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

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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 crust-mantle structure model, a quasi-static tectonic loading model, a dynamic rupture propagation model, and a data assimilation module. In 2004 we optimized a computer code of viscoelastic slip response for the 3D standard plate interface model (developed in 2003) and a code of quasi-static tectonic loading, and completed a prototype of the simulation system for crustal activities in and around Japan by combining the quasi-static tectonic loading code and the dynamic rupture propagation code (developed in 2002). As a demonstration we carried out the predictive simulation of earthquake generation cycles at the source region of the 1968 Tokachi-oki earthquake, northeast Japan. Recently Takada and Matsu'ura (2004) introduced the concept of partial collision to describe a boundary process between the Indian and the Eurasian plates at Himalayas, and defined a collision rate as c = 1 - *steady subduction rate* / *steady convergence rate*. With the tectonic loading model considering the effects of partial collision we succeeded in reproducing the observed East-West compression in northeast Japan by taking the collision rate c to be 0.1 on average.

Keywords: plate subduction, earthquake generation cycle, stress accumulation, partial collision, predictive simulation

1. Introduction

Figure 1 shows the global epicenter distribution of shallow earthquakes with M > 4.5 for 1968-1995. Good agreement of the epicenter distribution with the geometry of plate boundaries suggests that the essential cause of earthquake generation is in mechanical interaction at plate interfaces.

The occurrence of large earthquakes can be regarded as the process of releasing tectonically accumulated strain energy by sudden dynamic rupture of faults. Then, the process of earthquake generation cycle consists of tectonic loading due to relative plate motion, quasi-static rupture nucleation, dynamic rupture propagation and stop, and fault strength recovery. In the last decade there has been great progress in the physics of earthquake generation; that is, the introduction of laboratory-based fault constitutive laws as a basic equation governing earthquake rupture and the quantitative description of tectonic loading driven by plate motion [2]. We can now quantitatively describe the entire process of earthquake generation by a coupled nonlinear system, which consists of a slip-response function that relates fault slip to shear stress change and a fault constitutive law that prescribes shear strength change with fault slip and contact time (Figure 2).

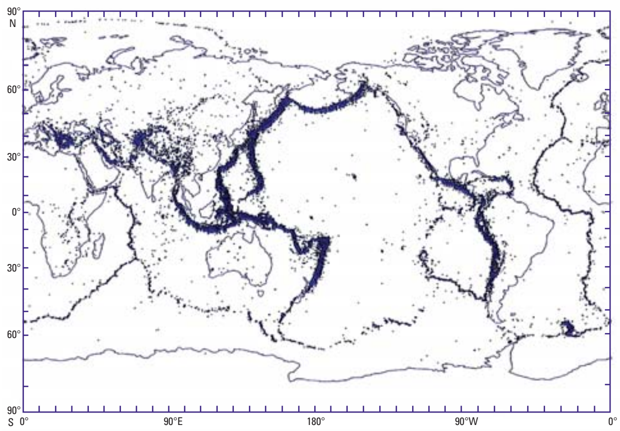

Fig. 1 The epicenter distribution of shallow (< 100 km) earthquakes with M > 4.5 for 1968-1995 [1]

The driving force of this system is observed plate motion. The system to describe the earthquake generation cycle is

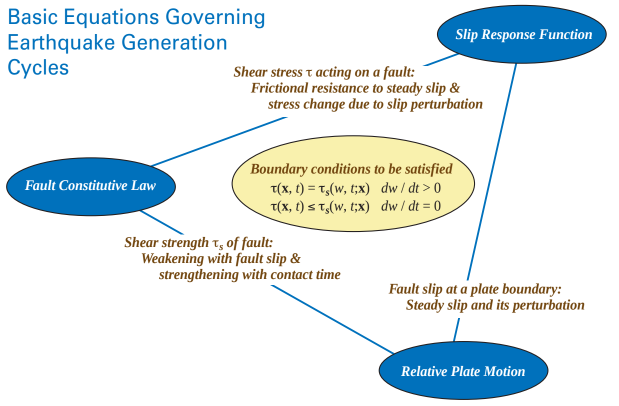

Fig. 2 Relationship between the basic equations that govern the earthquake generation cycle [3]

conceptually quite simple. The complexity in practical modeling mainly comes from complex structure of the real Earth.

