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Seismic Activities along the Nankai Trough

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Occurrences of large earthquakes with estimated magnitudes as large as 8 along the Nankai Trough have been well documented in historical materials, and the oldest documented earthquake dates back to A.D. 684. The recurrence periods are fairly constant, and are approximately 200 years for the earthquakes occurring before 1361, and about 100 years for those after 1361. However, the number of smaller earthquakes observed by the on-land seismic stations is very small. Both seismic and tectonic couplings along the interface between the overriding and subducting plates are estimated to be nearly 100% from seismic and geodetic data. Therefore, it has been considered that relatively simple physics govern the generation of the historical large earthquakes along the Nankai Trough. With the availability of abundant information on large earthquakes and modern data sets from dense seismic and geodetic networks, the Nankai Trough is one of the best-studied seismogenic zones. Although improvements have been seen in estimating the fault-plane parameters for the historical earthquakes, there still remain important unanswered questions, such as if there have been unidentified earthquakes that fill in the 200-year recurrence period. Estimates of precise fault-plane parameters are being demanded to have a better understanding of earthquake generation. One of the most important topics is where the updip limit of the seismogenic zone is located. The location had not been resolved by on-land seismic observations. Seismic observations using ocean bottom seismometers have recently been conducted in both western and eastern regions along the Nankai Trough. The observations in the western region confirm that the updip limit coincides well with both the updip limit of the estimated fault plane for the 1946 Nankaido earthquake and the estimated 150℃ isotherm along the interplate interface. Earthquake activitiy has been proved to be very low in both regions.

Key words: Nankai Trough seismic activity, seismogenic zone, updip limit, OBS seismic observation

1. Introduction

The Nankai Trough runs off the coast of the southwestern part of Japan, where the Philippine Sea Plate subducts beneath the overriding Eurasian Plate in the northwest direction at a rate of approximately 4.5 cm/yr (Seno *et al.,* 1993) (Fig. 1). Large earthquakes with estimated magnitudes around 8 repeatedly occurred throughout history along the trough, and had caused severe disasters in southwest Japan. These large earthquakes are well documented in historical materials, and it has been known that their recurrence periods are remarkably regular; these are approximately 100 years for earthquakes after an event in 1361, and approximately 200 years for those before 1361 (Fig. 2). The state of tectonic coupling between the overriding Eurasian and subducting Philippine Sea Plates has been studied using data from the dense Global Positioning System (GPS) network covering Japan, and it has been estimated to be nearly 100% over the landward slope of the entire Nankai Trough (complete fault locking) (e.g. Mazzotti *et al.,* 2000). Hyndman *et al.* (1995) proposed a model of a thermally controlled locked zone. According to their hypothesis, the downdip limit of the seismogenic interplate interface coincides with a 350℃ isotherm where common crus-

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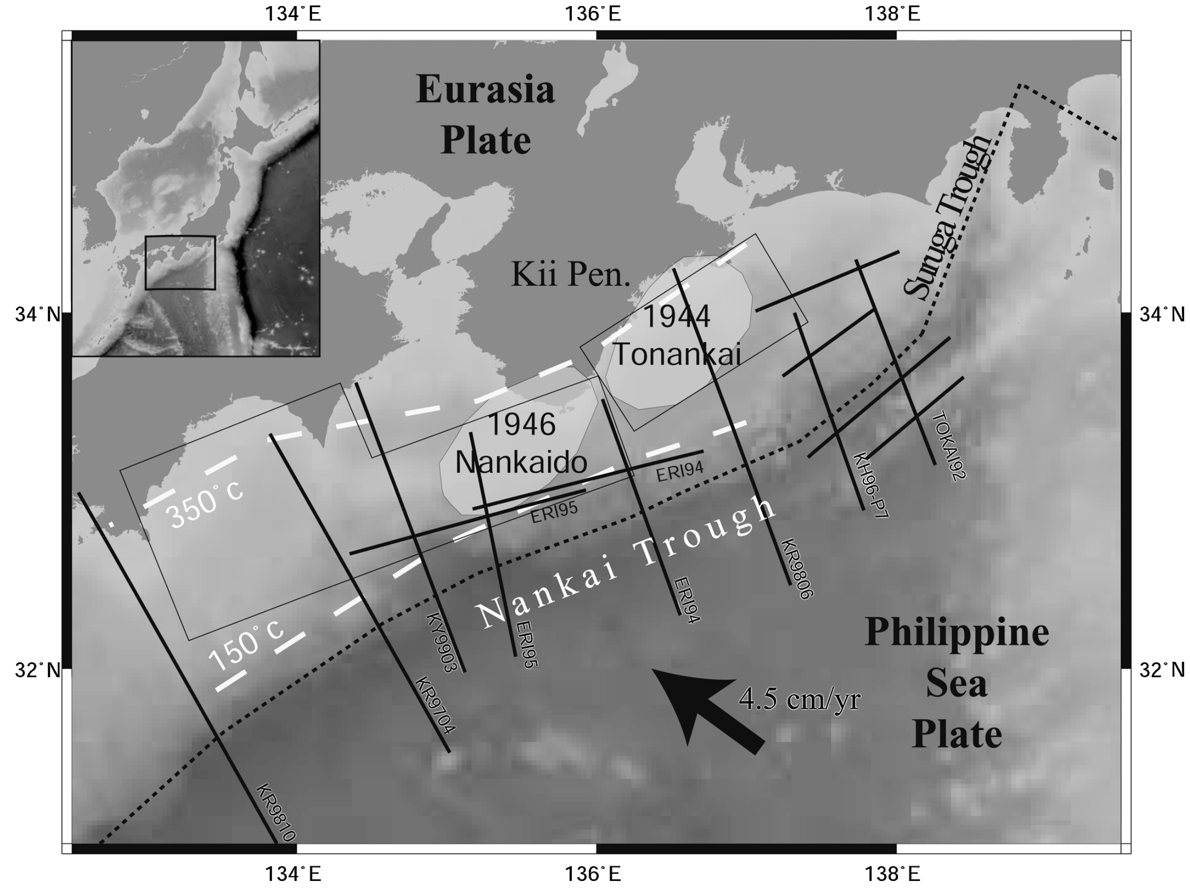

