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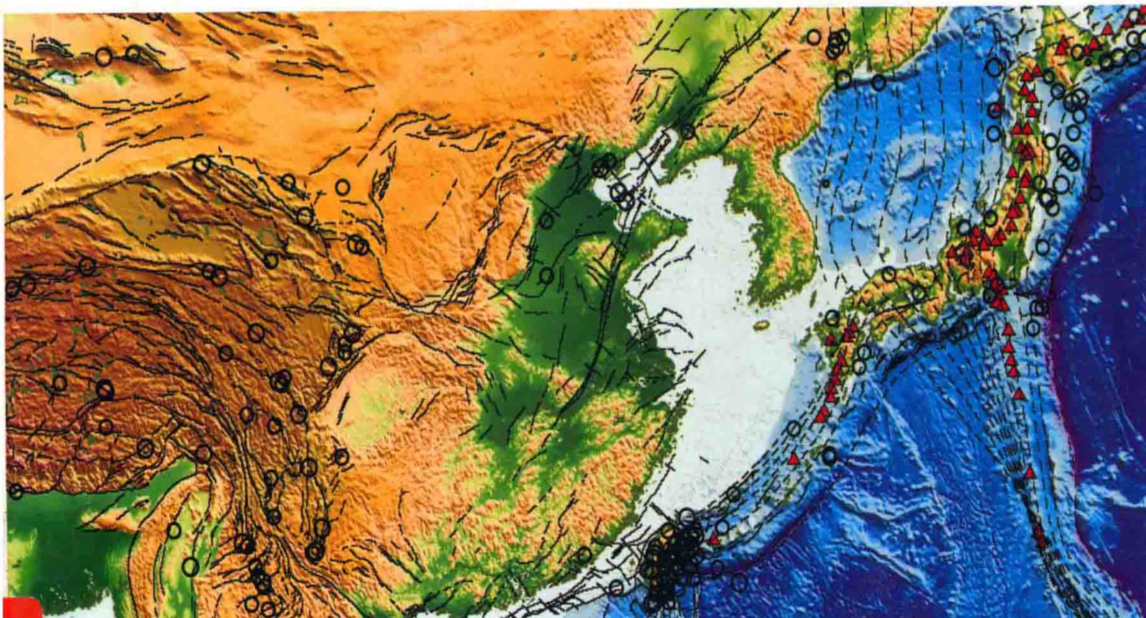

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*Wang Zhi, Huang Runqiu, Wang Xuben, He Zhenhua*



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# Preface

> *In general we look for a new law by the following process: First we guess it. Then we computer the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiments or experience, compare it directly with observation, to see if it works. If it disagrees with experiment it is wrong. In that simple statement is the key to science.*
>
> ***Richard P. Feynman***

*This book presents a generalized summary of the natures of the slab dehydration, arc volcanism, interplate coupling and forearc seismotectonics under the sbuduction zones in the western Pacific island arcs, together with the approaches of offshore earthquake location and the entire-arc tomography. To investigate structural heterogeneities and its implication for genesis of the most geological and geophysical phenomena in the subduction zones, the seismic tomography using arrival time data from local and telesiesmic events has been used. New hypocentral location methods have been developed and then used for relocating the hypocenters of both onshore and offshore earthquakes, which include the utilizations of sP-depth phase, Master-event location method, and the double-difference method.*

*The present book is divided into ten chapters to discuss the correlation between the structural heterogeneities and the genesis mechanisms of the most geological and geophysical processes along the western Pacific island arcs from Hokkaido of Japan to the Taiwan province of China. The three-dimensional P-wave and S-wave velocity structures together with other physical parameters calculated from the corresponding velocity models of the subduction zones, synthesized from a large-quantity of high-quality direct P-wave and S-wave arrival times from the well located onshore events and offshore earthquakes that are relocated by using the developed location methods provide a compelling evidence for a highly hydrated and serpentinized forearc mantle and dehydrated fluids in the mid-to-deep crust and upper mantle that consistent with the thermal and petrological models of subduction zones. The book begins with the introduction and methodology in the first chapter, which emphasizes some new approaches of the offshore earthquake location methodologies and the importance of seismological researches on both onshore and offshore regions in the subduction zones. Each chapter, in general, contains data and method, synthetic test, and discussion subsections. Finally, this book ends with the concluding remarks in chapter ten, in which some new reliable conclusions related to most of the important issues debated by previous studies along the subduction zones have been made based on the present work.*

