Characteristics of Earthquake Distribution in the Japanese Archipelago —Plate tectonics has not caused earthquakes—

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Abstract. In this paper, I re-examine the occurrence of earthquakes based on the distribution of hypocenters in the Japanese Archipelago. Analysis of hypocenters at different depths shows different distribution characteristics in some depth ranges. The distribution of earthquakes deeper than 300 km is the lower part of the deep seismic surface, which is quite different from the upper part. Earthquakes with a depth of 50 to 300 km show a distribution of hypocenters that form the upper part of the deep seismic surface that dips from the trench to the island arc side, but this is not seen in the Nankai Trough. Earthquakes of 20-50 km depth are rarely found beneath the spine of the island arc, suggesting that the lower crust in this region may be melting. Earthquakes with depths of 0-20 km are distributed on the spine of the island arc and the surrounding continental slope, with many occurring in the upper crust of the island arc. The upper part of the deep seismic surface dips from the landward side of the trench to the island arc side, and is not subducted from the trench axis. Most earthquakes occur at the boundary between sedimentary basins and their surrounding mountains, not due to subduction of a plate, but due to uplift of island arcs by molten bodies in the lower crust.

Keywords: earthquakes, hypocenters, deep seismic surface, uplift of island arcs, plate subduction.

Introduction

This year marks the tenth anniversary of the massive earthquake that devastated the northeastern part of the Japanese Archipelago, the Tohoku-Pacific Coast Earthquake (The Great East Japan Earthquake). This earthquake occurred at 14:46 on March 11, 2011, with its hypocenter at a depth of about 24 km off Sanriku on the Pacific coast. The magnitude of the earthquake was M 9.0, which is the largest earthquake ever recorded in Japan and the fourth largest earthquake in the world since 1900. This earthquake is considered a typical trench-type earthquake.

The total number of victims of this earthquake and the resulting tsunami was more than 20,000, including the dead and missing. In addition, this earthquake and the resulting tsunami caused a serious accident at the Fukushima Daiichi Nuclear Power Plant, and the radiation released continues to cause enormous damage not only in the Tohoku region but also throughout Japan.

Fig. 1 shows the hypocenter distribution of earthquakes with magnitudes ranging from M 0.1 to M 9.0 that occurred in and around the Japanese Archipelago from October 1, 1997 to August 28, 2011. The hypocenter data was obtained from the Japan Meteorological Agency's hypocenter data, and the distribution map was created using Scat3D software provided by Professor Takayuki Kawabe of Yamagata University. The depth of the hypocenter is indicated by the color of the circle, and the magnitude is indicated by the radius of the circle, but these legends are omitted here because the focus is on the location of the hypocenter.