Fig. 1. Location of the Nankai Trough. Solid black thick lines are profiles of seismic surveys. Gray-shaded ellipsoidal regions around the tip of the Kii Peninsula are the regions of aftershocks one day after the corresponding 1944 Tonankai and 1946 Nankaido earthquakes, and the surrounding thin black polygons are fault plane solutions (Ando, 1975). White dashed lines are 150 and 350℃ isotherms estimated by Hyndman *et al.* (1995). A large arrow indicates the direction of subduction of the Philippine Sea Plate at a speed of about 4.5 cm/yr (Seno *et al.,* 1993).

tal rocks show a change in behavior from velocity weakening to stable-sliding velocity hardening. The updip limit corresponds to a temperature of 150℃ where dehydration of stable sliding clays occurs. Locations and dimensions of the tectonically locked zones along the interplate interface determined by the GPS studies agree well in general with that expected from the hypothesis of the thermally controlled locked-zone model introduced by Hyndman *et al.* (1995). Extents of dislocation of both 1944 Tonankai and 1946 Nankaido earthquakes were determined to be about 4 meters on average (e.g. Ando 1975). Taking into account the convergence rate of about 4.5 cm/yr between the Eurasian and Philippine Sea Plates and the interval between recent earthquakes of about 100 years, seismic coupling is also estimated to be nearly 100%. These remarkable regularities of earthquake occurrences and complete tectonic and seismic couplings may imply that relatively simple physics are incorporated in the mechanisms of earthquake generation along the Nankai Trough. With the availability of various data from dense onshore/offshore surveys, as well as well-documented information on large historical earthquakes, the Nankai Trough has been one of the best-studied seismogenic zones, regions of thrust faulting in the shallow part of subduction zones.

Micro-earthquake activities along the Nankai Trough, however, have not been well understood, because the number of micro-earthquakes observed by the onshore seismic networks is quite low compared to the other regions, such as northeast Japan along the Japan Trench. Depths of the observed earthquakes near the trough axis are greater than 20 km, and they are not located near the interplate interface (Fig. 3). This may be because the seismic