*Wang Zhi*

*May 4, 2008*

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2007 is the forth year of working on this book and much of it comes from the earlier approaches conducted in Japan and the experience of researches done in China. The manuscript of this book has reached its final form as a result of collaborations with many collogues. Most works on this book would not have been finished without the supports of Profs. D. Zhao (Department of Earth Science, Tohoku University, Japan) and T. Irifune (Director of Geodynamics Research Center, Ehime University, Japan). We thank them for their strong support and constructive suggestions and commentary upon a variety of topics during the progress of the earlier works.

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Wang Zhi

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# *Overview*

*The present book is about the determination and construction of images of physical parameters, such as velocity, Poisson's ratio, crack density, bulk sound velocity and so on, in the crust and upper mantle along the western Pacific island arcs from Hokkaido to the Taiwan province of China. The data, including arrival times and waveforms, used in this book comes from local, regional and teleseismic events. A basic goal of data processing is an image that shows the earth itself, not an image of our data acquisition tracks.*

*Seismic tomography has now established its credential in the domain of investigating deep structure and regimes and regarded as one of the most powerful tools of imaging subduction zones. Because of advancement in seismic tomography with leaps and bounds with regards to both theory and observations by high sensitivity and dense seismographic networks installed at the land areas along the western Pacific island arcs, seismologists have made significant progresses in understanding the structure, magmatism and dynamics of subduction zones in the region. The high seismicity of most subduction zones provide a huge amount of direct and converted seismic phase data for high-resolution three-dimensional seismic tomography, which can delineate the position of the slab-wedge interface, arc magmatism and nature and extent of fluid-related structural heterogeneities in the backarc-arc-forearc regions of the world.*

*Much progress has been made in the last decade in understanding the structures and dynamics of subduction zones along the western Pacific island arcs. Improved data sets and methods have enabled 3-D seismic imaging of subduction zones with great details. The detection and analysis of converted and reflected waves revealed that the upper boundary of the subducting Pacific slab is a sharp seismic discontinuity and the P-wave velocity contrast between the slab and the mantle wedge amounts to 6%. A joint analysis of local and teleseismic data showed that the subducting Pacific slab has a thickness of 85-90 km. Travel time tomography imaged clearly the high-velocity subducting Pacific slab and arc-magma related low-velocity anomalies in the crust and upper mantle wedge under the active arc volcanoes. However, all the above-mentioned studies are confined to the land areas along the western Pacific subdcution zones. The structure under the Pacific Ocean and the Philippine Sea is poorly studied because few seismic stations exist there and so the suboceanic earthquakes are poorly located by the routine procedure of the seismic network on the land areas. However, more large and small earthquakes occurred beneath the surrounding oceanic regions along the subduction zones than those under the land areas. The frequent occurrence of great thrust earthquakes in the arc system under the Pacific Ocean and the Philippine Sea has caused widespread damages to the coastal areas through strong shakings and tsunamis. Information on the detailed structure of the forearc-backarc regions of subduction zones is crucial for our understanding of the initiation of subduction, the interplate seismic coupling and the rupture nucleation of destructive thrust earthquakes. However, such information is very scanty because the forearc regions are generally covered under oceans and so there are few seismic stations available there to record the suboceanic earthquakes. Seismic velocity structure in the forearc region is estimated only along a few* *profiles at shallow depth by using the data recorded by ocean bottom seismometers (OBS) due to that the deployment of OBS stations is an expensive affair because of constraints of spatial coverage and deployment time. Here, we applied 3-D tomography to study the entire-arc regions along the western Pacific subduction zones to better understand most of the geophysical phenomena involved in arc magmatism, interplate coupling, slab dehydration, and forearc seismogenesis because of availability of a large number of the high-quality phase (P, S, Pn, Sn and sP) arrival times from a large number of onshore and offshore earthquakes recorded by the dense seismic networks.*