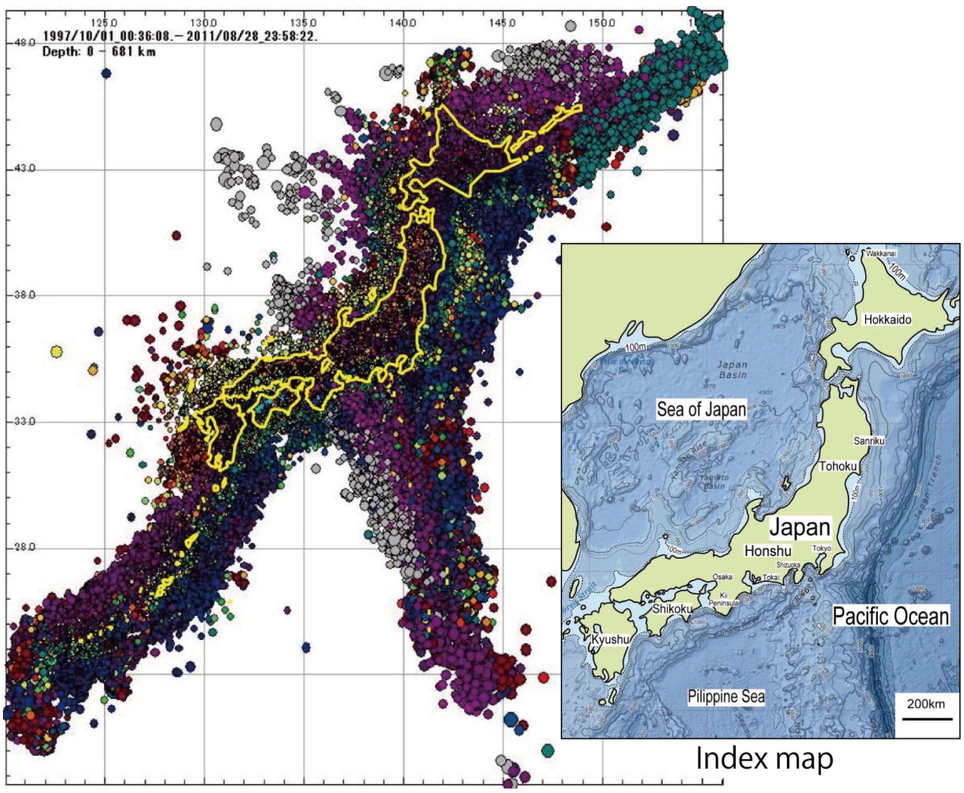

Fig. 1 Left map shows the hypocenter distribution of earthquakes with magnitudes ranging from M 0.1 to M 9.0 that occurred in and around the Japanese Archipelago from October 1, 1997 to August 28, 2011. The Japanese Archipelago appears to be a nest of earthquakes. Right map is the index map.

These data show that many earthquakes occur along the trenches and island arcs around the Japanese Archipelago, and the Japanese Archipelago appears to be a nest of earthquakes. Seismologists have explained that earthquakes around the Japanese Archipelago are caused by plate subduction. But is it true? Where are the earthquakes actually occurring? In this paper, I will re-examine the occurrence of earthquakes based on the actual hypocenter distribution of earthquakes.

As a result, when the hypocenters of these earthquakes are analyzed by their depths, different distribution characteristics are observed in several depth ranges. And it clearly shows that earthquakes are not caused by the plate tectonics.

Characteristics of earthquake distribution due to differences in hypocenter depth

Depth 300 km to the deepest (681 km)

The earthquakes occurring at this depth range (Fig. 2) are composed of three sets. One is a linear distribution of westward-dipping deep earthquakes from north-northwest to south-east direction that starts south of the Bonin Islands, passes through Ise Bay and Wakasa Bay, and ends near the Yamato Bank in the Sea of Japan. Secondly, there is a north-trending linear distribution in the east-northeast to west-southwest direction extending from the northern part of the Kuril Basin to the vicinity of Wakkanai in Hokkaido. The remainder is distributed in the Japan Basin between these two areas. The entire distribution of earthquakes at this depth appears to be orthogonal as shape of the letter "L" tilted upside down. The hypocenter distribution in this depth range is the lower part of the so-called deep seismic surface, which is discontinuous with the upper part and shows a completely different distribution.

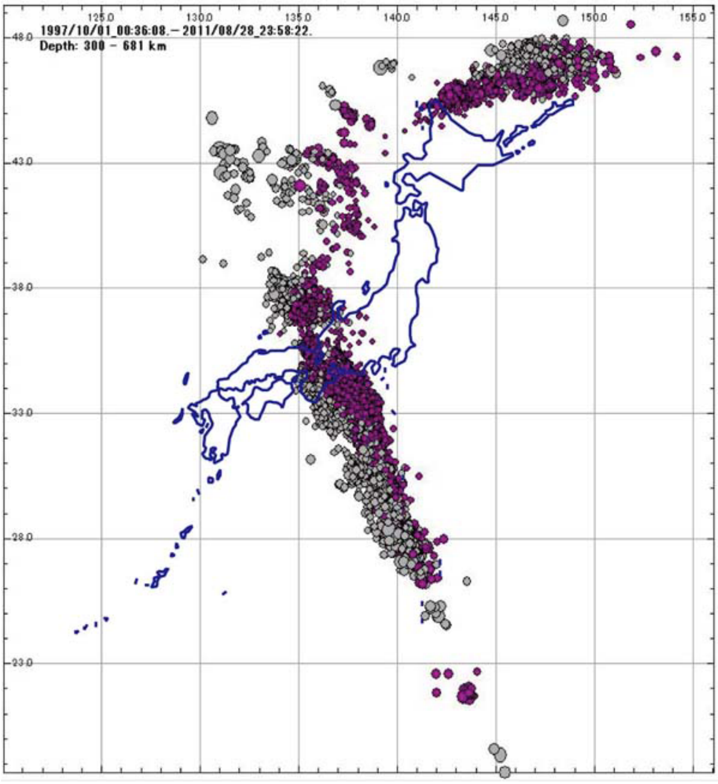

Fig. 2 Distribution of hypocenters in and around the Japanese Archipelago from 300 to 681 km depth. This is the lower part of the so-called deep seismic surface, which is discontinuous with the upper part and shows a completely different distribution.