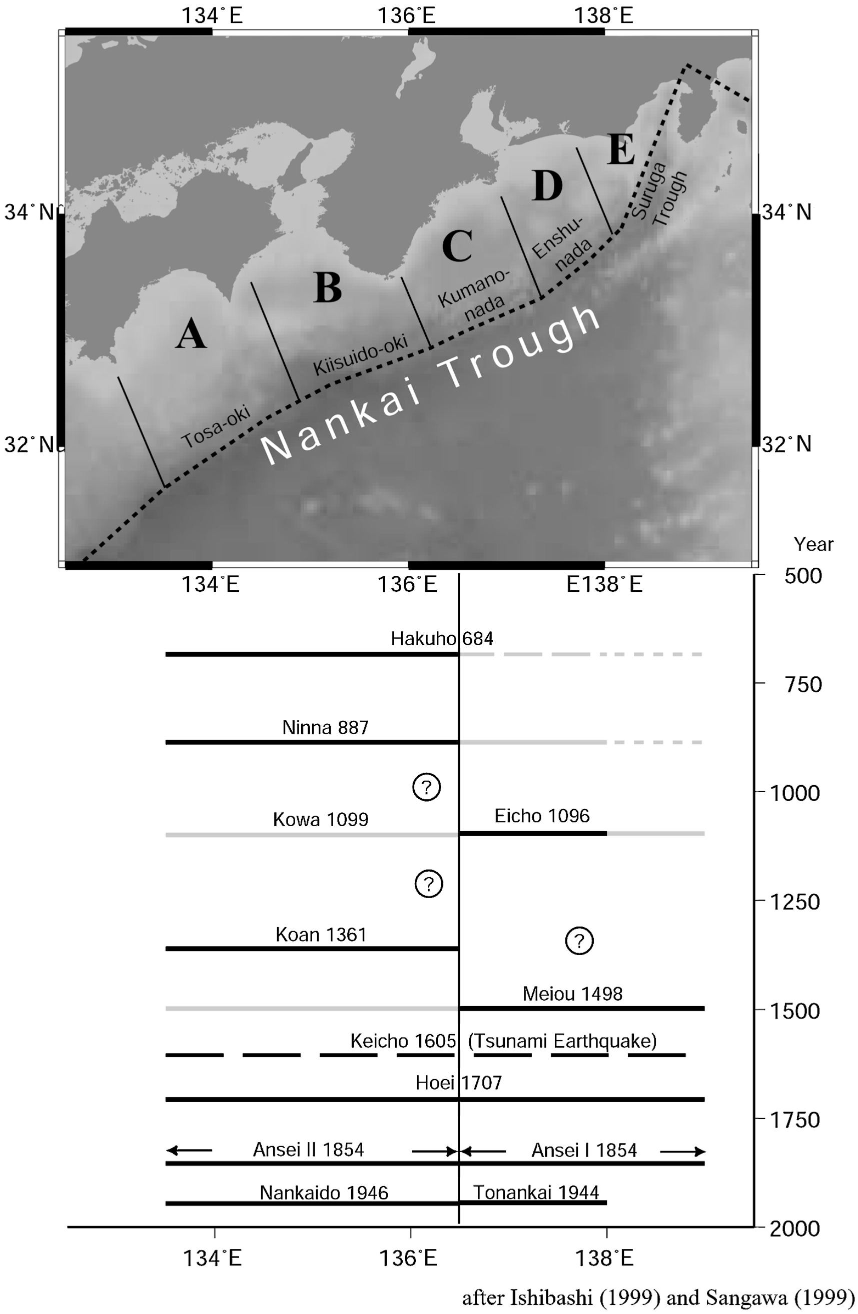

Fig. 2. History of large earthquakes along the Nankai Trough (after Ishibashi, 1999 and Sangawa, 1999). Seismogenic fault planes along the Nankai Trough are divided into five sub-planes (A〜E) based on the fault plane solutions for the 1944 Tonankai and 1946 Nankaido earthquakes (Ando, 1975; Ishibashi 1981). A vertical line in the chronological table shows the location of the most prominent seismic boundary among the sub-planes. Horizontal solid black lines in the table show the most likely regions of fault planes. Thickness of colors represents the probability of fault-plane extensions as dotted gray lines show the least possible fault regions. The 1605 Keicho earthquake shown by a black dashed line is a tsunami earthquake, and has clearly different characteristics from the others. Traces found in excavations of possible but yet unrecognized events are indicated by question marks (Sangawa, 1999).

stations are situated too far away from the activities to observe for their magnitudes, and/or because the activities are in fact very low due to the fact that tectonic coupling between the Eurasian and Philippine Sea Plates is near 100% (complete fault locking), and that most of the accumulated stress is released only by large earthquakes. Understanding micro-earthquake activities may provide direct evidence to