*In order to accurately relocate the earthquakes occurred in the suboceanic regions of the Pacific Ocean and the Philippine Sea, we developed a combined method (master-event location: MEL) that makes use of the sP depth phase data along with the P-wave and S-wave double-difference arrival times. The method was assessed to be an effective way to determine the precise hypocenters of the offshore earthquakes that occurred outside of the land-based seismic network. The obtained results confirmed the major features delineated by previous studies and revealed some new features of the structural heterogeneity beneath the entire-arc regions of the subduction zones along the western Pacific island arc system.*

*Low-velocity anomalies in the hot mantle wedge of the subduction zones along the western Pacific island arcs are imaged. The low-velocity anomalies are possibly caused by the fluids liberated by the dehydration reaction of the subducting slabs. The depths of dehydration process of the subducted Pacific lithosphere under Northeast Japan and the Kanto district are different from those of the Philippine Sea slab under Southwest Japan and the Taiwan province of China due to the different conditions of the subducting slabs, such as plate age, dipping angle, as well as the temperature and material components of the plate.*

*The cold subducted Pacific plate in Northeast Japan and the warm Philippine Sea lithosphere are imaged as continuous high-velocity anomalies. Strong low-velocity anomalies are distributed extensively along the volcanic front and extend to the back-arc side in the crust and upper mantle along the western Pacific subduction zones. Such low-velocity perturbations are attributed to large quantity of fluids liberated by the dehydration reaction of the subducting slabs. At the shallow depths in the mantle wedge of the subduction zones, fluids related to the serpentinization of the forearc mantle could be released from the subducted Pacific and Philippine Sea slabs. At depths of 70-150 km, the dehydrated fluids mixing with the hot upwelling materials may cause partial melting there due to increasing of temperature and pressure in the mantle wedge. Such melted materials will weaken the seismogenic layer and finally reach to the surface in the arc or back-arc regions to form the volcanoes in these subduction zones. However, the descending Philippine Sea slab that overlies on the subducted Pacific plate has possible influence on the arc volcanism in the Kanto district, Japan. Our study suggests that the Unzen volcanism is produced by the fluids supplied by the dehydration processes of the descending Philippine Sea slab mixing with the hot upwelling materials related to the opening of the Okinawa Trough.*

*Strong lateral heterogeneities are imaged on the upper boundaries of the Pacific and Philippine Sea slabs under the forearc regions, showing a good correlation with the spatial distribution of large interplate earthquakes, i.e., most of the great thrust earthquakes are located at the high-velocity areas or away from the low-velocity zones. These observations indicate that strong coupling sections and weak-coupled or* *decoupled patches might exist along the upper boundaries of the subducting slabs in Northeast Japan, Southwest Japan, Kyushu and the Taiwan province of China. The spatial distribution of the great thrust earthquakes is possibly controlled by the lateral heterogeneities, which is expected to be a common feature for the megathrust earthquakes in the subduction zones.*

*In the back-arc regions of the subduction zones along the western Pacific island arc system, a large number of intraplate earthquakes occurred due to the fluids intrusion associated with the dehydration process of the subducting slabs along with the metamorphism of the lowermost crust, such as the 2004 and 2007 Niigata earthquakes (Mb 6.8) and the 2005 west off Fukuoka prefecture earthquake (M7.0), Japan. Low-velocity and high-Poisson' s ratio anomalies in and/or below the main-shocks are revealed by using the double-difference location method with the utilization of a large number of arrival times. The determined seismic velocity and Poisson' s ratio structures suggest that the generating mechanisms of them are closely related to the fluids associated with the dehydration reaction of the subducting slabs. Such fluids might have reduced the seismic velocity of the crustal materials around the mainshock hypocenter and weakened the mechanic strength of the fractured rock matrix in the source areas, and thus triggered the crustal earthquakes.*

