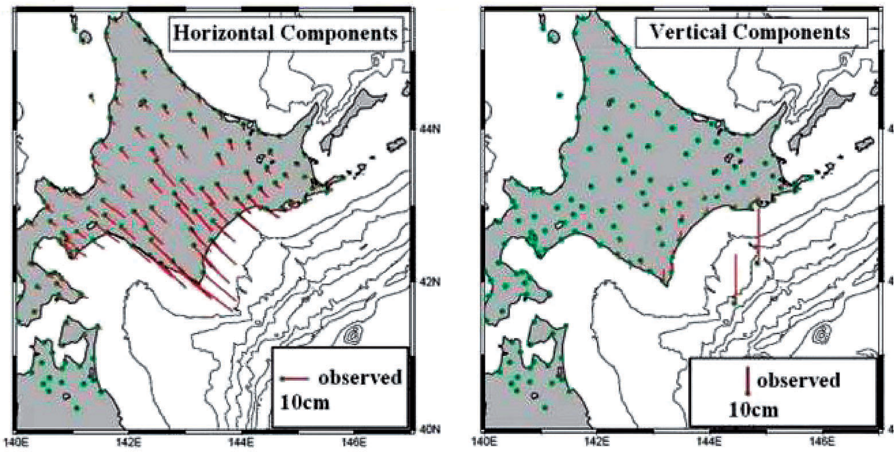

Fig. 7 The observed horizontal and vertical postseismic displacements for the 2003 Tokachi-Oki earthquake.

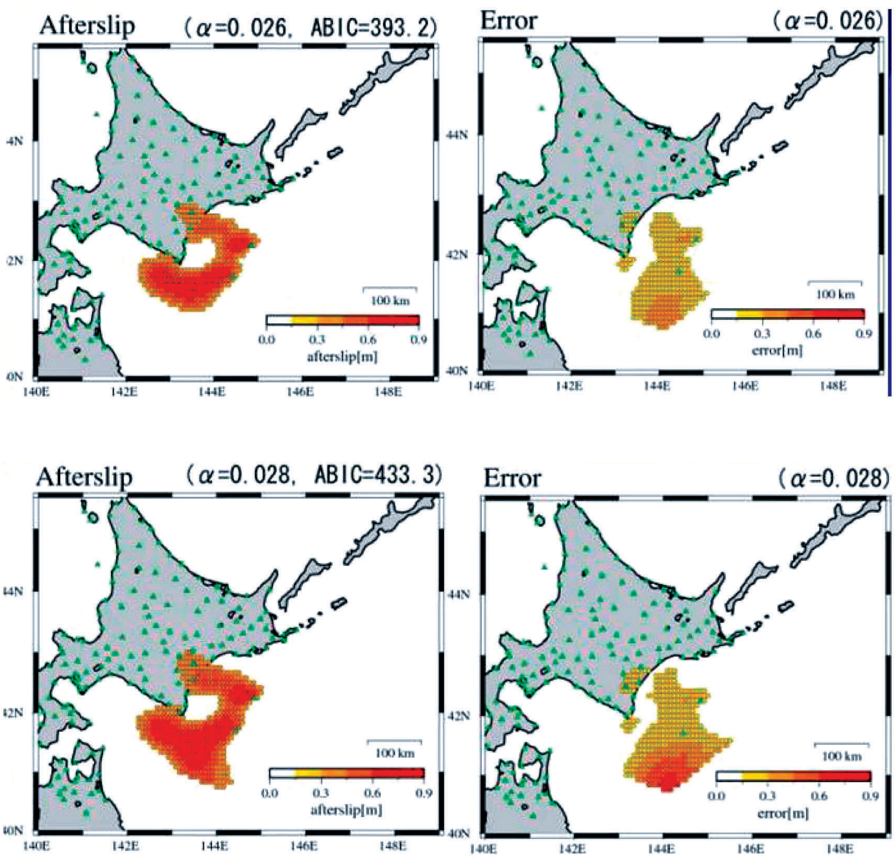

Fig. 8 Estimated afterslip distributions together with the errors for (a) the homogeneous (upper) and (b) heterogeneous (lower) elastic models, respectively.

4. Temporal stress changes on inland faults in southwest Japan in a viscoelastic medium during the Nankai trough earthquake cycles

In our project, we are now simulating earthquake cycles along the Nankai trough or along the Japan trench. Final simulation of our project should include also the inland earthquake cycles in a viscoelastic medium. To investigate the effect of viscoelastic stress interaction between the interplate and the intraplate earthquakes, we simulate the temporal stress changes on inland faults due to the subducting Philippine Sea plate and the earthquake slips. The inland earthquakes in southwest Japan are caused by east-west compressive stress, but stress perturbation due to the subduction of the Philippine Sea plate and the earthquakes along the Nankai trough might control the occurrence time of inland earthquakes (Hori and Oike, 1999).