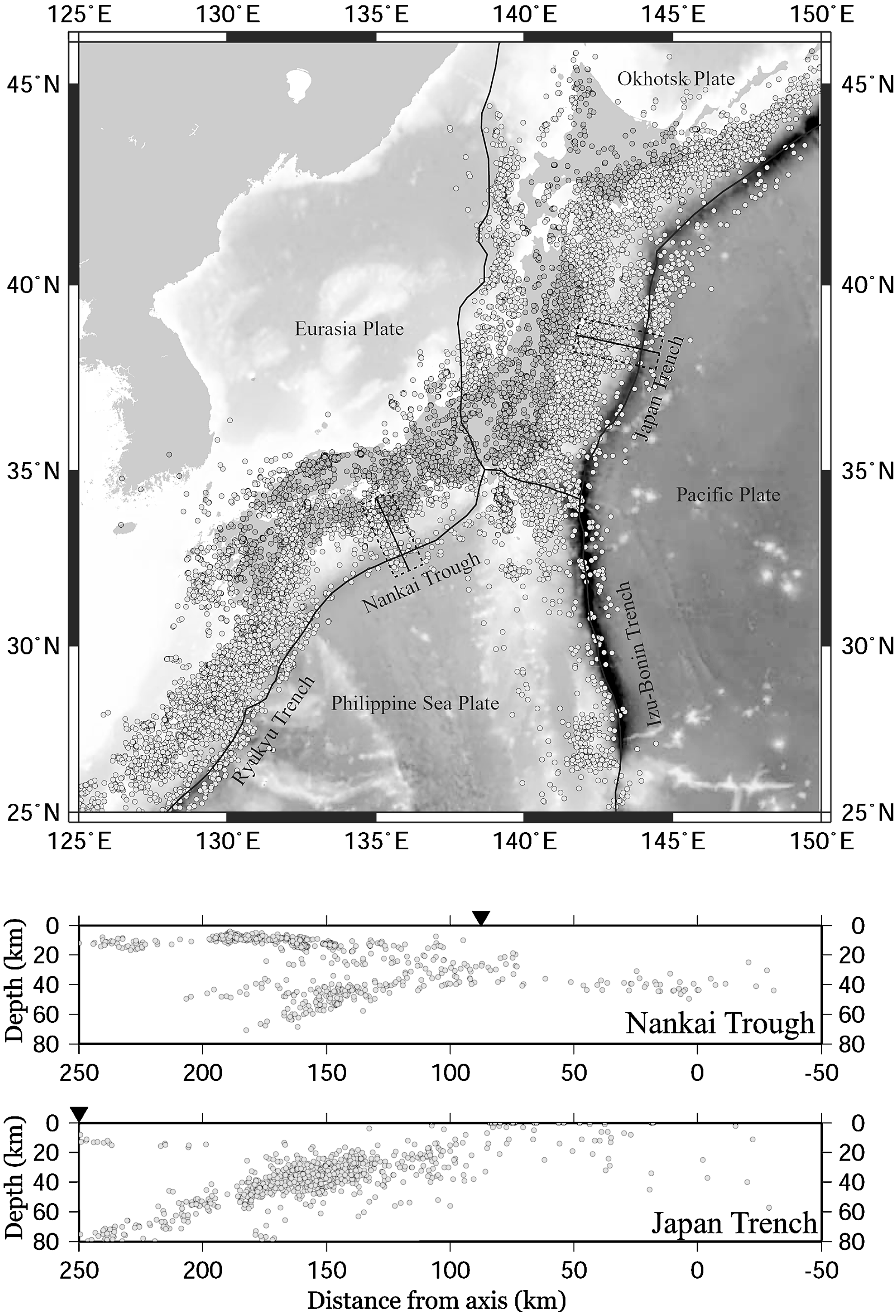

Fig. 3. One-year microearthquake activities around Japan. Gray circles show the epicentral locations of earthquakes occurring from July 31, 2000 through July 31, 2001 determined by Japan Meteorology Agency using data from the on-land seismic stations. Microearthquake activities along the Nankai Trough are significantly low compared to the regions along the Japan Trench or along the Ryuku Trench. The bottom figures show sectional plots of the hypocenters in the areas closed by dashed lines. The distance is measured from the trench axis. Inverted triangles point to projected locations of nearby coastlines. It can be seen that there is no earthquake around the interplate interface for more than 50 km landward from the Nankai Trough axis as opposed to activity along the Japan Trench.

put more constraints on the state of tectonic coupling, and the location of the updip limit of the locked zone.

This paper summarizes seismic activities along the Nankai Trough including the results of recent seismic observations using Ocean Bottom Seismometers (OBSs) off Muroto (Nankai area) and off Omaezaki (Tokai area).

2. Historical earthquakes

Large earthquakes with estimated magnitudes around 8 repeatedly occurred throughout history along the Nankai Trough, and caused severe disasters in southwest Japan. These events are well documented in historical materials, and the oldest event occurred in A.D. 684 (e.g., Ishibashi, 1999).

The most recent large earthquakes were the 1944 Tonankai and 1946 Nankaido earthquakes. Several previous studies determined the fault parameters by analyzing seismic data, geodetic measurements, and tide gauges (Tonankai: Kanamori, 1972; Ando, 1975; Ishibashi, 1981; Nankaido: Fitch and Sholz, 1971; Kanamori, 1972; Ando, 1975, 1982). Kanamori (1972) determined the fault parameters for these earthquakes by analyzing seismic data. The hypocenter locations of the two earthquakes were determined to be only 70 km from each other near Cape Shionomisaki, the tip of the Kii Peninsula. The fault-plane dimensions were estimated from the spread of their aftershocks one day after the main shocks. The fault plane of the 1944 Tonankai earthquake extends to the east, and that of the 1946 Nankaido earthquake extends to the west from their hypocenter locations, and the fault planes seem to be isolated from each other without any overlap (Fig. 1). Consequently, the two earthquakes can be regarded as a pair of earthquakes covering the entire length of the Nankai Trough. Ando (1975) derived fault parameters for three historical large events, in addition to the most recent earthquakes, by fitting geodetic and tsunami data. He divided the Nankai Trough seismogenic zone into four major sub-planes (A～D) according to his source mechanism solutions for the 1944 Tonankai and 1946 Nankaido earthquakes (Fig. 2). Each historical large earthquake was then modeled by assigning a combination of the four fault planes based on the argument that these large historical events belong to the same group of shocks related to Nankai Trough tectonics, and that the source mechanisms of the 1944 and 1946 earthquakes may well be applied to other large historical earthquakes: plane C is assigned for the Tonakai earthquake (1944), A+B for the Nankaido earthquake (1946), A+B for the Ansei II earthquake (1854), C+D for the Ansei I earthquake (1854), and A+B+C+D for the Hoei earthquake (1707). Two earthquakes in 1854 (Ansei I and Ansei II) are also considered to be a pair of earthquakes, besides the 1944 Tonankai and 1946 Nankaido earthquakes. The fault planes of the pair earthquakes are always divided by the boundary between planes B and C. It has been a rule for all of the past earthquakes that the fault planes in the east (planes C+D) slipped first, then a slip in the west (planes A+B) followed by a time separation ranging from days to a couple of years.

The fault plane of the 1946 Nankaido earthquake was divided into two sub-planes (A and B) following Omote's (1948) discovery by analyzing tsunami data that a phase of small and faint disturbances was observed leading the principal tsunami waves. Ando (1975) reconsidered the tsunami data, and argued that the principal tsunami was radiated by a sudden breakage on the seismic fault, which was then followed by slow propagation of the fracture to the west, generating a faint phase of tsunami disturbances. Kanamori (1972) also pointed out that there is a substantial discrepancy between the solutions derived by modeling geodetic data (Fitch and Sholz, 1971) and by modeling seismic data for the fault plane dimensions of the 1946 Nankaido earthquake. In order to explain this discrepancy, he noticed that the aftershock area one month after the main shock extended farther west from the area of aftershocks in the day following the main shock. He argued that the dislocation to the west of the one-day aftershock area took place with an intermediate time constant between seismic and geodetic time constants. Ando (1975) determined the dimensions of the fault plane (A and B) by fitting the geodetic and tsunami data, and concluded that a sudden brittle rupture occurred on plane B, which was followed by the slow propagation on plane A.