*Seismic structure together with the crack parameters suggest that the generating mechanism of the low frequency tremors (LFT) in the Nankai subduction zone, Southwest Japan, is attributed to the dehydrated fluids associated with the serpentinization of the forearc mantle at the temperature of 350-500°C. Low-Vp, low-Vs, high-Poisson' s ratio, high-crack density, high-saturation rate and low-porosity lateral zones are clearly imaged at depths of 25-45 km along the LFT belt, which suggests the existence of fluids liberated by the dehydration process associated with the descended Philippine Sea plate. The velocity, Poisson' s ratio, crack-density and saturation-rate structures together with spatial distribution of the tremors demonstrate that the source region of the tremors corresponds to a distinct zone that is close to the triple boundaries of the lowermost crust, mantle wedge, and the subducting Philippine Sea slab. The tremors may be caused by the dehydrated fluids migrating in the faults and/or by crack opening, closing and extending along the surface of the subducting Philippine slab below the down-dip limit depth of the thrust zone due to the high pore fluid-pressure and high-crack density under the forearc region of the Nankai subduction zone.*

*For the first time a combined data set that are recorded by three seismographic networks simultaneously including the stations installed by the Taiwan province of China, Japan and China was used, which enables us to determine the high-resolution P-wave velocity structure in the crust and upper mantle under the entire-arc system. A high-velocity zone is imaged clearly at depths of 50-300 km along the Ryukyu Arc system from South Kyushu to North Taiwan of China, showing good agreement with the spatial distribution of the seismicity under the subduction zone. The relative residuals from different quadrants also exhibit early relative arrivals at the stations corresponding to the high-Vp regions, we, thus, interpret the high-Vp zone as the subducting PHS slab. Along the volcanic front from South Kyushu to North Taiwan of China, low-Vp areas are visible, which are mainly caused by the fluids liberated by the extensive dehydration process of the subducting PHS slab. Such a fluid-related low-velocity zone is located at depths of 20-120 km along the arc with a total length of 1200 km from North Taiwan of China to*

*South Kyushu. We also calculated the gradient images, independent of the selection of reference model or color scale, using the inverted P-wave velocity model, providing further information for us to understand and explain the tomographic structures. Three sub-blocks of the Ryukyu Arc system are revealed from the inverted velocity images and the calculated gradient maps. Those features of the velocity anomalies together with other parameters determined by the present study suggest that the Okinawa Trough extension, arc magmatism and seismicity are mainly attributed to the dehydration process associated with the PHS slab subducting and the oblique subduction of the plate.*

*A tomographic image of the crust and upper mantle beneath the Taiwan province of China revealed a high-velocity zone with a thickness of 65-80 km and subducted down to a maximum depth of 300 km under South Taiwan of China, whilst it has not been observed beneath North Taiwan of China. We interpret this high-velocity zone to be the subducted Eurasian lithosphere, which is different from a global tomograpy study that shows the Eurasian plate subducts beneath most part of the island of Taiwan province down to 670 km depth. A consequence of this down-going model of the Eurasian lithosphere supports the proposed models of arc-continent collision and skinned collision. Our results also indicate that the Philippine Sea slab is underthrust northwestward from the Ryukyu Trench down to a depth of 200 km, showing good agreement with the previous seismic, geochemical and geophysical studies. The plate convergence of the Eurasian plate varies from subduction beneath South Taiwan of China to collision with the Philippine Sea slab under North Taiwan of China. These observations suggested that the subducted Eurasian lithosphere colliding with the Philippine Sea slab would have contributed to the mountain building, active seismicity and crustal deformation in the study region due to the lower part of the Eurasian continental plate subducted beneath South Taiwan of China while the upper part of the plate being deformed.*