First, we calculate stress changes on inland faults due to a unit dislocation with a direction of N55° W on five segments A-E along the Nankai trough as shown in Fig. 9, employing GeoFEM based on the 3-D viscoelastic FEM model with 3,563,520 elements which was constructed by CHIKAKU software last year. The shear stress on the inland fault which promotes earthquake occurrence $\tau(t)$ due to the subduction of the plate and the earthquake slips on segments A–E is calculated by

$$\tau(t) = \sum_j V_{p,j}\, t \cdot T_j(\infty) - \sum_k \sum_j u_j^k T_j(t - t_j^k) \quad (1)$$

where suffixes j and k mean five segments A-E and k-th earthquake in the earthquake cycle. Vpj, uj^k and Tj(t) are the plate convergence rate (Heki and Miyazaki, 2002), slip of the k-th earthquake, and slip response function for j-th fault segment, respectively. The normal stress σ is calculated also in the same way. Then, the Coulomb stress function ΔCFF is defined as

$$\Delta CFF = \Delta\tau + \mu'\Delta\sigma \quad (2)$$

where $\Delta\tau$ and $\Delta\sigma$ represent the changes of the shear stress and the normal stress, and μ' is effective frictional coefficient. Here, the tensional stress on the fault is taken to be positive, and we set $\mu' = 0.3$ in this study. The positive ΔCFF means that the earthquake tends to occur, and the negative one indicates that the occurrence of the earthquake does not become likely.

We know the occurrence times of the historical Nankai trough earthquakes, but not the slip amounts. Therefore, we assume that the amount of earthquake slip uj^k is determined according to the time-predictable or the slip-predictable model (Shimazaki and Nakata, 1980).

Figure 10 shows the temporal stress changes for the Nobi and Kita-Tango earthquake faults. Earthquake slips according to the slip-predictable model explain the occurrence of the Nobi earthquake better than those according to the time-predictable model. Therefore we show only the results based on the slip-predictable model. The calculated earthquake cycle includes the 1707 Hoei, the 1854 Ansei and the 1944 and 1946 Showa Nankai trough earthquakes. The Nobi earthquake fault has positive ΔCFF coseismically, After that, ΔCFF is further increased by the viscoelastic effect in some time and then decreases due to the plate subduction. Therefore, ΔCFF has its maximum in each Nankai earthquake cycle, and the Nobi earthquake occurred in 1891 when ΔCFF is in the maximum in the Nankai earthquake cycle for the case of the slip-predictable model (black line). In contrast, ΔCFF for the Kita-Tango earthquake fault decreases due to the respective Nankai earthquakes, and hence we call this type of fault as the stress shadow fault. The viscoelastic effect creates the minimum of ΔCFF in each Nankai earthquake cycle. The Kita-Tango earthquake occurred in 1927 when the deceased ΔCFF recovers to the stress level before the 1854 Ansei earthquake.

The above preliminary simulations of ΔCFF also in other inland faults suggest that the inland earthquake on the fault with positive ΔCFF tends to occur during a period from the coseismic time to the time when ΔCFF has its maximum. And the stress shadow inland fault with negative ΔCFF has high-possibility of the earthquake occurrence after the recovery of ΔCFF. Now we assume the slip amount of the Nankai trough earthquakes. By adjusting the ΔCFF curve to the occurrence times of old inland earthquakes, however, we possibly know the slip amounts of the respective Nankai trough earthquakes. Or the Nankai trough earthquake cycle simulation needs to produce the earthquake slips which explain the

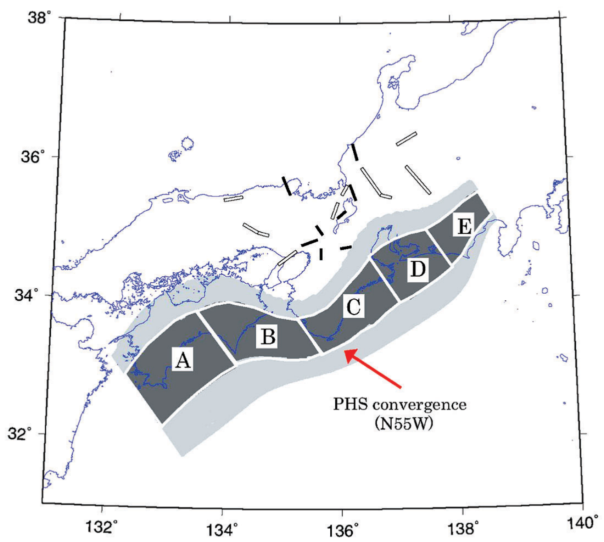

Fig. 9 Locations of the five fault segments A–E on the Philippine Sea plate interface, and of the inland faults. White and bold rectangles indicate the inland faults with ΔCFF>0 and ΔCFF<0 due to an earthquake slip along the Nankai trough, respectively.