Earthquakes at depths of 50 to 300 km

The earthquakes at this depth range (Fig. 3) show the distribution of hypocenters that form the upper part of the so-called deep seismic surface, which dips from near the trench to the island arc side. Such deep seismic surfaces are also observed along the Japan Trench, the Kuril Trench, the Izu-Bonin Trench, and the Ryukyu Trench. However, on the Pacific side along the Nankai Trough, there is no equivalent to this deep seismic surface. This may mean that there is no plate boundary in the Nankai Trough that corresponds to a deep seismic surface. In the Nankai Trough area, however, small-scale epicenters are distributed in the Kii Peninsula, the Kumano-nada (the southeast off the Kii Peninsula), and the southeast off the coast of Shikoku.

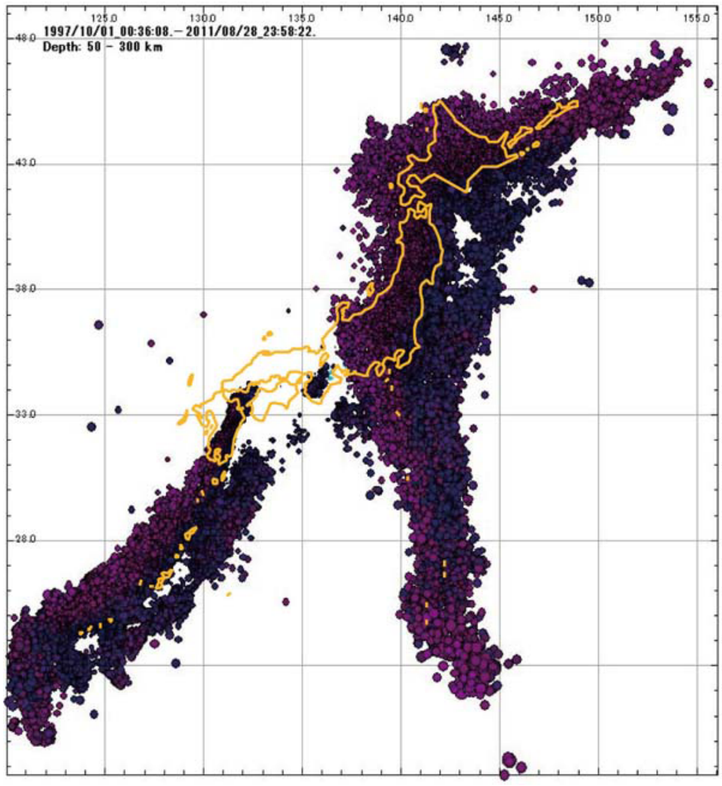

Fig. 3 Distribution of hypocenters in and around the Japanese Archipelago from 50 to 300 km depth. This forms the upper part of the so-called deep seismic surface, which dips from the trench to the island arc side, but is not seen along the Nankai Trough.

Earthquakes at depths of 20 to 50 km

Earthquakes of this depth range (Fig. 4) are distributed on the continental slope on the Pacific side of the island arc, and on the continental slope on the Sea of Japan side in the Tohoku region and near Wakkanai. There are few earthquakes of this depth in the spine of the island arc, and many are not distributed on the Sea of Japan side in southwest Japan. This depth range corresponds to the lower continental crust below the island arc. In the absence of these earthquakes, there are many very low-frequency earthquakes distributed under the volcanic belts. For those in the lower part of this depth range, it is likely that earthquakes at the top of the deep seismic surface are also included. There are few earthquakes south of the Bonin Islands, and they are concentrated at depths of 25 to 40 km in the Kuril Arc.

Since earthquakes are caused by brittle failure, the absence of earthquakes may indicate that the region is composed of elastic or molten material. The distribution of earthquakes at this depth range also roughly coincides with the distribution of volcanic belts and very low-frequency earthquakes. This suggests the presence of molten magma in the spine of the island arc at depths of 20 to 50 km.