The fault plane of the 1854 Ansei I earthquake extended farther to the east (C+D) from the fault plane of the 1944 Tonankai earthquake (C), based on the documents on crustal movements and tsunami.

Ishibashi (1981) argued, mainly on the basis of a record of tsunami excitation at the time of 1854 Ansei I earthquake, that the fault planes extended farther to the Suruga Trough, an extension of the Nankai Trough into Suruga Bay. The extended part of the fault planes was thus named plane E (Fig. 2).

Efforts to read traces of earthquakes recorded in excavations, liquefaction of ground in most cases, have also been made (Sangawa, 1999). The results of research not only support the presence of the earthquakes documented in the historical materials, but also suggest additional events even before the first documented earthquake (A.D 681). Some additional traces of possible earthquakes have been found to fill in the 200-year intervals between the earthquakes before 1361, and this may suggest the regular 100-year recurrences of large earthquakes (Fig. 2). However, there remain some difficulties in identifying traces, such as discerning traces of seismogenic-zone earthquakes from those of inland earthquakes. Further studies are necessary to estimate the timing of earthquake occurrences from records of excavations more reliably.

Ishibashi (1999) reviewed the dimensions of fault planes of historical earthquakes until the 1099 Kowa Nankai earthquake. He also argued that some evidence given by several previous studies for possible events in the 1200's and in 1331 to fill the 262-year interval between the 1099–1096 Eicho-Kowa earthquakes and 1361 Koan earthquake was not convincing. He concluded that the question of whether an interval of about 200 years for the earthquakes before 1361 is true has not yet been answered.

3. Microearthquake Activities

As described in the previous section, fault plane parameters were obtained by several previous studies for the 1944 Tonankai and 1946 Nankaido earthquakes by analyzing seismic, geodetic, and tsunami data. The fault plane parameters for the other historical earthquakes were estimated on a hypothesis that the source mechanisms of those earthquakes are similar to those of the 1944 Tonankai and 1946 Nankaido earthquakes. Observations of microearthquakes provide essential information to put more constraints on fault parameters. For example, as the fault plane of a large earthquake is considered to be lying along the interface between overriding and subducting plates, the geometry of the interplate interface can be defined by a trace of hypocentral locations of microearthquakes. The shallowest part of the interplate interface is aseismic, as subducted materials at the top of the subducting plate are not consolidated enough to store elastic strain energy. The updip limit of the seismogenic zone can be defined by microearthquake observations as the locations of the shallowest microearthquakes along the interplate interface. Hyndman *et al.* (1995) suggested a model of a thermally controlled locked zone: the updip limit of the seismogenic zone coincides with a 150℃ isotherm along the interplate interface, where dehydration of stable sliding clays is supposed to occur. This hypothesis can be evaluated from microearthquake observations.

The onshore seismic networks have not observed many microearthquakes near the axis of the Nankai Trough, compared to other regions around Japan, such as northeast of Japan along the Japan Trench (Fig. 3). Hypocenters of earthquakes observed near the trough axis are located substantially deeper than the interplate interface. The absence of observed earthquakes may be because the seismic stations are situated very far from the locations of earthquakes for their magnitudes, or because the activities themselves are quite low as inferred from near-100% tectonic coupling, and the accumulated stress is released only by large earthquakes. Even for the observed microearthquakes, errors in hypocentral locations determined by the onshore seismic networks are large, especially in the direction perpendicular to the general trend of the coastlines. Therefore, offshore microearthquake observations at the proximity of the seismogenic zone using Ocean Bottom Seismometers (OBSs) are necessary.

3.1. Nankai OBS observations

Five sets of micro-earthquake observation using OBSs have been conducted since 1998 near the trough axis off Cape Muroto (Fig. 4). Each set of observations lasted 1.5 to 2 months. The overall period of the observations was about nine months. Detailed descriptions of the observations and the analyses were summarized by Obana *et al.* (2003). A brief summary of the observations is presented here.

Seismic events were detected by eye-picking on continuous records. Arrival times of P- and S-waves for each event at different stations were picked