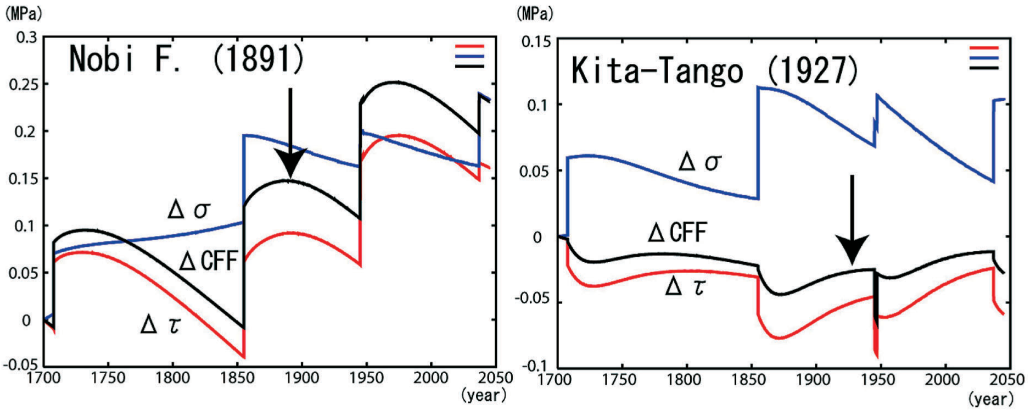

Fig.10 Temporal stress changes for (a) the Nobi (left) and (b) Kita-Tango (right) earthquake faults during a period from 1700 to 2050. The Nobi and the Kita-Tango earthquakes occurred in 1891 and 1927. Red, blue and block lines represent $\Delta\tau$, $\Delta\sigma$ and ΔCFF for the subduction of the Philippine Sea plate and the Nankai trough earthquake slips according to the time-predictable models, respectively. Arrows point at the occurrences times of the earthquakes.

occurrence of the old inland earthquakes. Thus, the occurrence times of the historical earthquakes are another constraints for the Nankai trough earthquake cycle simulation.

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複雑断層系の地震発生過程シミュレーション

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東北日本および西南日本における3次元不均質粘弾性FEMモデルを構築し、複雑断層系における海溝型巨大地震ならびに内陸地震の発生過程のシミュレーションを行うことを目的として、開発を進めている。均質半無限弾性体における準静的地震サイクル計算では、南海トラフ巨大地震発生サイクルシミュレーションにおいて、プレート境界面の屈曲した3次元形状をモデルに組み込みシミュレーションを実行した。平面境界の場合に、実際に歴史地震履歴に見られる規模の変化や発生間隔の変化を再現した、不均質摩擦パラメータ分布を用いて計算したが、3次元プレート形状モデルでのシミュレーションでは、これらがうまく再現されなかった。曲面プレート境界での場合に、平面断層の場合に見られた時間予測モデル的な振る舞いを再現するには、強度回復がかなり短い時間で発生する必要があることが分かった。また、これらのシミュレーション結果に基づき、地表の上下変動パターンを計算し、観測値と比較した。これらの結果から、現在のシミュレーションモデルの修正すべき点を検討した。次に、弾性媒質の不均質性の効果が、余効すべりの推定に及ぼす効果を評価するため、地殻やプレートを含む3次元不均質弾性FEM北海道モデルを用いて、2003年十勝沖地震の余効すべり分布を推定した。その結果、均質弾性モデルに比べ、不均質モデルでは、30％大きなモーメントが求められることが分かった。粘弾性モデルを含むシミュレーションでは、西南日本内陸活断層における、フィリピン海プレートの沈み込みと南海トラフ巨大地震による応力変化（ΔCFF）を調べた。その結果、南海トラフ巨大地震によるΔCFFが正の活断層では、南海トラフ地震時からΔCFFがピークを迎えるまでに、内陸地震が発生し、逆に、ΔCFFが負の断層では、南海地震後低下したΔCFFが回復した後に、その内陸活断層で地震が発生しているように見えることが分かった。このように、西南日本における内陸地震は東西圧縮応力場で発生しているが、断層により南海地震サイクルのどの次期に地震発生する確率が高くなるかを予測できる可能性がある。

キーワード：準静的地震サイクル, 屈曲した3次元境界面, フィリピン海プレート, 南海トラフ, 地殻変動, 十勝沖地震, すべり応答関数, 内陸地震, 応力の時間変化