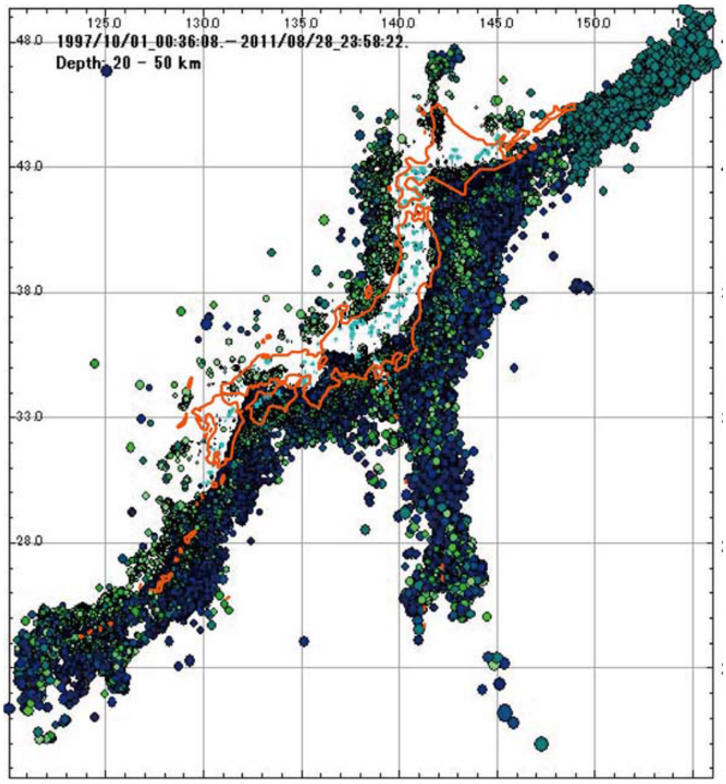

Fig. 4 Distribution of hypocenters in depths of 20 to 50 km in and around the Japanese Archipelago. Light blue circles indicate very low-frequency earthquakes. There are few earthquakes at this depth in the spine of the island arc, and they are accompanied by very low-frequency earthquakes.

Earthquakes at a depth of 0 to 20 km

Earthquakes of this depth range (Fig. 5) are distributed on the spine of the island arc and the surrounding continental slopes. Those shallower than 10 km are concentrated on land and in some areas, while those 10-20 km deep are distributed on the continental slope. In some areas along the coastline, there are seismic gaps. There are few earthquakes at this depth range in the south of the Bonin Islands, and there is a gap between Hokkaido and the Kuril Arc, where large earthquakes are distributed around 15 km depth. The distribution of earthquakes shallower than 10 km in the land area of the island arc indicates that earthquakes are occurring in the upper continental crust below the island arc.

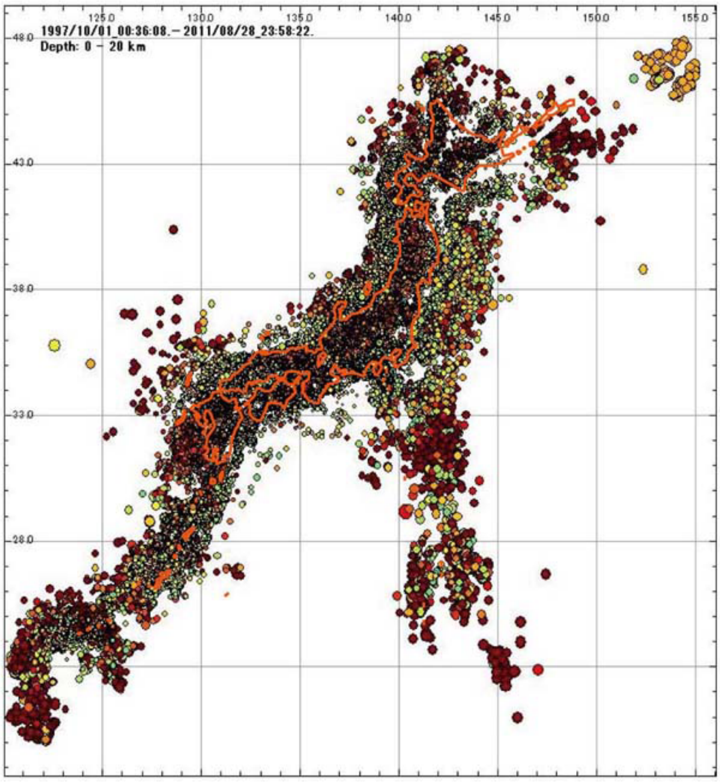

Fig. 5 Distribution of hypocenters from 0 to 20 km depth in and around the Japanese Archipelago. They are distributed on the spine of the island arc and the surrounding continental slopes.

