Development of a Predictive Simulation System for Crustal Activities in and around Japan - Ⅲ

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Our research group aims to develop a physics-based predictive simulation system for crustal activities in and around Japan. The total system consists of a quasi-static tectonic loading model, a dynamic rupture propagation model, and seismic/geodetic data assimilation software, developed on a realistic 3-D structure model. In 2004 we completed a prototype simulation system for crustal activities by combining the quasi-static tectonic loading model and the dynamic rupture propagation model on the Earth Simulator. In 2005 we developed a method of geodetic data inversion to estimate the spatiotemporal variation of interplate coupling. Applying this inversion method to various time-scale geodetic data, we revealed that the North American-Philippine Sea plate interface beneath the Kanto region can be partitioned into four regions with different stress release modes; steady slip without stress accumulation, intermittent stress release by slow slip events, sudden stress release by large interplate earthquakes, and tectonic stress release by inelastic crustal deformation. We developed also an inversion method to estimate seismogenic stress fields from CMT data of seismic events, and examined its validity through the analysis of observed data in northeast Japan. Combining these inversion methods with the computer simulation of tectonic loading, we can predict the spatiotemporal variation of stress states at plate interfaces.

Keywords: inversion analysis, interplate coupling, seismogenic stress fields, predictive simulation

1. Introduction

Our research group aims to develop a physics-based predictive simulation system for crustal activities in and around Japan, where the four plates of Pacific, North American, Philippine Sea and Eurasian are interacting with each other in a complicated way (Fig. 1). The total system consists of a quasi-static tectonic loading model, a dynamic rupture propagation model, and seismic/geodetic data assimilation software, developed on a realistic 3-D structure model [1]. In 2004 we completed a prototype simulation system for crustal activities by combining the quasi-static tectonic loading model and the dynamic rupture propagation model on the Earth Simulator [2, 3].

Output data of this simulation system are the crustal deformation, internal stress change, and seismic wave radiation associated with seismic and/or aseismic slip at plate interfaces. Comparing the simulation output data with actual observed data, we can extract useful information to estimate the past slip history and the present stress state at the plate interfaces by using an inversion technique [4]. Given the past slip history and the present stress state, we can predict the next step fault-slip motion through computer simulation. In 2005 we developed two inversion methods using Akaike's Bayesian Information Criterion (ABIC), one of which is the method to estimate the spatiotemporal variation of interplate coupling from geodetic data, and another is the method to estimate seismogenic stress fields from CMT data of seismic events.

2. Diversity of stress release modes at the NAM-PHS plate interface inferred from geodetic data inversion

We constructed a Bayesian model for geodetic data inversion by combining both direct and indirect prior information with observed data [5]. Such flexible Bayesian modeling enables us to unify the two different types of inversion methods by Jackson and Matsu'ura [6] and Yabuki and Matsu'ura [7] in a rational way. We examined the validity of the uni-

