

Evaluation of earthquake occurrence from active faults

— Evaluation of rupture probabilities of active faults using the Cascade Earthquake Model based on behavioral segmentation —

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In order to assess the probability of the occurrence of future large earthquakes based upon the past activities of active faults, we divided active faults into behavioral segments, and adopted the Cascade Earthquake Model, that is, a model that considers that an earthquake is sometimes caused by a single segment and sometimes caused by multiple segments. Using this model, we can evaluate the rupture probability of active faults by a uniform standard without any inconsistencies with field data. The result was published as the *Rupture Probability Map of Major Active Faults in Japan*.

Keywords : Active fault, earthquake, assessment, rupture probability, behavioral segment

1 Objective and background of the research

Japan is frequently struck by earthquakes and experiences damages almost every year. Particularly, the earthquakes that are caused by the rupture of active faults occur in the shallow part of the inland region and can cause major damages. Therefore, from the viewpoint of effective earthquake damage prevention, it is extremely important to be able to accurately predict the earthquakes that are caused by active faults. Recently, the survey of active faults has progressed throughout Japan and scores of data have been obtained. However, the predictions based on these data are not sufficient. We conducted this research because we believe that even if the information is not sufficiently accurate, the transmission of information based on the most rational and most uniform method at this point is extremely important, as a researcher and as a research institution whose mission is geological survey.

An “active fault” is a fault that has repeatedly ruptured in the past and possesses possibility of causing a major earthquake in the future. The interval of cyclic rupture is extremely long, normally from a thousand to several tens of thousands of years. Although the slip of a fault in one earthquake may be only a few meters, when the slippages are repeated in the same direction over several thousand or several million years, a displacement of several tens or hundreds of meters may accumulate. As a result, if the displacement is in the vertical direction, the upthrust side becomes a mountain range and the downthrust side becomes a plain or a basin. If the displacement is in a horizontal direction, valleys and peaks become bent. The study of active faults from such geomorphological perspective advanced rapidly in the 1960s to the first half of the 1970s. The background was the

diffusion of the plate tectonics theory that states that the Japanese Archipelago is being compressed as it is pushed by the Pacific Plate. The landforms such as mountain ranges and basins of Japan were created by fault activities. The study of active faults started as an attempt to answer one of the main themes of geomorphology and geology: “Why is a mountain high?” This can be positioned as *Type 1 Basic Research*.

On the other hand, since great earthquakes are caused by the rupture of active faults, the study to predict future earthquake occurrences from the past rupture and their frequency started in the latter half of the 1970s. The method involves digging a trench across an active fault, and the past dates of fault ruptures are investigated from the slippage and the age of the geological layers (Fig. 1). This method is called trench survey, and such investigations were conducted in many places in the 1980s. With the diffusion of trench survey, various data on the past ruptures (past earthquakes) of active faults were accumulated, and they aggregated into a discipline called “paleoseismology.” While conventional seismology concentrates on the observation of current earthquakes, paleoseismology offers possibility of predicting future occurrences of great earthquakes by studying the cycle of ruptures from geological history. In other words, the study of active faults evolved into its utilization by society, or *Type 2 Basic Research*.

The importance of active faults became widely known to the public in the Great Hanshin-Awaji Earthquake (Hyogoken-nanbu Earthquake) of 1995. The fact that this earthquake was caused by the rupture of active faults was widely publicized through the mass media, and the awareness for “active fault” rose sharply in society. Immediately after this earthquake, the Headquarters for Earthquake Research Promotion was

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established by the Japanese government, and the nationwide survey of active faults and the long-term assessment (probability prediction) of active faults were started. In an attempt unseen elsewhere in the world, the scale of the earthquakes that may occur in the next 30, 50, and 100 years and the probability of their occurrences were assessed for each major fault zone (98 fault zones at the time) in Japan, and the figures were publicized. This was one way for the *Product Realization* of the results of active fault research.