Trench-type earthquakes

Trench-type earthquakes are generally described as earthquakes that occur beneath the landward slope of an oceanic plate as it subducts in an oceanic trench. This is believed to be caused by the accumulation of strain on the landward plate, which is pushed by the subducting oceanic plate, causing the landward plate to spring up and generate an earthquake fault, which in turn causes an earthquake. Therefore, earthquakes can occur anywhere along the subduction zone of a plate.

In Japan, the area from the Enshu-nada (off the coast of Hamamatsu) to Suruga Bay (off the coast of Shizuoka) along the Nankai Trough has been threatened by the possibility of large earthquakes due to the subduction of the Philippine Sea Plate for the past 50 years (Fig. 6). This is because this area has never had a major earthquake before, i.e., it was a blank area, and therefore, the Tokai Earthquake or the Nankai Trough Earthquake was assumed to occur.

In the case of the Nankai Trough Earthquake, the plate boundary is traced onshore north of Suruga Bay, but no major earthquakes have occurred onshore. If M 7.0 to M 8.0 (and sometimes up to M 9.0) earthquakes can occur anywhere in the plate subduction zone, why do they occur only in the ocean? The plate boundary is extended on land, but why don't seismologists assume the source region in the landward extension of the Nankai Trough? Also, if earthquakes occur in the subduction zone of a plate, they should occur anywhere in the horizontal direction of the subduction zone, so why is the hypocenter distribution concentrated as the source region?

The Great East Japan Earthquake, which caused extensive damage to the Japanese Archipelago, is considered a typical trench-type earthquake, which is said to occur at plate boundary. In this section, I will take a closer look at this reality. Fig. 7 shows the east-west cross section of the hypocenters of the earthquakes that cut off Sanriku in the Tohoku region. Here, the deep seismic surface has two rows of the upper and the lower seismic surfaces (double deep seismic surface). The top edge of the upper deep seismic surface is not in the trench, but extends to the western margin of the deep-sea terrace. The main shock of the Great East Japan Earthquake is distributed below the trench side than the upward extension of the upper deep seismic surface (24 km depth of a black inverted triangle in Fig. 7).

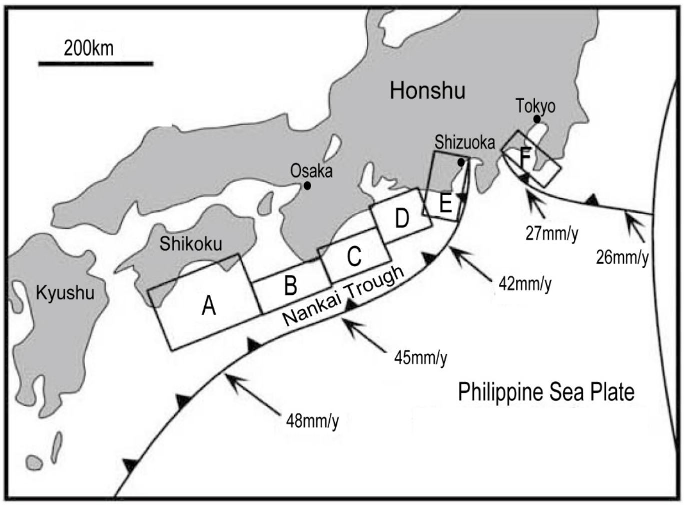

Fig. 6 The source regions of the Nankai Trough Earthquake, which are estimated to occur as a result of the subduction of the Philippine Sea Plate. Squares the A to the C and the D to the E indicate the estimated source regions of the Nankai Earthquake and the Tokai earthquake, respectively. The F indicates the source region of the Kanto Earthquake. Arrows and numbers indicate the direction and speed of the Philippine Sea Plate relative to Honshu (Koyama, 2008).

The top edge of the upper deep seismic surface is not in the trench, but on the landward side, which is a fact not only in the Northeast Japan Arc but also in the Izu-Bonin Arc and the Ryukyu Arc. If the top of the deep seismic surface is not subducting from the trench, is the oceanic plate subducting from the trench? How can the mechanism of the trench-type earthquakes be explained when the subduction zones of oceanic plates do not coincide with deep seismic surfaces?

At the end of the 1960s, a seismologist and a marine geologist showed that the characteristics of the epicenter distribution of the trench-type earthquakes are closely related to the distribution of the deep-sea terrace (forearc basin).

