Modelling of plate boundaries and intra-arc active fault systems in and around Japanese Islands

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Abstract

To construct a regional crustal model of Japanese Island for an earthquake cycle we need a consistent and detailed model for realistic plate boundaries. Also a crustal deformation due to intra-arc seismicity should be properly modeled. We model plate boundaries from hypocentral distribution data and crustal structure data obtained by seismological study including controlled and passive source studies. A deformation process of the intra-arc crust is modelled as a system of active fault and a detachment fault in the crust. The intra-arc fault system at depth is recently clarified by integrated active and passive seismic source experiments.

Introduction

The Japanese Island Arc is located on the boundaries of Eurasia, North America, and Philippine Sea Planes. Pacific Plate subducts beneath Eurasia Plate from southeast at a speed of about 10 cm per year, and Philippine Sea Plate subducts from south at a rate of 5 cm or less per year. Many large earthquakes occur repeatedly on the plate boundaries among plates. For modeling such earthquakes, we need to construct a realistic 3D plate boundary model in and around Japan ($30° \times 30°$) as a first step. The subducting slab is well documented by seismicity associated with the oceanic plates. The intermediate-to-deep seismicity beneath the Tohoku arc, for example, forms a double-planed seismic zone (Hasegawa et al., 1978[2]). The upper boundary of the subducting Pacific Plate is directly inferred from P-to-S converted waves and estimated to be located slightly above the upper seismicity of the double-planed zone. We, therefor, model the plate boundary based on the distribution of hypocentres of the intermediate-to-deep earthquakes. The shallower extension of the plate boundary smoothly continues to the oceanic trench, where a low angle thrusts, or, detachment faults are imaged by reflection profiles.

The crustal deformation interior of the plates originates from thickening and/or thinning of the crust due to compressional and/or extensional stress regime generated by plate interactions. One main mechanism of the crustal deformation is a low angle thrusting movement in the upper part of the arc crust. We model these deformations by movement of a system of active faults that merge at a depth of the boundary of the upper and lower crust. The boundary corresponds to a transition from brittle to ductile deformation. Our recent studies indicate that many active faults observed at surface in Japan may form a system in which each fault merges at depth and interacts each others (e.g., Sato et al., 1998[4]).

Method

The detailed distribution of the seismicity, however, has considerable irregularities in depth due to both the real undulations of the plate boundary and an apparent irregularity that is caused by clustering of the seismicity. Since we need a model of the plate boundary which generates a regional-scale response of interaction among the plates, we smooth out a local heterogeneity, which may be investigated in later studies, by introducing a roughness criterion on the geometry of the plate boundary. We defined a smooth function which represents a depth of the upper surface of the oceanic plates. We use the smooth function as a superposition of the base functions so that the function well represents the shape of the upper bounds of the seismicity.

We set a model region from longitude 125°E to 155°E, from latitude 20°N to 20°N and from depth 0 km to 100 km, and take x-axis along longitude, y-axis along latitude and z-axis toward depth. Then the plate boundaries is supposed to be described with $z = z(x, y)$ which is superposition of basis functions Ψ_{kl} defined on (x, y)-plane;

$$z(x,y) = \sum_{k=1}^{K} \sum_{l=1}^{L} a_{kl} \Psi_{kl}(x,y) \quad , \tag{1}$$

where we supposed that Ψ_{kl} would line up at equal space Δs. The detailed definition of $\Psi_{kl}(x, y)$ is given in Appendix A.

A trade-off of the spatial resolution of the model surface and the least roughness condition is objectively determined by introducing ABIC criterion. The original idea for the analysis method has been proposed by Yabuki and Matsu'ura (1992)[5]. We define "roughness" based upon the prior information that plate boundary would be smooth without artificially irregularity;

$$r = \int_S \left\{ \left(\frac{\partial^2 z}{\partial x^2} \right)^2 + 2 \left(\frac{\partial^2 z}{\partial x \partial y} \right)^2 + \left(\frac{\partial^2 z}{\partial y^2} \right)^2 \right\} dS \quad . \tag{2}$$

Then we solve numerically to gain model parameters a_{kl} in equation (1) for a data set $\vec{d} = (d_1, \cdots, d_N)^T$ weighting α^2 on the roughness r, equation (2) by analogy with ABIC technique, where data set is the distribution of the seismicity associated with the subducting oceanic plates.