2 Relationship of active fault and earthquake scale

In predicting future earthquakes, it is important to predict the scale as well as the place and time of the occurrence. The size of an earthquake is proportional to the length of the active fault that ruptures during the earthquake and the amount of slip. Also, the amount of slip is proportional to the length of the active fault. Therefore, to predict the scale of the earthquake that may happen in the future, it is necessary to estimate the length of the active fault related to that earthquake.

Considering the length of an active fault, it is not easy to judge from what point to where should be considered one fault, since numerous active faults are distributed like a network throughout the Japanese Archipelago. Moreover, according to the surveys so far, there are several geological and geomorphological evidences that indicate that a slip of certain magnitude has been occurring repeatedly at the same interval from the past in a certain point of a certain active fault. However, according to the historical records of earthquakes and careful geological survey, the range of active faults that rupture during earthquakes that occur repeatedly in a region may be different for each earthquake, and the active faults may not necessary rupture within the same range.



Fig. 1 Example of trench investigation of an active fault (Nukumi Fault of the Nobi Fault zone, Ohno City, Fukui Prefecture).

This active fault is known to have ruptured in the Nobi Earthquake in 1891. The bump on the earth surface is the slip that occurred in 1891. Since the lower layer (older layer) show more pronounced horizontal displacement than the top layers, it can be seen that the slippage of the fault accumulated repeatedly.

In the Nobi Earthquake (magnitude 8.0) that occurred in 1891, the Nobi Fault System that crossed the Gifu and Fukui Prefectures ruptured, and a slip of about 6 m high occurred in Midori, Neo-mura (current Motosu City) located in the center of the fault zone. From the distribution form of the fault, it is determined that this fault zone is composed of the Nukumi Fault, Neodani Fault, Umehara Fault, and other smaller active faults (Fig. 2). It is recorded that during the earthquake of 1891, the western half of the Nukumi Fault, Neodani Fault, and Umehara Fault ruptured together and caused a slip in the earth surface^[1]. However, looking at the past ruptures of this fault, it was found that the past rupture periods of Nukumi, Neodani, and Umehara faults differed^{[2][3]}. This means that in certain periods in the past, the Nukumi and Neodani faults, and the Neodani and Umehara faults did not rupture in unison.

One problem arises. If the ranges of fault destruction when the earthquake occurs (i.e. length of the fault) are different, the amount of slip at a certain point should be different each time because the length and the amount of slip are proportional. Moreover, since the rate of an average slip of a fault (average rate of displacement) is thought to be constant over a long term, if the amount of slip differs every time, the rupture interval of the fault (interval of earthquake occurrence) must be different each time accordingly. However, as mentioned earlier, from the geomorphological and geological studies, it has been concluded that the amount of slip did not change greatly in the past except in certain points. If the amount of slip and the rupture interval of the faults differ for each earthquake, the cyclic nature of active fault rupture mentioned earlier will be negated and future prediction of earthquake occurrence becomes impossible.

The author and others looked at the Cascade Earthquake Model as a model that offers rational explanation without

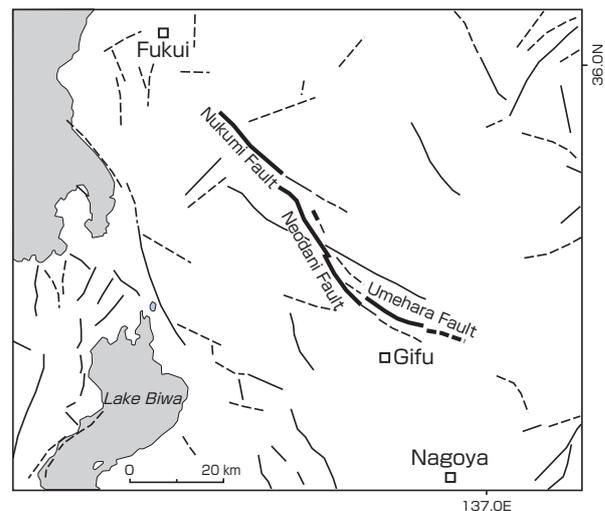


Fig. 2 The Nobi Fault zone and the distribution of surrounding active faults.