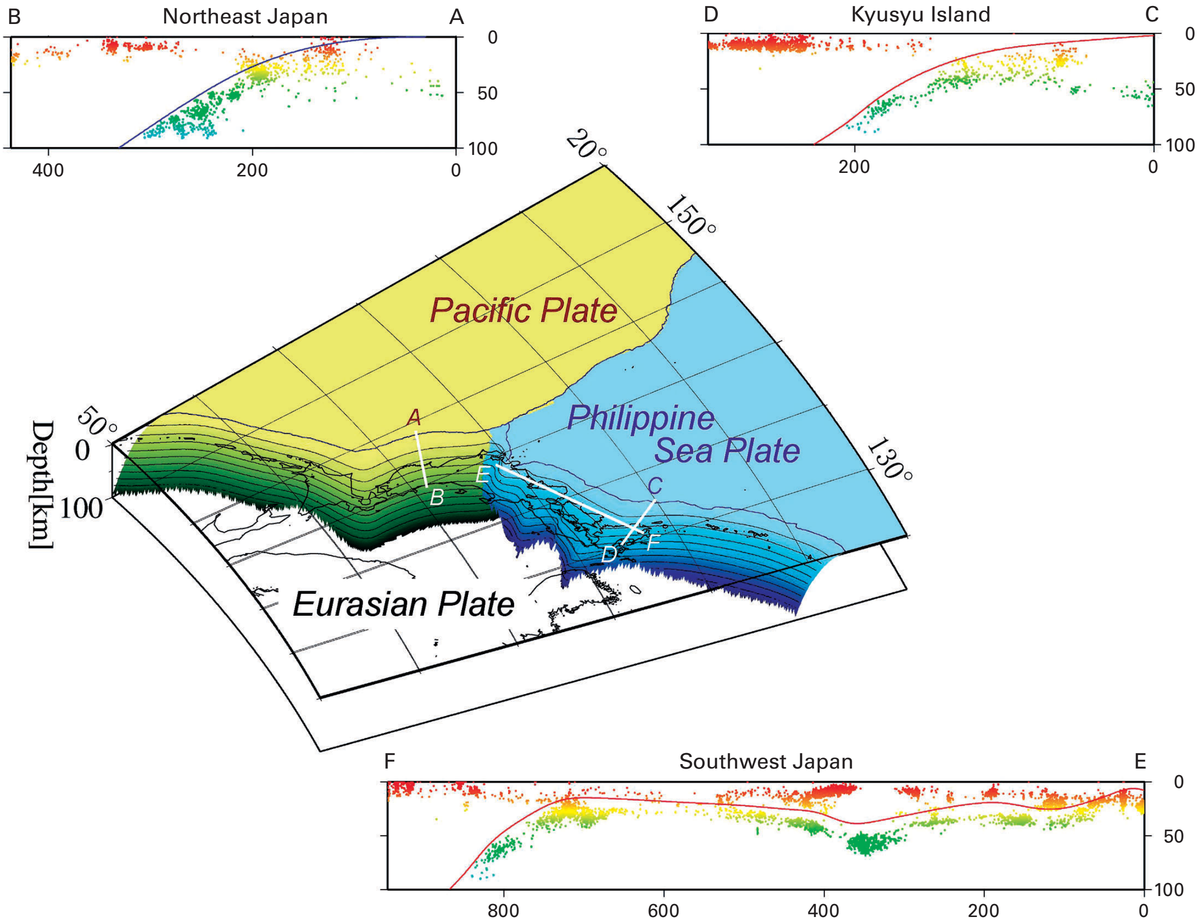

Fig. 1 A standard 3-D model of plate interface geometry in and around Japan [1]. The vertical sections of the modeled plate interfaces are compared with observed earthquake distributions along the three segments; northeast Japan (A-B), Kyusyu Island (C-D), and southwest Japan (E-F).

fied inversion method by choosing the Kanto region, central Japan, as a test field. The Kanto region is in a complex tectonic setting, where the Pacific (PAC) plate is descending beneath the North American (NAM) and Philippine Sea (PHS) plates, and the PHS plate is descending beneath the NAM plate and running on the PAC plate at its eastern margin. Furthermore, the PHS plate is colliding with the mainland of Japan at the northern end of the Izu peninsula. Because of such a complex tectonic setting, crustal movements in the Kanto region are manifold from instantaneous coseismic movements to long-term tectonic deformation. The essential cause of these crustal movements is in mechanical interaction at the interfaces between the NAM, PAC and PHS plates.