Data

We originally base on the hypocentre distribution determined by ISC. It is uniform over the whole region regardless of less number and accuracy than local data set. First we apply some filtering and/or smoothing treatments on the data. We examined on

Model	Coverage	Δs	Resolution	Num (PHS)	Num (PA)
Coarse	whole	1°	100 km	357	488
Medium	partially	0.25°	25 km	1376	2633
Fine	partially	0.1°	10 km	*9000*	*16000*

Table 1: Three models we have constructed and are constructing now. The third column "Resolution" means the horizontal characteristic wave length which the model can express. The forth and fifth ones refer to the number of basis functions necessary to express the Philippine Sea Plate (PHS) and the Pacific Plate (PA). The fine model is in preparation.

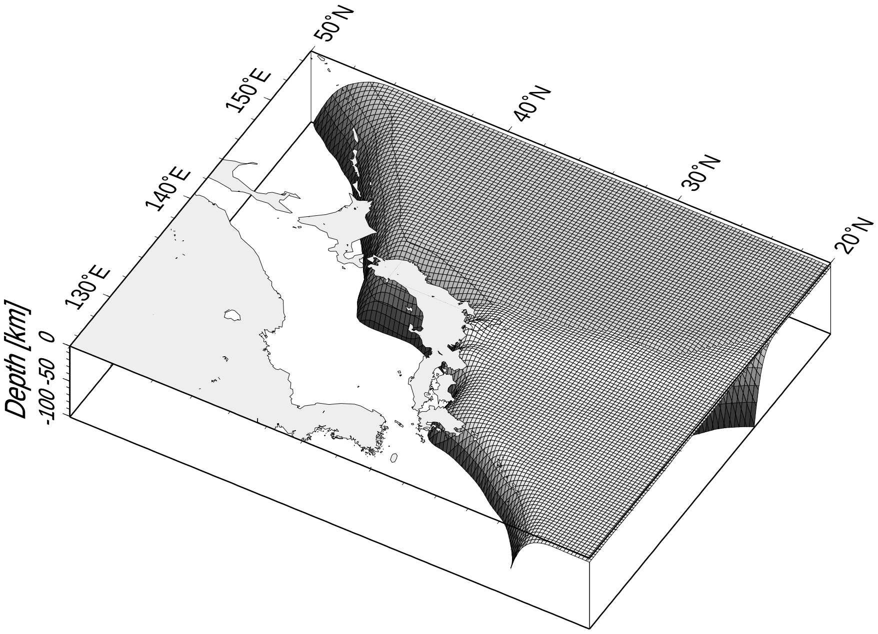

Figure 1: Plate boundary model with coarse resolution. We draw the Philippine Sea Plate only above the depth 60 km.

a lot of cross sections across the trench axes compiling other data sets referred in the report edited by GJI (1994)[1] at the same time, and then approximates the plate boundary as a polynomial of degree 3 using a least square method. From preliminary data analysis, we applied the method in the previous section. Looking for the appropriate value of α^2, we took the solution minimizing the error.

Result

We develop three models with a different resolution length, that is, a distance Δs between two basis functions, 1°, 0.25° and 0.1° (in preparation) listed on Table.1.