The heavy lines show the faults that ruptured in the Nobi Earthquake of 1891. Dashed lines are inferred faults.

inconsistencies. This model was employed for the active faults in California, U.S.A. as an earthquake model for a very long active fault running several hundred kilometers^[4]. In this model, a continuous active fault is divided into several behavioral segments that have their own unique amount of slip and rupture intervals^[5]. These segments rupture while maintaining their unique cycles and sometimes in conjunction with the neighboring segments.

The greatest characteristic of the Cascade Earthquake Model is that the length of the segment can be fixed regardless of the range value of fault rupture, by considering the large-scale fault rupture as a co-movement of the behavioral segments. By doing so, the earthquake time-varying position at a certain point can be kept constant while maintaining the proportional relationships of the fault length, the amount of displacement by earthquake, and the earthquake size. Therefore, the cyclic nature of fault rupture at a certain point can be explained extremely easily. We decided to employ the Cascade Earthquake Model as the most realistic model at this point, to achieve predictions utilizing the geomorphological and geological research results.

The schematic diagram of the Cascade Earthquake Model is shown in Fig. 3. Conventionally, active faults were given the name "X Fault" from their geographical distribution without any particular criterion. However, since the range that was given a name may not necessarily cause the next earthquake, it is impossible to estimate the earthquake scale from the length of that fault. Therefore, these active faults were categorized into behavioral segments (here four categories from A to D) as "units" that may cause earthquakes, with certain criteria such as past rupture history and distribution, regardless of the conventional fault names. By thinking that an earthquake occurs when these segments rupture individually or in conjunction with the neighboring segments, the size of the earthquake can be predicted from the length of the individual fault (behavioral segment) and its co-movement relationship with the neighboring segments.

To apply this model to the small-scale and complex faults of Japan, the data of earthquake faults with records of rupture were listed, and we prepared a trial plan for the relationship of earthquake scale and criterion for behavioral segment category^[6]. Using the Kinki area as an example, the probability of future earthquake occurrence for each

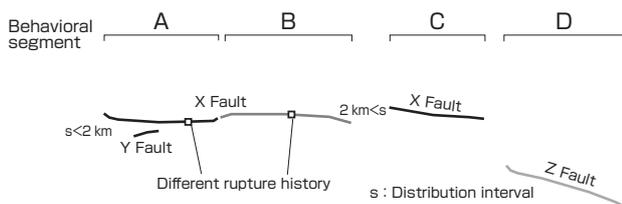


Fig. 3 Schematic diagram of the behavioral segment categories.

behavioral segment was calculated and publicized^[7]. Although this calculation was only a result of one research, it was meaningful as an assessment obtained by logical deduction based on a model.

3 Publication of the *Rupture Probability Map of Major Active Faults in Japan*

To develop this research further and to actually make it useful in society to reduce the risk of earthquake damage, it was necessary to apply this model on a national scale. Therefore, the author and others started to compile the *Rupture Probability Map of Major Active Faults in Japan*^[8].

The criteria for categorizing the behavioral segments are summarized in Fig. 4. The behavioral segments were categorized according to this criterion based on the distribution map of active faults. When covering all active faults in Japan, it was inevitable that some active faults were surveyed heavily and had plenty of data while others had hardly any specific data. In our map, we placed emphasis on obtaining uniform values for the entire country. Therefore, even in cases where no data was available, some assessment was obtained using provisional and empirical values rather than labeling them "unknown." By placing priority on national coverage, we aimed for the *Product Realization* in