The crustal movements in the Kanto region have been precisely measured through leveling, triangulation, trilateration and/or GPS since the 1880s. We analyzed the coseismic, interseismic and episodic movements with a realistic 3-D plate interface model [1] to reveal diversity in stress release mode at plate interfaces beneath the Kanto region. From the analysis of coseismic vertical and horizontal displacement data, we found that the coseismic slip of the 1923 Kanto earthquake on the NAM-PHS plate interface is characterized by a bimodal distribution with the 5 km-deep western and 15 km-deep eastern peaks of about 8 m, extending to 30 km in depth. The slip vectors are almost parallel to the direction of plate convergence except for their clockwise rotation near the Sagami trough. From the analysis of GPS velocity data for the interseismic calm period of 1996–2000, we found a broad and high slip-deficit rate zone, extending from the area east off the Boso peninsula to the northern end of the Izu peninsula along the Sagami trough on the NAM-PHS plate interface. This result indicates strong interplate coupling in the source region of the 1923 Kanto earthquake and the Izu-Mainland collision zone. From the analysis of daily GPS coordinate data associated with the 1996 and 2002 off-Boso slow slip events, we found that these events have unimodal forward slip distributions with the peak of 40 mm and 80 mm, respectively, in almost the same area east off the Boso peninsula on the NAM-PHS plate interface. These slow slip events accompany earthquake swarms. The series of slow slip events occurred east off the Boso peninsula at the average interval of 2–4 years would have similar characteristics to the 1996 and 2002 events.

Putting together the interseismic slip-deficit rate distribution, the coseismic slip distribution of the 1923 Kanto earth-

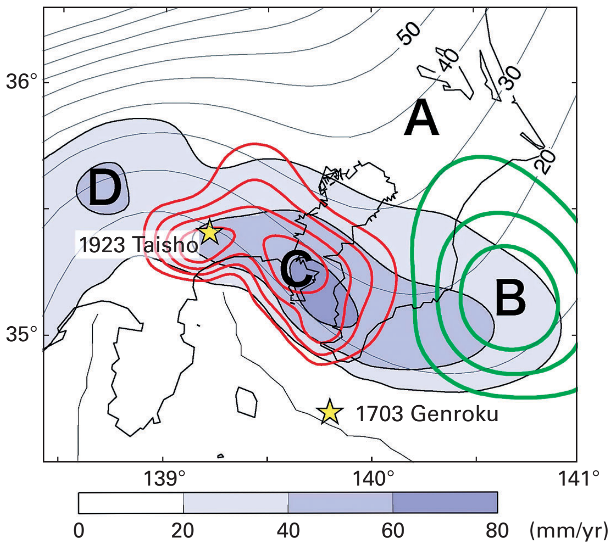

Fig. 2 Partitioning the NAM-PHS plate interface based on difference in stress release mode [5]. A) Steady slip without stress accumulation; B) Intermittent stress release by slow slip events; C) Sudden stress release by large interplate earthquakes; and D) Tectonic stress release by inelastic crustal deformation. The blue color-scale contours show the interseismic slip-deficit rates. The red contours at 2 m intervals show the coseismic slip of the 1923 Kanto earthquake. The green contours at 5 mm/yr intervals show the average slip rates estimated from the slip distribution and recurrence interval of the off-Boso slow slip events. The stars indicate the epicenters of the 1703 Genroku-Kanto earthquake and the 1923 Taisho-Kanto earthquake.

quake, and the average slow-slip rate estimated from the slip distribution and average recurrence interval of the 1996 and 2002 off-Boso events, we revealed that the NAM-PHS plate interface beneath the Kanto region can be partitioned into the following four regions with different stress release modes: A) steady slip without stress accumulation in the northern part of the Boso peninsula, B) intermittent stress release by a series of slow slip events east off the Boso peninsula, C) sudden stress release by large interplate earthquakes along the northern Sagami trough at the recurrence interval of several hundreds years, and D) tectonic stress release by inelastic crustal deformation around the collision boundary at the northern end of Izu peninsula. Such difference in stress release mode between these regions can be ascribed to difference in frictional properties there.

3. CMT data inversion using a Bayesian information criterion to estimate seismogenic stress fields

Seismological data contain direct information about stress states in the earth's crust, because earthquake occurrence can be regarded as a stress release process. In the 1980s, to estimate crustal stress fields from focal mechanism data, several methods of stress inversion have been proposed. The common idea of these methods is to determine the pattern of average deviatoric stress for each partitioned area by minimizing the difference between the directions of observed fault slip and those of the tangential component of traction vectors acting on fault planes in the least-squares sense. However, these methods have a serious problem that the inverted stress pattern strongly depends on the way of area partitioning. Another weakness of these methods is that errors in determining focal mechanism solutions and ambiguity in choosing true fault planes would degrade the reliability of inversion results.