Den (1968) showed the distribution of earthquakes of M 6.0 or greater occurring at depths of 60 km or shallower from 1926 to 1965 and the distribution of the deep-sea terraces, and pointed out that the epicenters are concentrated at the edge of the deep-sea terraces. Den's (1968) figure shows that the Nankai Earthquakes and the East Nankai Earthquake of the 1940s occurred on the margins of the deep-sea terraces in the Kii Channel and off the coast of the Kii Peninsula, respectively, and that no major earthquakes occurred in the Enshu-nada, which has no wide deep-sea terrace.

Hoshino (1969), based on the relationship between the development of the deep-sea terraces and the distribution of epicenters of extremely shallow earthquakes (shallower than 10 km), found that extremely shallow earthquakes occur frequently where only one level of the deep-sea terrace is developed, and that no extremely shallow earthquakes occur at all where two levels of the deep-sea terrace are distributed, as in Tosa Bay, or where several narrow levels of the deep-sea terrace with different depths are distributed, as in the Enshu-nada. It also states that extremely shallow earthquakes occur where the margins of the Neogene sedimentary basins are isolated and develop into basins with strata thicker than 1,000 meters.

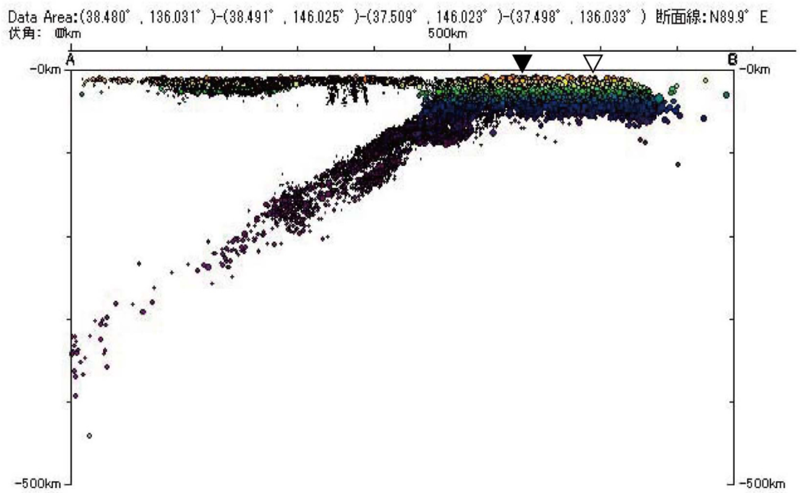

Fig. 7 East-west cross section of the hypocenters of the earthquake that cut off the Sanriku coast in the Tohoku region. The hypocenter of the main shock of the Great East Japan Earthquake was located 24 km beneath at a black inverted triangle, and the Japan Trench at a white inverted triangle. If we assume that the deep seismic surface is a plate subduction zone, then the plate is not subducting in the trench, but is subducting from the landward side by more than 100 km.

The distribution of the epicenters of the Great East Japan Earthquake and its aftershocks published by the web page of the Japan Meteorological Agency is superimposed on the detailed distribution of deep-sea terraces off the Pacific coast of Tohoku (Iwabuchi, 1967), and the main shock of the Great East Japan Earthquake occurred at the eastern margin of one deep-sea terrace off Miyagi (Fig. 8).

As mentioned earlier, the Nankai Trough, where the Tokai Earthquake or the Nankai Trough Earthquake are expected, does not have a deep seismic surface (Fig. 3). The trench-type earthquakes are said to occur when oceanic plates subduct, which means that they do not occur in the Nankai Trough. However, all seismologists continue to shout that huge earthquakes in the Nankai Trough will occur in near future.

From the perspective of earthquakes and sedimentary basins, the Tokai Earthquake is examined, although strata of the Neogene and later periods are distributed in the Enshu-nada, they are not distributed in a thick basin-like pattern, and the seafloor topography does not consist of a single level of deep-sea terrace (Fig. 9). This suggests that the seafloor of the Enshu-nada may not be a place where earthquakes occur. In other words, it seems to be that this is one of the reasons why the Tokai Earthquake, which was supposed to occur in the Enshu-nada, did not occur for 50 years.