# *Contents*

# Chapter 1
# General Introduction and Methodology

## 1.1 Purposes of this work

The subduction zones along the western Pacific Ocean and the Philippine Sea in the margins of East Asia are the sites of important processes associated with the subducting Pacific slab under the Japan islands and the subducted Philippine Sea plate under the regions of Southwest Japan, the Okinawa Trough, and Taiwan, including interplate coupling, arc magmatism, backarc spreading, slab dehydration, occurrence of large interplate and intraplate earthquakes, along with mountain building and sepentinization of the forearc mantle. The Pacific slab subducts into the mantle Northwestward (NWW) with a dipping angle of about 30° and at a rate of 10 cm/yr from the Japan-Kuril Trenches (Figure 1-1). The Philippine Sea plate is under-thrusting NWW beneath the Eurasian plate from the Nankai Trough at a rate of 2-4 cm/yr (Seno, 1977), and overlying on the subducted Pacific plate. Figure 1-2 shows three-dimensional distribution of the subducted Pacific plate and the Philippine Sea plate. The tectonic background together with the seismic activity and active volcanism demonstrate an urgent need for a better understanding of the structure heterogeneities under these subduction zones along the western Pacific island arcs (Figure 1-1). Therefore, accurate imaging of seismic velocity structures throughout the entire-arc regions of the western Pacific island arcs will help us understand the geodynamics and seismotectonics there.

Many previous studies have been made to investigate the seismotectonics under these subduction zones (e.g., Hasegawa et al., 1991; Zhao et al., 1992a, 1996, 2002; Seno et al., 2001; Nakajima et al., 2001). However, all of those studies have focused on studying the land areas under the Japan islands. Few detailed offshore studies of the seismic velocity structure have been made for the entire-arc regions, especially for the forearc regions, of the Pacific and Philippine Sea subduction zones due to the difficulties in locating the suboceanic earthquakes accurately.

In the present work, we study the subduction zones along the Western Pacific island arcs from Hokkaido to Taiwan with the following purposes:

1) Relocating suboceanic earthquakes accurately and determining the P- and S-wave velocity structures under the entire-arc regions of the Japan islands.

Detailed 3-D seismic images under the entire-arc regions of the subduction zones are very curial for us to better understand the plate motions, seismicity, slab dehydration and arc magmatism. Accurate locations of the earthquakes occurred in the offshore regions outside the land-based networks in the forearc region are one of the most important factors for the determination of high-resolution velocity structures under the suboceanic regions. For this aim, we first applied a three-dimensional perturbation algorithm (TDPA) to relocate the suboceanic earthquakes accurately using a large number of P-wave, S-wave and sP phases (Wang and Zhao, 2005, 2006a). Then, we extended the double-difference location method and combined it with the use of sP depth phase to relocate a large number of offshore earthquakes in central Japan and in Kyushu. We then determined the seismic structure in the entire-arc regions beneath Northeast Japan (Wang and Zhao, 2005; Wang et al., 2005), Kanto district (Wang and Zhao, 2006a), and Kyushu (Wang and Zhao, 2006b), respectively.