In order to overcome these weaknesses of the previous methods, we developed a new inversion method to estimate the stress field related to earthquake generation (seismogenic stress field) from the centroid moment tensor (CMT) solution of seismic events [8]. This method is based on the idea that each seismic event releases a part of the seismogenic stress field around its hypocenter. The CMT of a seismic event can be represented by a weighted volume integral of the true but unknown seismogenic stress field. As the weighting function we take the 3-D Gaussian type distribution with its peak at the hypocenter and the variance proportional to the two-thirds power of the seismic moment (the square of the source dimension). In this method we need not partition the study area in advance. Instead, we represent the seismogenic stress field by the superposition of a finite number of known basis functions. Then, we obtain a set of linear observation equations to be solved for the expansion coefficients (model parameters). Incorporating prior constraints on the roughness of seismogenic stress fields with observed data by Bayes' rule, we can construct a highly flexible model (Bayesian model) with unknown hyper-parameters. The optimum values of hyper-parameters are objectively determined by minimizing ABIC. Given the optimum values of hyper-parameters, we can estimate the optimum values of

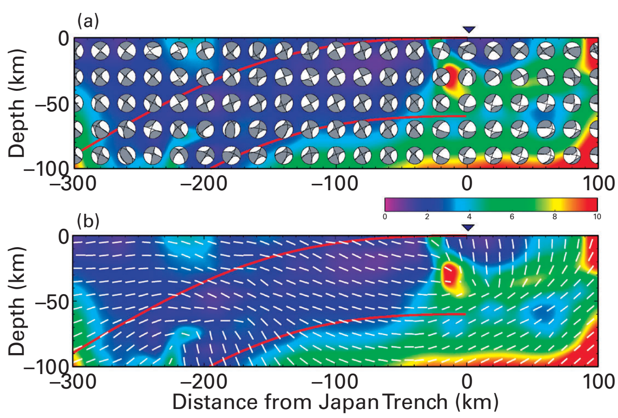

Fig. 3 The inverted seismogenic stress field on a vertical section along the direction of plate subduction in northeast Japan [8]. (a) The inverted seismogenic stress field with the focal sphere representation. (b) The directions of the maximum compressive principal stress axes projected on the vertical section. The red lines represent the upper and lower boundaries of the descending Pacific plate. The color scales in both figures show the degree of uncertainty.

model parameters by using a maximum likelihood method.

To test the validity of the new stress inversion method, we applied it to a set of about 2500 seismic events (M3.5-5.0) in northeast Japan (NIED Seismic Moment Tensor Catalogue, 1997–2005), and estimated the spatial pattern of the seismogenic stress field associated with the subduction of the PAC plate (Fig. 3). From this inversion result we can expect the occurrence of normal faulting with a strike parallel to the Japan trench in the shallow part of the oceanic plate beneath the outer rise and reverse faulting in the continental crust. These inverted stress patterns are consistent with the stress patterns expected from geophysical and geological observations.

4. Summary

We developed a method of geodetic data inversion to estimate the spatiotemporal variation of interplate coupling that is represented by slip excess or deficit. Given the spatiotemporal variation of slip excess or deficit, we can compute the internal stress state of the lithosphere (Fig. 4). On the other hand, we developed another inversion method to estimate seismogenic stress fields from CMT data of seismic events. The inverted stress fields can be compared with the computed stress fields to estimate actual stress states at plate interfaces.