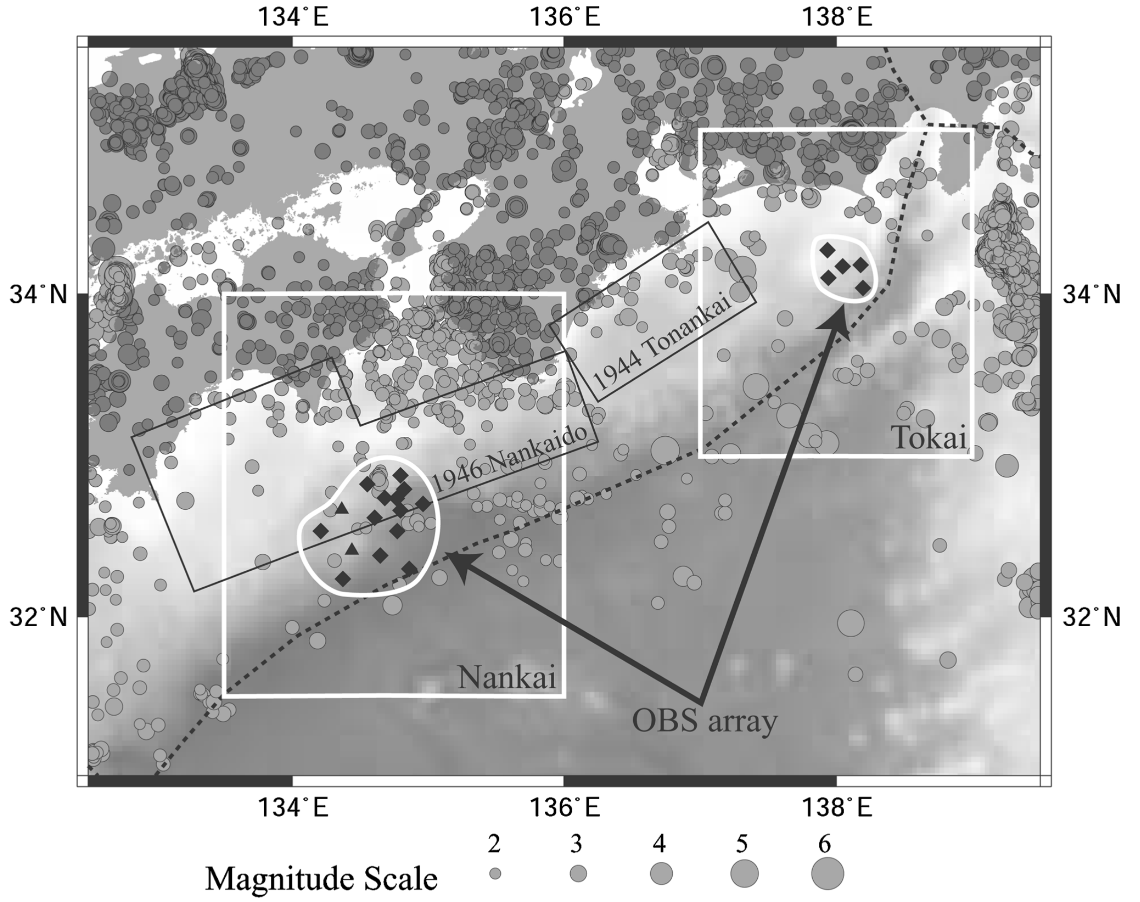

Fig. 4. Locations of microearthquake observations in the Nankai and Tokai regions. Gray circles are epicentral locations of earthquakes occurring in the same period as in Fig. 3. OBS locations are also shown by diamonds. Triangles in the Nankai region are cable OBSs.

manually. Hypocenters were determined in a grid-searching manner incorporating a three-dimensional velocity structure model for a more precise hypocenter determination. The 3-D structural model was constructed by interpolating existing structural models obtained by the seismic surveys along the Nankai Trough (Fig. 1). S-wave velocities were estimated from corresponding P-wave velocities and Vp/Vs ratios that were determined by referring to a Vp/Vs structure model obtained along a seismic line running a little more than one hundred kilometers west of the region (Profile KR9810 on Fig. 1).

Figure 5 shows the results of the 9-month OBS observations. Determination errors of epicentral locations are ∼5 km and ∼3 km in the parallel and perpendicular directions about the trough axis, respectively. Earthquakes near the trough axis are deep ones, and do not lie around the interplate interface. Locations of the shallowest earthquakes along the interplate interface coincide well with the 150℃ isotherm and fairly well with the shallower boundary of the fault plane of the 1946 Nankaido earthquake (Fig. 5). The total number of seismic events recognized during the entire 9 months of observations was only 582, which corresponds to a rate of 2 events/day. The number of earthquakes whose hypocenters were determined was 301, and most of their magnitudes are less than 3. It has thus been proved that microearthquake activity off Cape Muroto is very low. This is consistent with near-100% tectonic coupling proposed from GPS studies.

Focal mechanisms of these microearthquakes are still unknown because the dimensions of the observations were not large enough to observe a sufficient range of incident angles to the OBSs to determine focal mechanisms by analyzing first-motion polarities. However, information on the focal mechanism is extremely important to determine