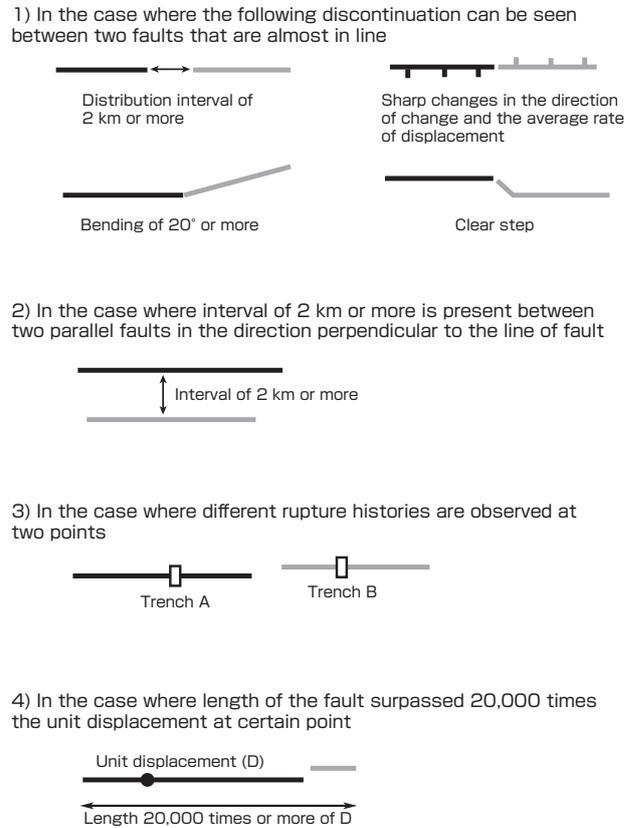


Fig. 4 Criteria for categorizing the behavioral segments used in the *Rupture Probability Map of Major Active Faults in Japan*.

this *Full Research*.

We assessed the active faults that were 20 km or more throughout Japan, and 547 behavioral segments were categorized. Of these, the parameters such as average displacement rate, amount of slip in an earthquake, and past rupture periods were estimated based on existing data for 295 behavioral segments that were 10 km or more long and had some degree of rupture level, and their future rupture probabilities were calculated. The behavioral segments grouped by color according to the rupture probability were plotted on the map of Japan (Fig. 5).

The *Rupture Probability Map of Major Active Faults in Japan* was published by the Geological Survey of Japan, AIST in September 2005. This map enabled comparison of the active faults under a uniform criterion for the entire country, although there were variations in confidence due to the fineness of data by region. As comparison became possible under a uniform criterion for the whole of Japan, it has been used for risk assessment by the insurance industry and by the regional infrastructure planners. By indicating the assessment criterion for individual behavioral segments, it could be used by users who need assessment based on different standards.

This assessment, of course, is a research result of a single

research institution, and therefore is simply one prototype. It is distinctly different in character from the long-term assessment of the Headquarters for Earthquake Research Promotion of the government, which is based on an official standard determined by a committee. Therefore, the figures shown differ greatly in some places, and some people have voiced concerns that this may cause confusion in society. Also, since the results are based on estimated values using provisional and empirical values, many researchers (particularly those of geomorphology and geology) who place importance on individual data commented that faults with insufficient data should not be assessed.

However, considering the difficulty of assessing the actual earthquake occurrence, it is natural that various assessment results exist, and we thought it was important to present figures as one of the assessment results.

As a result, the *Rupture Probability Map of Major Active Faults in Japan* obtained a certain degree of acclaim from the insurance industry, and we received several inquiries about using this assessment as basic data. It can be said that it is having some social impact.