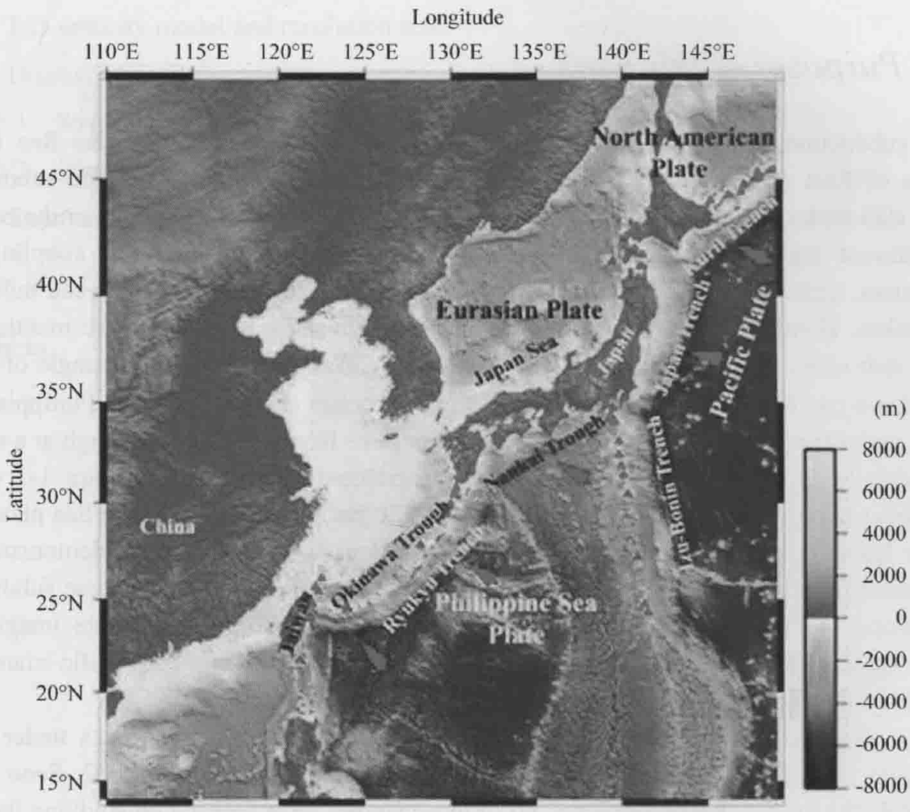


*Figure 1-1. Topographic and index maps showing tectonic framework in and around the subduction zones from Japan to Taiwan along the western Pacific island arcs. The distributions of active and quaternary volcanoes are along the arcs from Hokkaido in Japan to Taiwan. The color scale shows the topography. The Pacific slab subducts into the mantle northwestward (NWW) with a dipping angle of about 30° from the Japan-Kuril Trench. The Philippine Sea plate subducts NWW beneath the Eurasian plate from the Nankai Trough and is overlying the subducted Pacific plate. Arrows show the moving directions of the Pacific plate and Philippine Sea plate.*

2) Investigating the generating mechanism of the arc magmatism along the volcanic front.

The active volcanoes are located on the Northeast and Southwest Japan arcs form two volcanic fronts due to the convergences of the subducting Pacific and Philippine Sea plates under these regions (Figures 1-1 and 1-2). Some previous studies suggested that the arc volcanism in the subduction zones might be attributed to the fluids from the slab dehydration. We then determined 3-D high resolution seismic structures, along with other physical parameters calculated from the corresponding velocity models beneath the Japan islands using a large number of high-quality arrival time data of the P-wave, S-wave and sP depth phases, which enable us to better understand the generating mechanism of the arc volcanism in detail (Wang et al., 2005; Wang and Zhao, 2005, 2006a, b; Wang et al., 2006b, 2008a, b).

3) Understanding the generation mechanism of the large intraplate earthquakes and low-frequency tremors in the subduction zones.

Beneath the Japan islands and the island of Taiwan, a large number of crustal earthquakes occurred frequently, e.g., the 2004 and 2007 Niigata earthquakes (M6.8), the 2005 West off Fukuoka earthquake (M7.0) and the 1999 Taiwan Chi-chi earthquake (M7.9), which caused large damage to the human society because they are very close to the densely populated areas and occurred at the shallow depths (Figure 1-3). The genesis of the main-shocks and their aftershocks might be related to the structure heterogeneities in the crust and uppermost mantle. Therefore, tomographic images could provide evidence supporting our interpretations that these large crustal earthquakes are closely related to the fluids liberated by the dehydration reactions of the subducting slabs in the crust and upper mantle (Wang and Zhao, 2006c, d, Wang et al., 2008c).