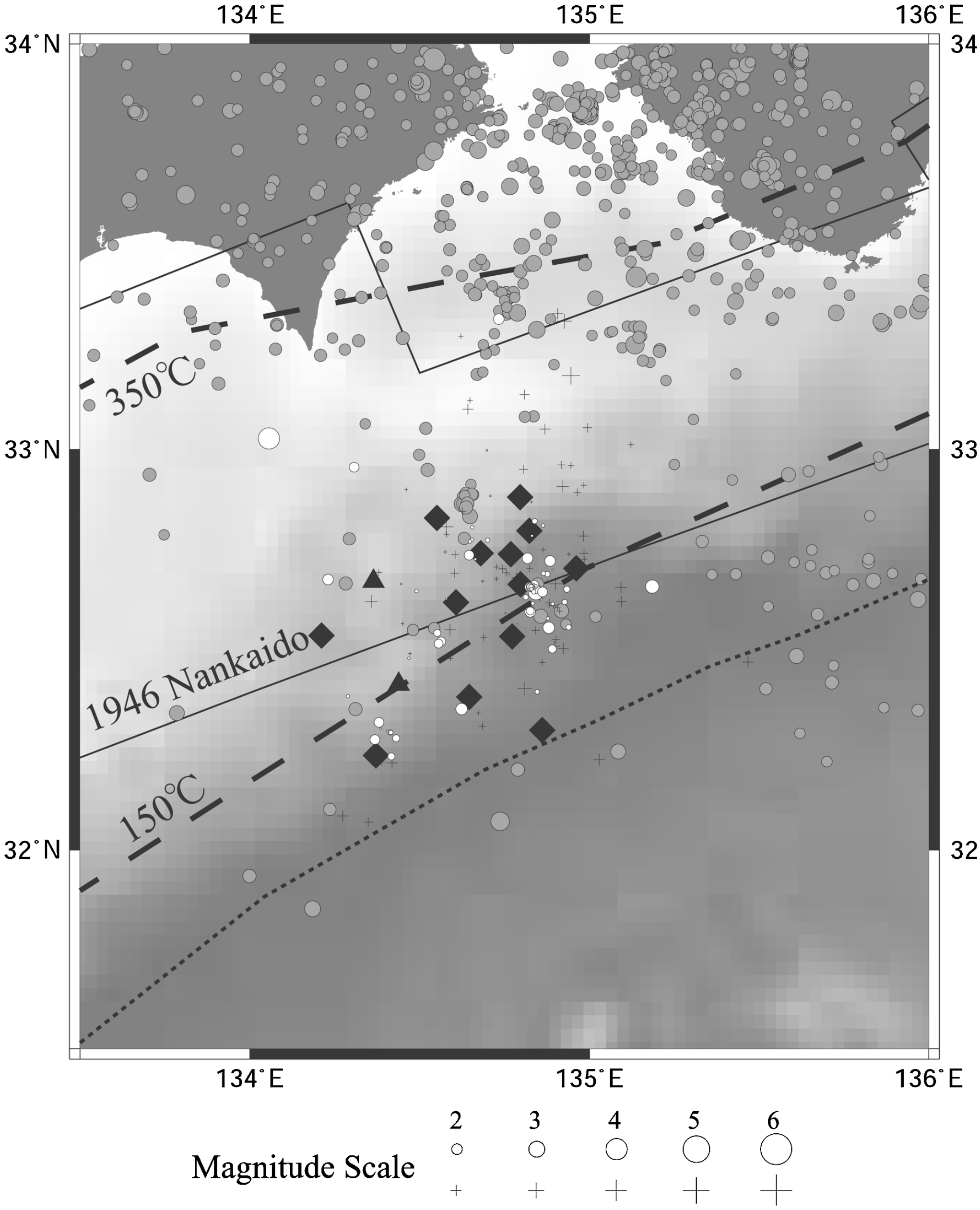

Fig. 5. Epicentral locations of earthquakes observed during a total of 9 months of microearthquake OBS observations (white circles and crosses), and of those observed by Japan Meteorology Agency in the same period as in Fig. 3 (gray circles). White circles are earthquakes shallower than 10 km, and crosses are those deeper than 10 km. OBS locations are shown by diamonds. Triangles are cable OBSs. Fault plane solutions for the 1946 Nankaido earthquakes as well as isotherms of 150 and 350℃ are shown. Most epicenters located seaward of the 150℃ isotherm are of deep earthquakes. Epicentral locations of the shallowest earthquakes show a good match with the 150℃ isotherm.

the surrounding stress field. Determining of focal mechanisms of microearthquakes remains a subject for future studies.

3.2. Tokai OBS observations

The same type of OBSs as those used for the Nankai observations was used for microearthquake observations in the Tokai area (Fig. 6). Five OBSs were deployed for 82 days in July 2000. Seismic events were automatically detected by comparing the ratio of the short-term-average to the long-term-average of amplitude through the continuous data. The first half of the observation period unfortu-