4 Limitation of prediction and future issues

Although the *Rupture Probability Map of Major Active*

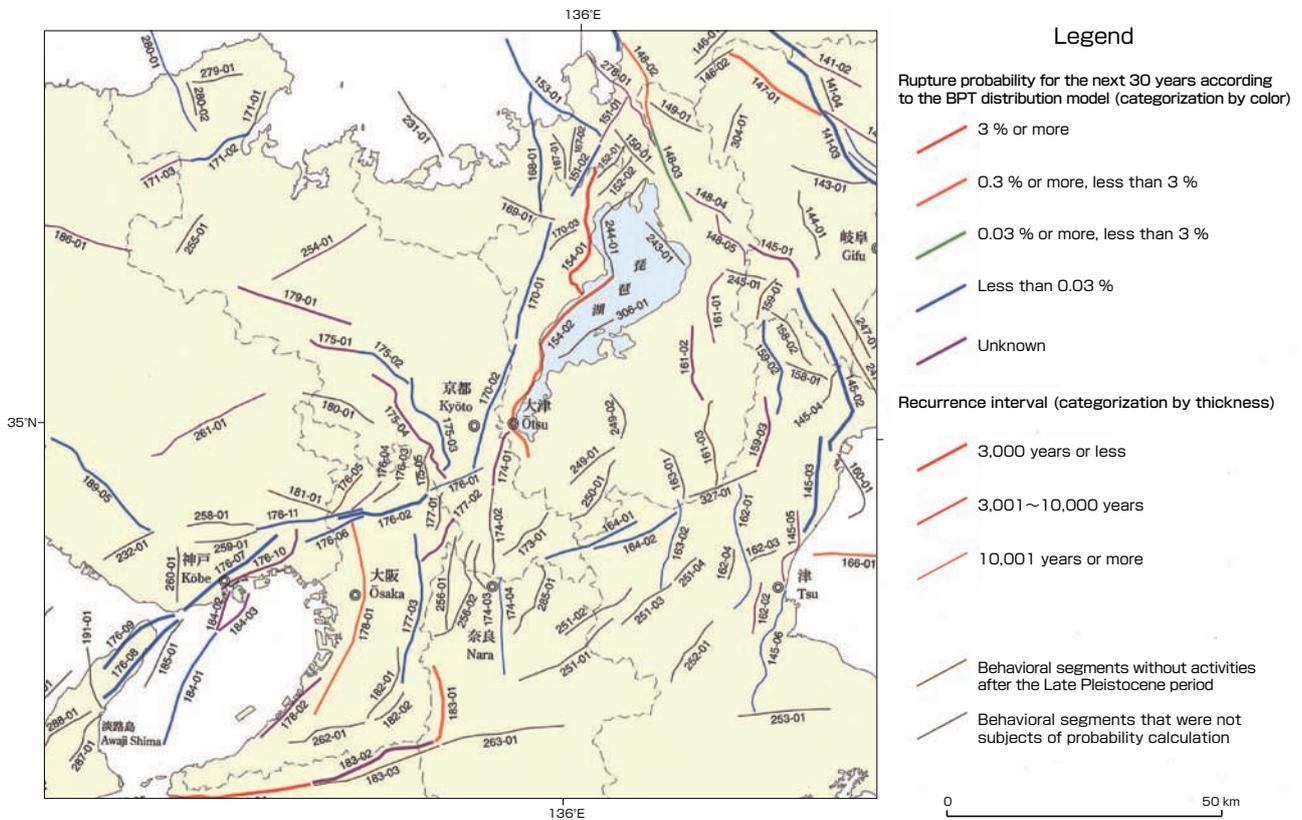


Fig. 5 Rupture Probability Map of Major Active Faults in Japan^[8] (close up of the Kinki area).

The numbers show the behavioral segment numbers.

Faults in Japan was innovative as a nationwide assessment based on a uniform model, the assessment of co-movement among the behavioral segments was difficult, and we were unable to directly predict the scale of earthquakes that may occur in the future. Research is being continued in this aspect, but determining whether two behavioral segments ruptured at the same time in the past earthquake, or whether they ruptured with some time lag, are beyond the time resolution of geological survey. This is the limitation of this method. To solve this issue, another group in the Geological Survey is gathering the historical record of the earthquake that occurred recently and analyzing the relationship between the distribution form of faults and the propagation of ruptures using the numerical simulation of dynamic rupture^[9].

Looking at some recent earthquakes that caused damage, there are cases where no major slip occurred in the active fault although the earthquake occurred along the active fault, as in the Mid-Niigata Prefecture Earthquake in 2004 (magnitude 6.8), as well as the case of Iwate-Miyagi Nairiku Earthquake in 2008, where no clear active fault was previously found although the earthquake of magnitude 7.2 occurred. Such earthquakes could not be predicted with the conventional assessment method.