2. Completion of a prototype of crustal activity simulation system

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. The total system consists of a crust-mantle structure model, a quasi-static tectonic loading model, a dynamic rupture propagation model, and a data assimilation module. In 2004 we optimized a computer code of viscoelastic slip response for the 3D standard plate interface model developed in 2003 [4] and a code of quasi-static tectonic loading, and completed a prototype of crustal activity simulation system by combining the quasi-static tectonic loading code and the dynamic rupture propagation code developed in 2002 [5].

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 output data with 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 [6, 7]. Given the past slip history and the present stress state, we can predict the next step fault-slip motion through computer simulation.

3. Predictive simulation of earthquake generation

Figure 3 is an example of predictive simulation for the occurrence of interplate earthquakes. On the left we show the quasi-static process of stress accumulation at the source region of the 1968 Tokachi-oki earthquake (M = 8.2). The subsequent process of rupture initiation, propagation and stop is shown on the right. In this simulation, although the stress state at the source region had not yet reached a critical level, we forced dynamic rupture to start by giving artificial stress drop at t = 35 yr. Then, unstable rupture started, but it was not accelerated. This means that the dynamic rupture is not accelerated, if the stress state has not reached to a certain critical level.

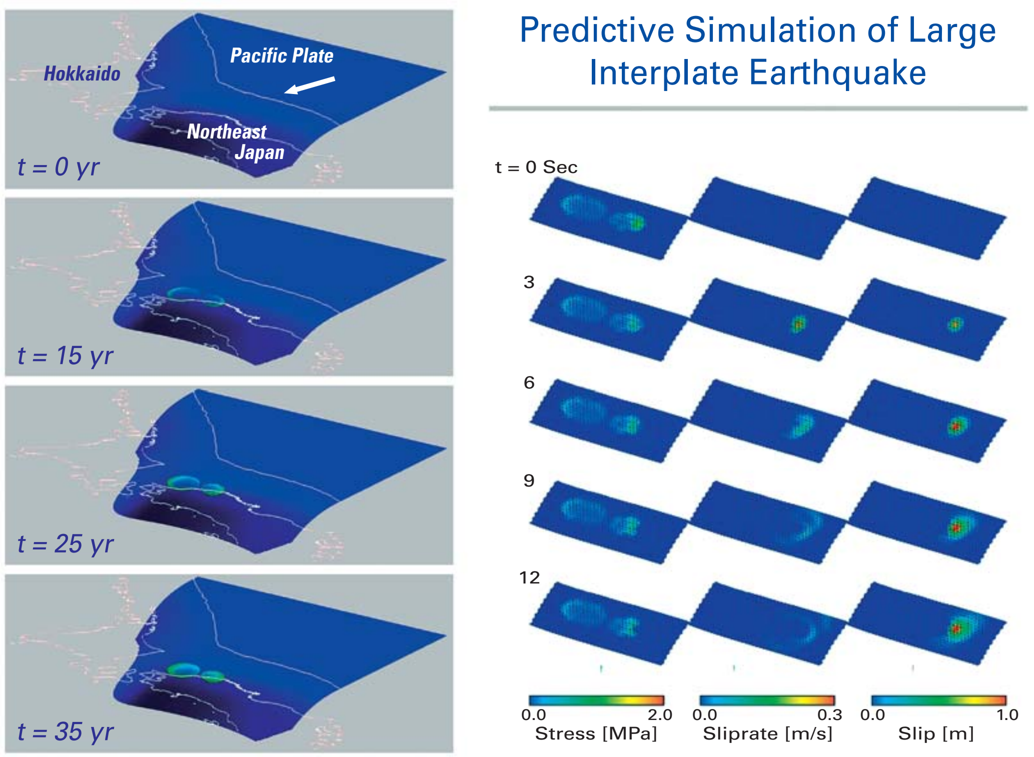

Fig. 3 Predictive simulation of earthquake generation at the source region of the 1968 Tokachi-oki earthquake [8]. Left: Quasi-static stress accumulation. Right: Changes in shear stress, slip velocity, and fault slip with time after the initiation of dynamic rupture. In this case, the dynamic rupture is not accelerated, because the stress stae is not critical.