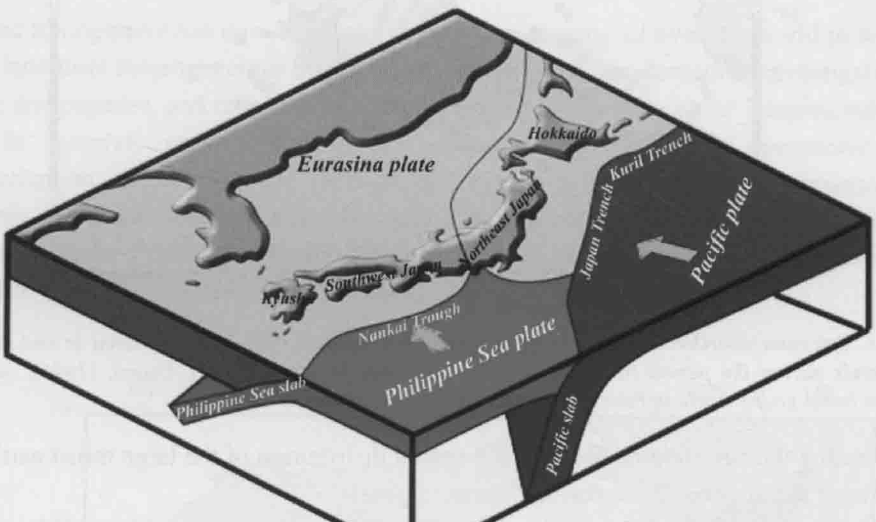


*Figure 1-2. Cartoon showing locations of the subducted Pacific and the Philippine Sea plates under the Japan islands modified from http://nun.nu/www.shobo. city.nagoya.jp/bousai/tokaijishin/philippine.html. The Philippine Sea plate is overlying the subducted Pacific plate under Southwest Japan. Two yellow arrows indicate the moving directions of the Pacific plate and the Philippine Sea plate, respectively.*

On the other hand, low-frequency tremors have been detected at depths of 20-45 km below the seismogenic layer in the Nankai subduction zone (Figure 1-4). However, the generation mechanism of this new seismic phenomenon is unclear. The variations in seismic velocity, Poisson's ratio and crack parameters in the source area of the tremors may reflect physical properties of the lowermost crust and uppermost mantle materials. If the physical properties of materials such as temperature, crack density, as well as the fluids pressure have influenced the tremor genesis, then they are expected to be imaged by the seismic velocity tomography.

Therefore, we determined the 3-D seismic velocity, Poisson's ratio, crack-density and saturation rate structures along the tremor belt to investigate the possible cause of the low-frequency tremors in Southwest Japan (Wang et al., 2006a).

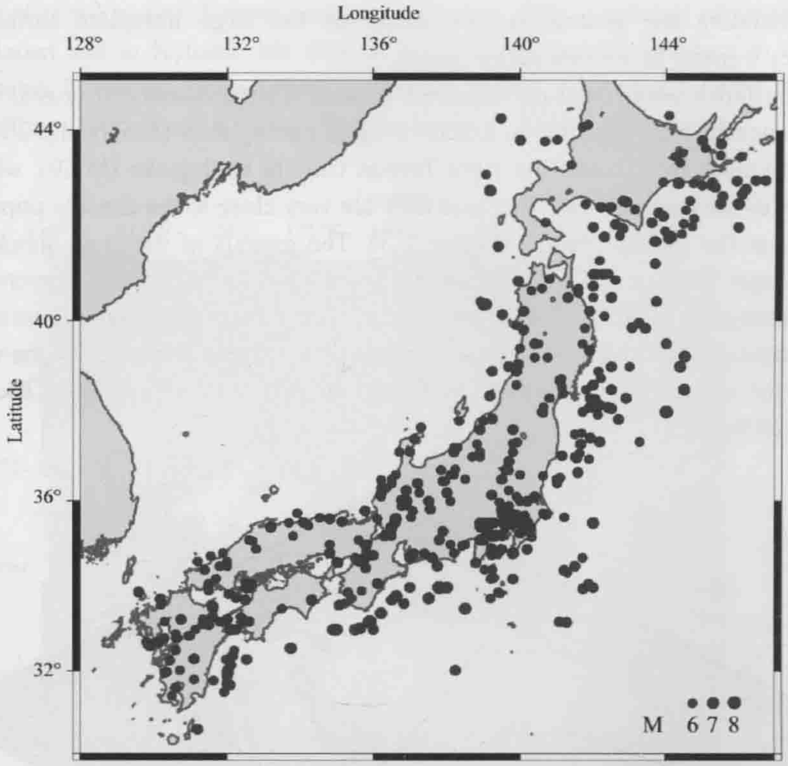


*Figure 1-3. Epicenter distribution of the large historical earthquakes (Mb ⩾6.0) occurred in and around the Japan islands during the period from 830 to 2005 estimated by Utsu, (1999), Usami, (1996), and Hi-net (www.hinet.bosai.go.jp). Scale of the earthquake magnitude is shown at the bottom.*

4) Revealing the correlations between the spatial distribution of the large thrust earthquakes and structural heterogeneities under the forearc regions.