Moreover, as a result of detailed survey of the active faults throughout Japan, there are data that show that the past rupture intervals of the active faults are not necessarily constant in some points. Although there are possibilities that there are flaws in the surveyed data or exceptions due to the uniqueness of the survey point, it will be necessary to review the model from the basic periodicity of the active fault ruptures.

However, the purpose may be defeated if the model becomes complicated in order to offer explanation to exceptional cases like the Iwate-Miyagi Nairiku Earthquake of 2008, and evaluation becomes impossible for the faults that do not have sufficient data for such a complicated model. Exceptions are inevitable in natural phenomena, and it is extremely important to discern what is an exception. Time range of several thousands and several tens of thousands of years is necessary to investigate the long-term prediction of earthquake occurrence, and the future issue is to build a model that is simple and universal because verification is virtually impossible.

5 Conclusion

The prediction of earthquakes that occur at active faults advanced dramatically in the past 10 years. However, we often feel the gap with what the society demands. For example, when an unpredicted earthquake occurs, society will not accept the explanation “this earthquake was unique and exceptional.” In that sense, the degree of achievement of

this study is low. Another issue is that the Japanese society tends to demand an *osumitsuki* or official endorsement that may lead to blaming the government, and therefore the government tends to publicize only things that are absolutely certain.

The author feels that our social responsibility is to organize the intellectual foundation that can be used to prepare against earthquakes, by presenting the prediction of active fault ruptures as accurately and as comprehensively as possible to society. Although presenting the information with sufficient accuracy or complete comprehensiveness cannot be realized immediately, I believe that the publication of the results on a nationwide scale is significant as the first step. Whether this research methodology was effective or not will be evaluated by how the society responds.

Acknowledgements

This research is a continuation of the “Research on the Assessment for the Potential of Earthquake Occurrence by Observing Active Faults and others (FY 1994~1999),” a special research of the Agency of Industrial Science and Technology conducted at the Geological Survey, which was one of the predecessors of AIST, as well as earlier researches. The research evolved through repeated researches and discussions of numerous researchers during that time. I am grateful to all people involved, and shall emphasize that this research is the result of the collaboration with many people including my joint researcher Dr. Yasuo Awata.

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Completed the master's course in geography at the Graduate School of Science, Tokyo Metropolitan University in 1986. Joined the Geological Survey of Japan, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in 1986. Obtained doctorate (Science) at Kobe University in 1995. Worked as Senior Researcher of Active Fault Research Center, AIST in 2001; Head of Active Fault Information Research Team in 2002; and Head of Active Fault Survey Team in 2004. Goes out in the field for geomorphological and geological survey of active faults, and has worked steadily on the prediction of future earthquakes from the survey results. Wrote and published the *Rupture Probability Map of Major Active Faults in Japan* in 2005 as the main author.



Discussion with Reviewers

1 The positioning as *Full Research* and descriptions in reference to “synthesiology”

Question and comment (Masaaki Mochimaru, Digital Human Research Center, AIST)

The positioning as *Full Research* is clearly stated in “1 Objective and background of the research.” The active fault research as a study in geomorphology and geology is *Type 1 Basic Research*, while the following active fault research for earthquake prediction is *Type 2 Basic Research*. The categorization of the active faults into behavioral segments using the Cascade Earthquake Model provided a breakthrough, and investigations were done for the Kinki region. Up to this point can be considered as *Type 2 Basic Research*. The survey was conducted nationwide and the results were published and presented to society. This can be positioned as *Product Realization Research*.

However, as an academic journal, *Synthesiology*, we would like you to describe, with scientific eyes, the researcher's dream of “what kind of society you wish to realize,” “why you selected”

the methods that lead to practical application of basic research to achieve the dream, and whether the selected method was “effective or not” in achieving the goal. The aim of *Synthesiology* is to build the “science of synthesis” by collecting the case studies of *Full Research*. Rather than just being a collection of papers, it is important that the individual papers are written with “synthesiology” in mind.