4. Partial collision and intraplate tectonic loading

From Figure 1, although most earthquakes occur in plate boundary zones, we can find several high-seismicity regions in continental plates. To understand the tectonic loading mechanism of continental plates, we investigated the case of continental collision. At the collision boundary along Himalayas, for example, the convergence rate between India and Eurasia is about 50 mm/yr. About 40% of the total convergence is accommodated by steady subduction of the Indian plate. The rest of 60% is consumed by internal deformation of the overriding Eurasian plate. Such a plate boundary process (partial collision) can be quantitatively described by introducing a collision rate defined as c = 1 - *steady subduction rate* / *steady convergence rate*. As shown in Figure 4, the long-term stress accumulation pattern in and around Tibet can be well explained by a plate convergence model with c = 0.6 [9].

In the case of northeast Japan where the Pacific plate is descending beneath the North American plate, taking the collision rate c at the plate interface to be 0.1 on average, we can reproduce the observed EW-compressional stress field as shown in Figure 5 [10]. This indicates that the concept of partial collision is crucial to understand the mechanism of intraplate tectonic loading.

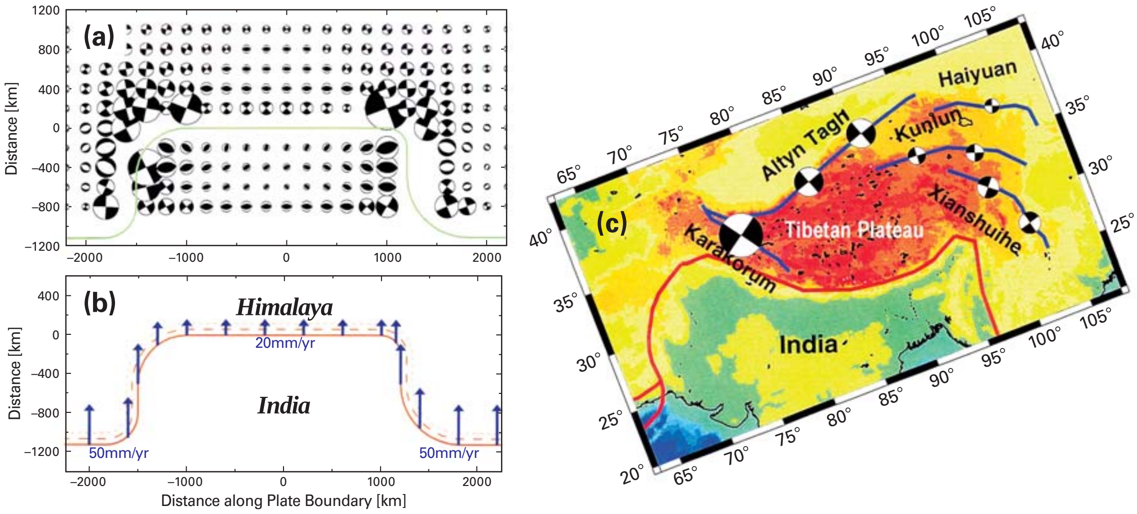

Fig. 4 Long-term tectonic loading in and around Tibet [9]. (a) Increase rates of deviatoric stress computed by a plate convergence model with c = 0.6. (b) Spatial variation of steady subduction rates along the India-Eurasia collision boundary. (c) Major active faults and their long-term averaged slip motion.