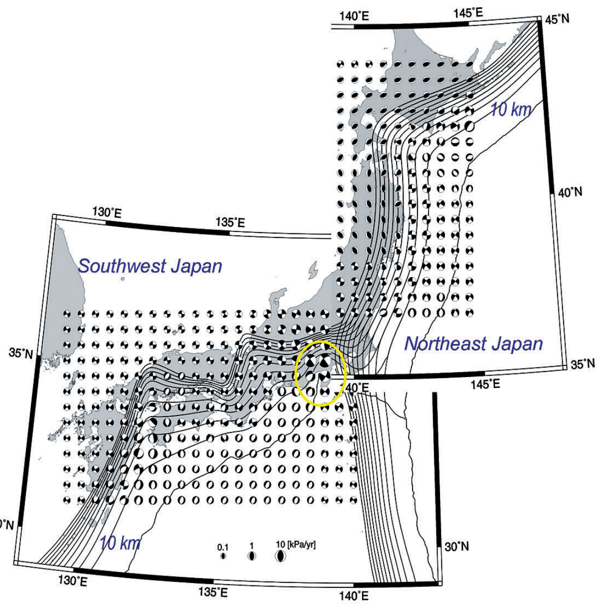

Fig. 4 Tectonic stress accumulation due to plate subduction in and around Japan [9]. The stress accumulation pattern is represented by using the upper focal hemisphere. The yellow circle indicates the the Izu-Mainland collision zone.

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日本列島域の地殻活動予測シミュレーション・システムの開発 - Ⅲ

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本研究プロジェクトは、複雑なテクトニック環境の下にある日本列島及びその周辺域を一つのシステムとしてモデル化し、プレート運動に伴う長期的な地殻変形から大地震の発生まで、時間・空間スケールの著しく異なる地殻活動現象を統一的且つ定量的に予測する並列シミュレーション・システムを開発し、モデル計算と観測データを併合した日本列島域の地殻活動予測シミュレーションを行うことを目的としている。

地殻活動予測シミュレーション・システムは、日本列島域の現実的な3次元標準構造モデル (Hashimoto, Fukui & Matsu'ura, PAGEOPH, 2004) 上に構築された準静的応力蓄積モデル、動的破壊伝播モデル、及び地震／地殻活動データの解析・同化ソフトウェアから成る。平成17年度は、前年度に開発した日本列島域の地殻活動シミュレーション・モデル (Matsu'ura, Hashimoto & Fukuyama, 4th ACES Workshop, 2004) を高度化する一方、広域地震／地殻変動観測データから地殻活動予測シミュレーションに有用な情報を抽出するインバージョン解析ソフトウェアを開発し、実際の観測データに適用してその有効性を検証した。

地殻変動データの解析に関しては、先ず、直接的および間接的な先験的情報をベイズの規則で観測データと結合して一般的なベイズモデルを構築し、新しいインバージョン解析手法を開発した。次に、この解析手法を関東地域の様々な時間スケールの地殻変動に適用し、大正関東地震時のすべり分布、地震間のすべり遅れ速度分布、1996年及び2002年房総沖スロースリップ・イベントのすべり分布を求めた。最後に、これらのインバージョン解析結果を総合することで、関東地域下の北米―フィリピン海プレート境界は応力蓄積・解放形態の違いにより4つの領域に区分されることを明らかにした (Noda & Matsu'ura, 5th ACES Workshop, 2006)。また、地震データの解析に関しては、地震は震源近傍の地震発生応力場を反映して起こるという考えに基づき、ABICをモデル選択の規準として用いて地震のCMTデータから地震発生応力場を推定するインバージョン解析手法を開発し、太平洋プレートが北米プレートの下に沈み込む東北地方の地震データ(NIED, Seismic Moment Tensor Catalogue) に適用してその有効性を検証した (Terakawa & Matsu'ura, 5th ACES Workshop, 2006)。これらのインバージョン解析の手法とプレート間相互作用による応力蓄積シミュレーションの手法 (Hashimoto & Matsu'ura, PAGEOPH, 2006) を併合することで、プレート境界面での応力蓄積状態、更には日本列島域の地殻内応力場の時空間変動の推定が可能となる。

キーワード：インバージョン解析，プレート間カップリング，地震発生応力場，予測シミュレーション