Question and comment (Shigeko Togashi, Evaluation Division, AIST)

I recommend this paper for publication in *Synthesiology* because it practices *Full Research* by conducting rupture probability prediction as *Type 2 Basic Research* based on the geological research of active faults and by contributing to society through the publication of results that may mitigate earthquake hazards. However, there is a lack of enough explanation, which will be indicated in Discussion 2, and there are points that should be added from the *Synthesiology* perspective. Please give the definitions of the terms such as active fault, fault, and earthquake-generating fault that were mentioned in the paper.

Answer (Toshikazu Yoshioka)

I added the description on the significance of this research for preventing earthquake disaster in the introduction of the paper. Also, I added the author's thoughts in the conclusion as follows.

“The author feels that our social responsibility is to organize the intellectual foundation that can be used to prepare against earthquakes, by presenting the prediction of active fault ruptures as accurately and as comprehensively as possible to society. Although presenting the information with sufficient accuracy or complete comprehensiveness cannot be realized immediately, I believe that the publication of the results on a nationwide scale is significant as the first step. Whether this research methodology was effective or not will be evaluated by how the society responds.”

The word “active fault” is used widely in general, and its definition may differ according to people and situations. Therefore, I added a clear definition. The terms like earthquake-generating faults were deleted to avoid confusion.

2 Selection of the research method and verification of its efficacy

Question and comment (Masaaki Mochimaru)

Please describe the selection of the research method and the verification of its efficacy as scientifically as possible. There are two points in this paper that are important in terms of synthesis. One is the application of Cascade Earthquake Model, and second is the nationwide survey and publication. For example, for the Cascade Earthquake Model, why did you consider using this model? Were there other models that could be used? Those are the important points in terms of synthesis. Of course, verification of the application of the Cascade Earthquake Model is also important.

Similarly, what were the reasons for selecting the method of nationwide survey and publication? Were there any other methods? What social effects did you expect by widening the area from Kinki to all of Japan? What was the effect? Were there any academic byproducts? Why did you focus on the data from a single research institute rather than obtaining consensus through a committee? What “merits” did that method bring?, and so on. It will also be good if you summarize how much of the goal (dream) you initially set was achieved, what were the limits, and how you would overcome them.

Question and comment (Shigeko Togashi)

Please describe the principle of the Cascade Earthquake Model simply, and explain specifically why you selected this model, how it was developed into a numerical simulation, and the relationship to other models.

For the limit of prediction, it is true that the accuracy of

prediction using other models had not met the demand of society, but in long-terms, the researches that address the mechanism of earthquakes are mandatory to increase the accuracy of prediction. Please state the relationship to these models objectively.

On the other hand, for the issue of contributing to society through the mitigation of earthquake hazards a simple and general model is very effective, even if it includes the case with low prediction reliability. The author has exemplified it by the publication of the *Rupture Probability Map of Major Active Faults in Japan*. The response of society should be described more clearly as a demonstration of its efficacy.

Answer (Toshikazu Yoshioka)

In the Cascade Earthquake Model, the unique regularity is not taken into account for the co-movement of multiple behavioral segments. They can act together completely randomly. However, we did investigate through numerical simulation assuming that there may be some factor in the co-movement. I added some explanation.

For the numerical simulation of dynamic rupture, the Active Fault Research Center investigated the co-movement of multiple fault rupture by dynamic rupture simulation, where various fault

geometries were assumed. However, in this paper, the emphasis was placed on the use of the Cascade Model to explain the cyclic fault ruptures, and therefore, the description of dynamic rupture simulation was left to a citation of a reference.

The Cascade Model is one of the models for cyclic fault rupture, and this model does not show the rupture process of the seismic center. Therefore, it does not conflict with the dynamic rupture model that shows the fault distribution form and the propagation of rupture using a numerical simulation, the physical model of earthquake occurrence process, or other models based on the observation/analysis of stress around the active fault and the understanding of geological structure. The models can coexist. I added in the text that the research to increase the prediction accuracy should be continued separately.

On the response of society, I added the following description in the text: "As a result, the *Rupture Probability Map of Major Active Faults in Japan* obtained a certain degree of acclaim from the insurance industry, and we received several inquiries about using this assessment as basic data. It can be said that it is having some social impact."