Figure.1 shows a coarse model of the plate boundaries in and around Japanese islands. Philippine Sea Plate is subducting beneath the southwest Japan, Pacific

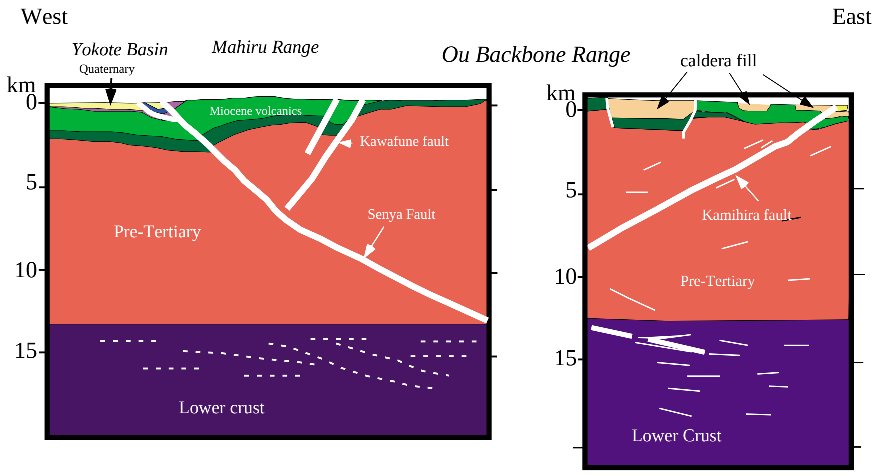

Figure 2: Model of a fault system across the Ou Backbone Range in Tohoku arc, Japan, based on the current results of deep seismic reflection profiles.

Plate is subducting beneath the northeast Japan and Philippine Sea Plate. The geometry of the plate surface is realistic in regional scale, but it still cannot express the complex structure below the Kanto and Tokai region because of coarse resolution. Even the medium model does not represent the realistic structure determined by Ishida (1992)[3]. As the model resolution becomes better, it is difficult to treat the large region at the same time and the convergence is bad producing small scale disturbance because of less data number. We are now constructing a fine model improving the pre-analysis method.

Discussion

We develop a plate geometry model that represents a realistic configuration of plate boundaries. We also need to model a deformation of the crust interior of the plate. In particular, a vertical displacement at surface is controlled by deformation interior of the plate: thickening and thinning of the crust due to compressional or extensional stress regime. An intra-arc deformation is the next target of our modeling study. Recent studies on the island-arc crust enable us to develop a new model of the intra-arc crustal deformation. One possible mechanism of the arc crust deformation is a fault-and-fold deformation of the upper crust. The upper crust can be detached by a low angle thrust from the lower crust in crustal scale. The upper/lower boundary of the crust can be a rheological boundary from brittle to ductile deformation. These rheological structures are partly imaged by a reflection profiling in Japanese Island-arc (e.g., Sato et al., 1996). We should combine a surface information of active faults and deep seismic profiling data to make a consistent deformation model. Some of examples from Tohoku arc is presented in Figure. 2, where a crustal-scale thrusting fault system is modeled based on the 1997-1998 seismic experiment conducted in Tohoku area.

References

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Appendix A: Expression for basis function

We introduce the basis functions in the following;

$$\Psi_{kl}(x,y) = 36\Delta s^2 M_{4,k+2}(x) M_{4,l+2}(y) \quad . \tag{3}$$

$M_{4,j}(s)$ is a B-spline function of order 4 (degree 3) with an equally spaced local support ($s_j - 4\Delta s \leq s < s_j$);

$$\begin{aligned} 24\Delta s^4 M_{4,j+2}(s) \quad = \quad & (s - s_j - 2\Delta s)^3 d(s; s_{j-2}) \\ & -\{3(s-s_j)^3 + 6\Delta s(s-s_j)^2 - 4\Delta s^3\} d(s; s_{j-1}) \\ & +\{3(s-s_j)^3 + 6\Delta s(s-s_j)^2 - 4\Delta s^3\} d(s; s_j) \\ & -(s - s_j - 2\Delta s)^3 d(s; s_{j+1}) \quad , \end{aligned} \tag{4}$$

where $d(s; s_m)$ is a box-car function defined by

$$d(s; s_m) = \begin{cases} 1 & \text{for } s_m \leq s < s_m + \Delta s \\ 0 & \text{otherwise} \end{cases} \quad . \tag{5}$$