A large number of megathrust earthquakes (Mb>7.5) have reoccurred frequently under the forearc regions along the western Pacific subduction zones from Hokkaido to Taiwan, which has inflicted widespread damage to the coastal areas of the Japan Islands through strong shaking and tsunami (Figure 1-3). The occurrence of the thrust earthquakes could be related to the structure heterogeneities under the forearc regions from the trenches to the coast areas of the Japan islands. However, no detailed seismic structures under the offshore regions around the Japan islands have been conducted for understanding the feature of the large thrust earthquakes. We then determined the seismic structure together with the Poisson's ratio images under the forearc regions of the Japan islands using a large number of offshore earthquakes that are relocated by using sP depth phases and/or by applying a combined method (MEL) for the first time. Our tomography results revealed some new features of the structure heterogeneities beneath the offshore regions, providing new information and evidence to support our interpretation on the genesis of the megathrust earthquakes under the study regions (Wang et al., 2005; Wang and Zhao, 2005, 2006a, b).

5) Investigating the backarc spreading in the subduction zones.

The Okinawa Trough, a backarc basin with rifting still in progress, is located northwest of the Ryukyu Trench (Figure 1-1). The Philippine Sea slab is subducting northwestward beneath the Eurasian plate at a relative rate of ~ 5.5 cm/yr from the Ryukyu Trench. Intensive seismic activity and active crustal deformation are caused by the interaction of these plates in the regional stress field in and around the subdcution zone. The studies of earthquake focal mechanism and fault geometries suggested the existence of localized areas of arc-parallel and arc-perpendicular extensions along the Okinawa Trough (Hirata et al., 1991; Sibuet et al., 1995; Fournier et al., 2001), but it is unclear to what degree of them, if any extension in the crust is coupled to the structural heterogeneities in the upper mantle. We consider that the detailed 3-D seismic velocity structure under this region is useful for us to better understand the original source of the Okinawa Trough extension.

## *1.2 Seismic tomography*

Seismic tomography has now been applied to many regions all over the world to reveal the detailed structural heterogeneities because of its credential in the domain of investigating deep structure and regimes, and regarded as one of the most powerful tools of imaging subduction zones. In general, seismic tomography contains the following operations: model parameterization, ray tracing for calculating travel times and ray paths, inversion, and evaluating the resolution of the obtained tomographic results. In this subsection, a tomographic method developed by the previous studies (Aki and Lee, 1976; Thurber and Aki, 1978; Zhao et al., 1992, 1994) is summarized.

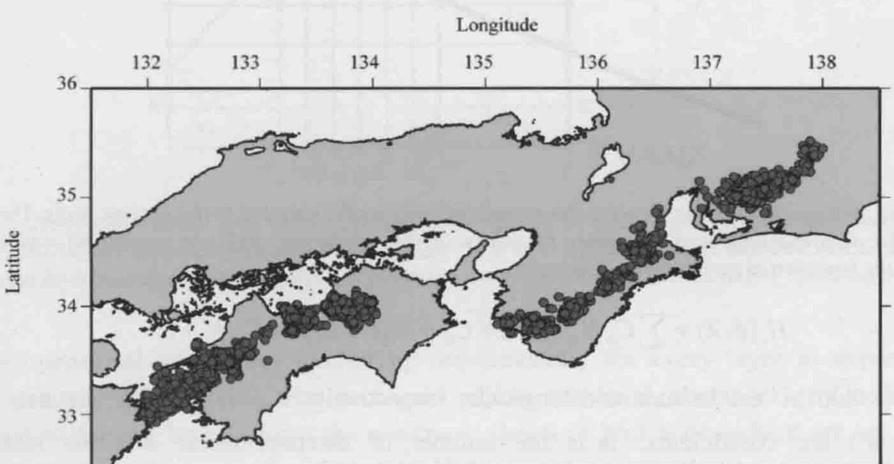


*Figure 1-4. Epicentral distribution of the low frequency tremors (LFT) occurred along the Nankai subduction zone in Southwest Japan during the period from June 2002 to October 2005. The hypocenters of the LFTs are located by Hi-net.*