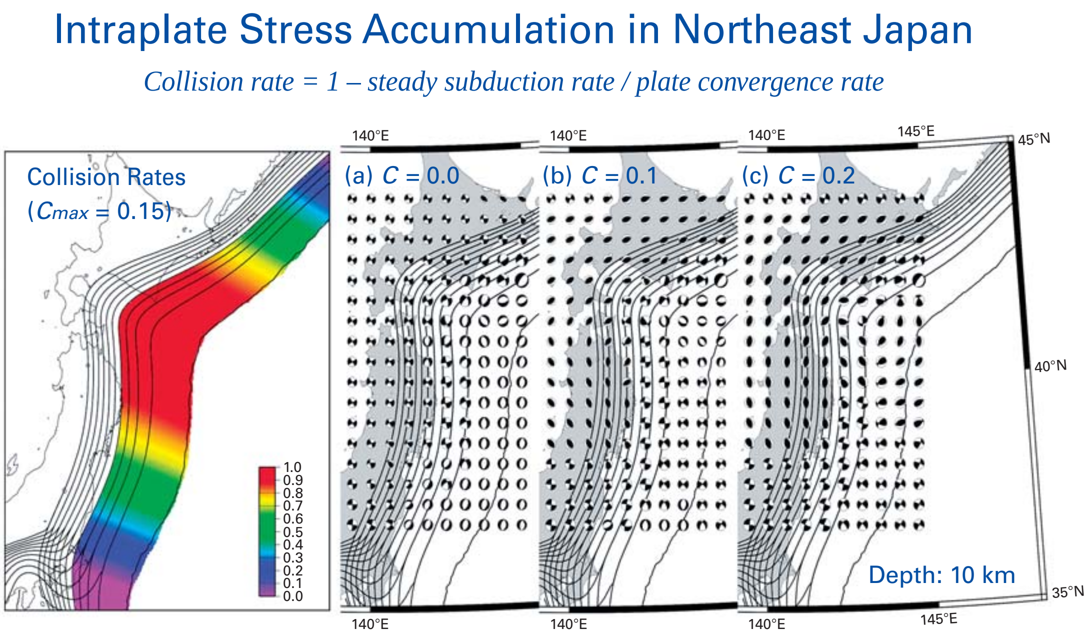

Fig. 5 The increase rates of internal stress produced by partial collision in northeast Japan [10]. Right: The pattern of stress increase rates represented with the upper focal hemispheres (white: compression, black: extension). (a) c = 0.0 (perfect subduction), (b) c = 0.1, and (c) c = 0.2. Left: The collision rates used for computation. The maximum collision rate is taken to be 15%.

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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 - II

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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、プレート運動によって駆動される準静的応力蓄積モデル、3次元曲面断層上の動的破壊伝播モデル、及び地殻活動データの解析・同化ソフトウェアで構成される。平成16年度には、準静的な粘弾性すべり応答計算コードのベクトル化及び並列化を完了し、平成15年度に作成した日本列島域の3次元標準構造モデル(Hashimoto, Fukui & Matsu'ura, PAGEOPH, 2004)に対する粘弾性すべり応答関数の計算を行った。また同時に、準静的応力蓄積モデルのベクトル化及び並列化も行い、平成14年度に完成している動的破壊伝播モデルとシステム結合することで、日本列島域の地殻活動シミュレーションモデルのプロトタイプを構築した(Matsu'ura, Hashimoto & Fukuyama, 4th ACES Workshop, 2004)。

開発した地殻活動シミュレーションモデルを用いて、太平洋プレートと北米プレートの境界で発生した1968年十勝沖地震の震源域における巨大地震の発生予測シミュレーションを試みた。このシミュレーション結果から、震源域に十分な応力が蓄積されていない場合は、何らかの原因で動的不安定破壊(地震)が発生したとしても、それが急激に加速され大地震にまで発展することはないということが分かった。逆に、震源域の応力が臨界状態に達していれば、何かの拍子にトリガーされた動的破壊は急激に加速され、ついには大地震にまで発展してしまう。

インド亜大陸がユーラシア大陸に衝突しているヒマラヤ・チベット地域の地殻変形運動のシミュレーション結果(Takada & Matsu'ura, Tectonophysica, 2004)を参考に、準静的応力蓄積モデルに部分衝突という考え方を取り入れ、東北日本弧を対象としてプレート内活断層地震の原因となる地殻内応力蓄積のシミュレーションを行った(Hashimoto and Matsu'ura, 2005)。このシミュレーション結果から、太平洋プレートの収束運動の約1割が地殻内非弾性変形で解消される(衝突率10％)とすると、第四紀の活断層運動から推定される東北日本弧の地殻内応力の蓄積パターンと蓄積レートを合理的に説明できることが分かった。

キーワード：プレート沈み込み，地震発生サイクル，応力蓄積，部分衝突，予測シミュレーション