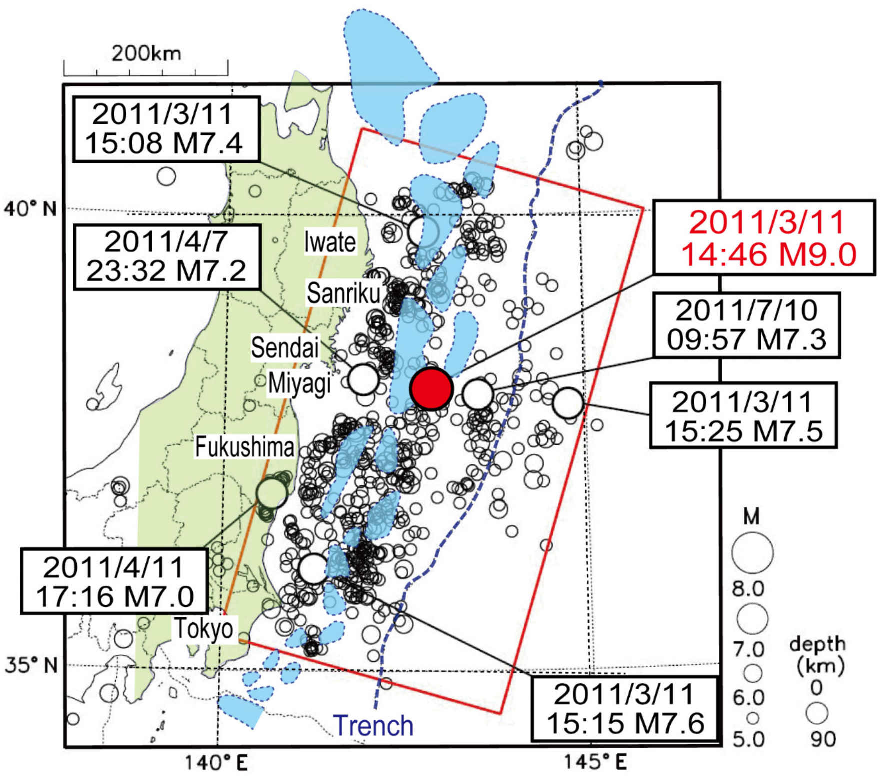

Fig. 8 The distribution of the epicenters of the Great East Japan Earthquake (the web page of the Japan Meteorological Agency) is superimposed on the distribution of the deep-sea terraces of Iwabuchi (1967). Most of the epicenters are not in the deep-sea terraces, but are distributed at the periphery of them.

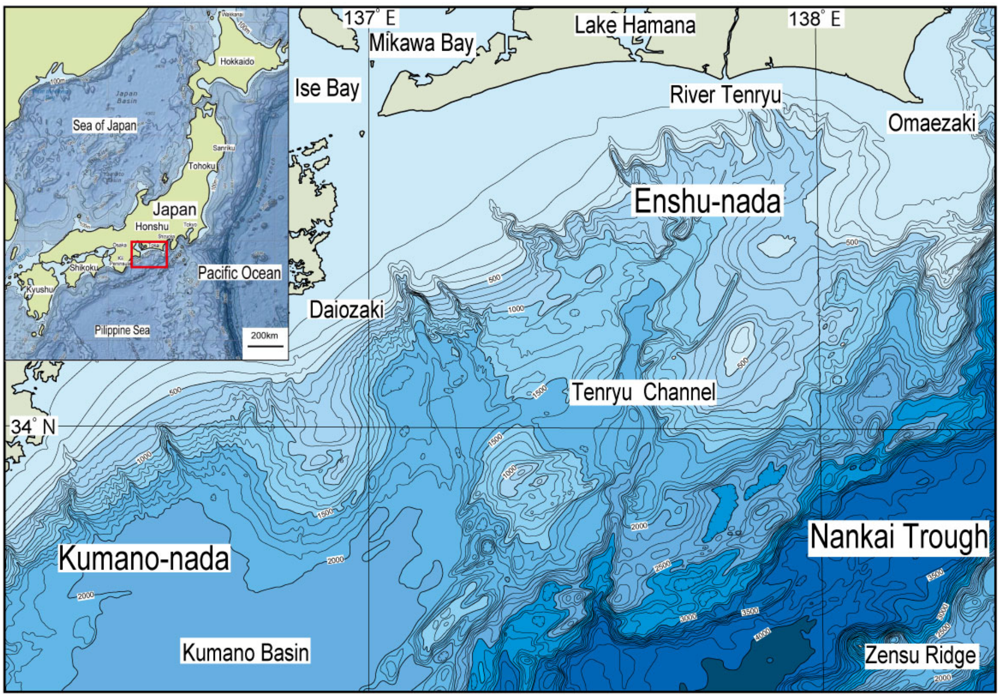

Fig. 9 Sea floor topography from the Enshu-nada to the Kumano-nada (Red box in the index map). In contrast to the Kumano-nada, where a deep-sea terrace (the Kumano Basin) develops, the Enshu-nada has no wide deep-sea terrace.