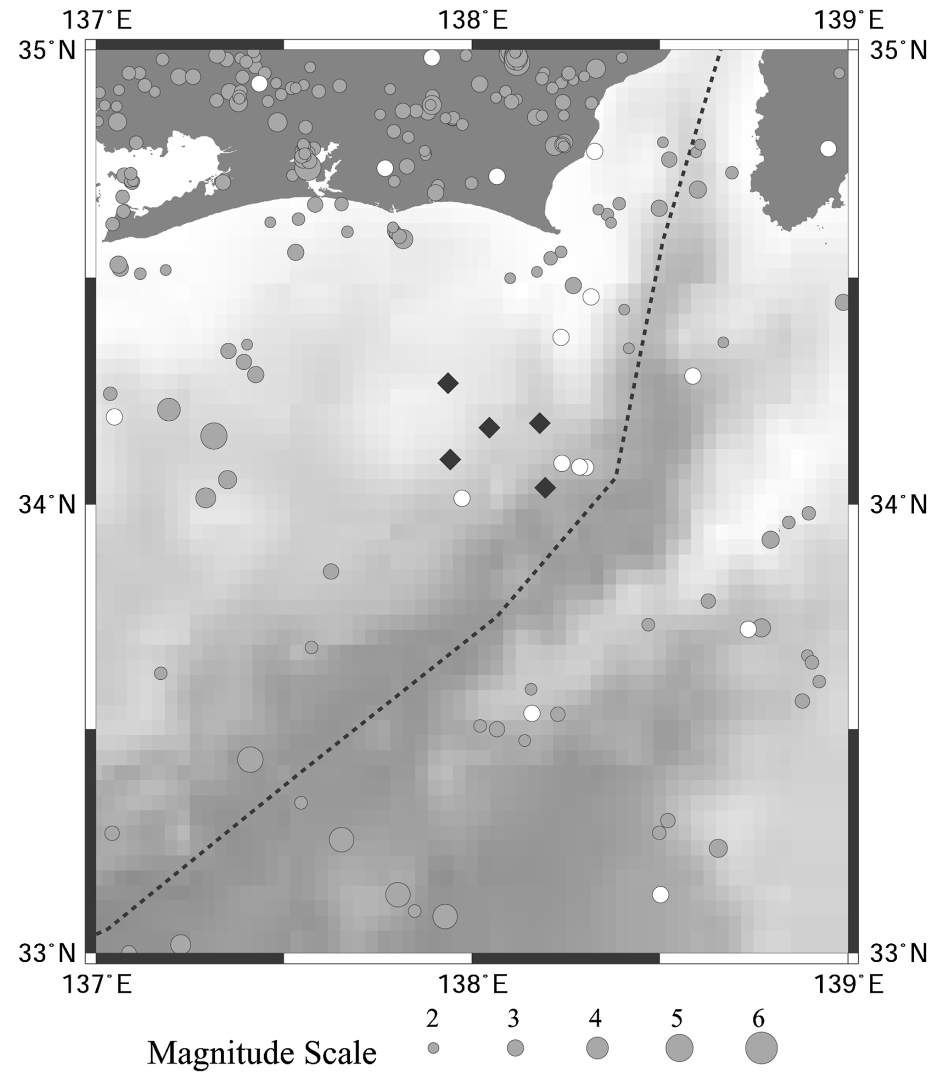

Fig. 6. Epicentral locations of earthquakes observed during 82 days of microearthquake observations using 5 OBSs. Diamonds show the locations of OBSs. Only 7 earthquakes were observed beneath the landward slope of the Suruga Trough (a northeast extension of the Nankai Trough). Microearthquake activity is very low.

nately overlapped a time of very high seismic activity triggered by an eruption event on Miyake Island, and over 5,000 seismic events were observed by the OBSs. Most of the events were of activities near Miyake Island. The arrival times of the events were automatically picked up using the Win system (Urabe and Tsukada, 1992). Hypocenters were determined by HypoMH (Hirata and Matsu'ura, 1987), incorporating a 1-D velocity structural model with a constant Vp/Vs ratio of 1.73. The 1-D velocity structural model was the result of compiling P-wave velocity structural models along the profiles of the 1992 seismic survey obtained by Nakanishi *et al.* (1994) (Fig. 1). The arrival times of P- and S-waves were checked manually for earthquakes whose hypocenters were determined around the Tokai region, and the final hypocenters were determined. The hypocenters determined of the earthquakes along the Nankai-Suruga Troughs numbered only seven. However, the occurrences of these earthquakes can be seen equally in both active and inactive times of seismic activity near Miyake Island. Therefore, it is safe to say that the number of earthquakes will not substantially increase if observations are conducted without disturbances. The magnitudes of these earthquakes have not yet been precisely determined, but they may be as small as 2. It has been proved that microearthquake activity in the Tokai area is also low. The depths of these events were determined to be deeper than the expected depths of the interplate interface. This could be because of the incorporation of a high Vp/Vs ratio for the sedimentary layers as discussed by Obana *et al.* (2003) for the case of the Nankai Observations.

Only a preliminary result of the observations is now available, although epicentral locations will not be relocated significantly by further analyses. Detailed discussions, such as on hypocentral locations, will be given in future studies.

4. Conclusions

Large earthquakes with a magnitude as large as 8 occurred along the Nankai Trough with remarkably regular recurrence periods; these are approximately 100 years for the earthquakes after an event in 1361, and approximately 200 years for those before 1361 (Fig. 2). Records of the events are well documented in historical materials, and they allow us to estimate the locations and the dimensions of their fault planes. Traces of earthquakes have been found in excavations, and some additional events to fill in the 200-year intervals are proposed. However, further studies are necessary to precisely match these traces with possible events. In spite of efforts to read traces of the historical large events, some questions still remain unanswered. These questions include whether the approximately 100-year recurrence period is true throughout the history, and whether the fault planes of these events can be represented by combinations of sub-planes defined on the basis of the fault parameters of the 1944 Tonankai and 1946 Nankaido earthquakes (Ishibashi, 1999).

The fault parameters of the 1944 Tonankai and 1946 Nankaido earthquakes were determined by several studies from various data, such as seismic observations, geodetic measurements, or tide gauges. The geometries of these fault planes are consistent with fully locked zones estimated by analyzing GPS data, and with the model of thermally controlled coupling zone proposed by Hyndmann *et al.* (1995). Therefore, the seismogenic zone is considered to be in a completely locked condition. Microearthquake activities can put more direct constraints on the geometry of the seismogenic zone.

Microearthquake observations were conducted in both Nankai and Tokai areas along the Nankai Trough using ocean bottom seismometers. Only 301 hypocenters were determined for a total of nine months of observations in the Nankai area, and only seven earthquakes for 82-day-long observations in the Tokai area. It has thus been proved that microearthquake activity along the Nankai Trough is extremely low, therefore, this supports the estimation of complete tectonic interplate locking. The locations of the shallowest plate-boundary earthquakes coincide very well with the 150℃ isotherm proposed by Hyndmann *et al.* (1995).

Although focal mechanisms give essential information on the stress field around the earthquakes, it has not been possible to make a determination by OBS observations as the dimensions of the observation area were too small and a simple analysis of first-motion polarity is not applicable. Further studies are required.

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