Sedimentary basins and earthquakes

Fig. 10 shows the distribution of the epicenters of the Southern Hyogo Prefecture Earthquake in 1995, superimposed on a map of the Osaka Plain from Awaji Island. Osaka Bay-Osaka Plain is a sedimentary basin that has accumulated thick sediments left over from the surrounding the Rokko and the Izumi Mountains, which were rapidly uplifted by the Rokko Movement as described by Huzita (1990). This earthquake occurred 16 km beneath the Akashi Strait at the northwestern margin of this basin, and strongly vibrated the northeast-southwest belt from the northern part of Awaji Island to the southeastern boundary of the Rokko Mountains, causing severe damage mainly to the city of Kobe.

Direct inland earthquakes, such as the Southern Hyogo Prefecture Earthquake (M 7.3), occur near the boundary

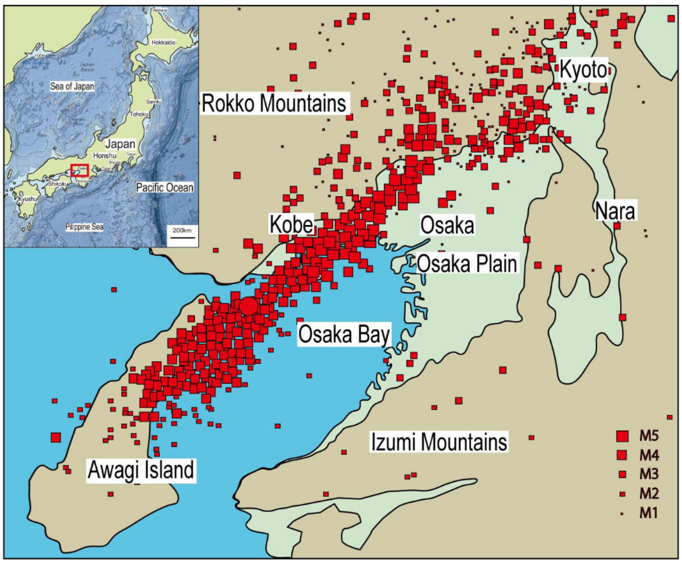

Fig. 10 Distribution of the epicenters of the main and aftershocks of the Hyogo Prefecture Earthquake in the area from Awaji Island to the Osaka Plain, superimposed on a map of the Osaka Bay area (Red box in the index map). A red circle indicates the location of the epicenter of the main shock and a red square indicates the location of the epicenter of the aftershocks. Most of the epicenters are distributed along the boundary between the Rokko Mountains and Osaka Bay-Osaka Plain.

between urbanized plains or basins and around rising mountains. The magnitude of these earthquakes is not as large as the trench-type one, but because the hypocenter is directly under the city, they can cause significant damage. Such earthquakes have often occurred in plains and basins throughout Japan. For example, in the Shizuoka Plain, the Shizuoka Earthquake (M 6.4) occurred in 1935 at the boundary between the southwestern part of the Udo Hills and the Shizuoka Plain, and in the Shimizu Plain, the Shizuoka Earthquake (M 6.1) occurred in 1965 at the boundary with the northern mountains. The 2009 Suruga Bay Earthquake (M 6.5) occurred in the northern margin of the Senoumi Basin in Suruga Bay (Fig. 11).

If the size of the plain or basin is small, the magnitude of the earthquake is small; if it is large, the magnitude of the earthquake is large. Some people believe that such earthquakes occur periodically in the same place in the same basin, but according to Shimamura (2011), earthquakes do not have a periodicity. An earthquake similar to the Southern Hyogo Prefecture Earthquake is known as the Keicho-Fushimi Earthquake, which is said to have occurred in 1596 on the Rokko-Awaji Island fault zone. The interval between the two earthquakes is about 400 years, but the two earthquakes did not occur in the same place.

If a trench-type earthquake occurs on a deep-sea terrace, i.e., at the margin of a forearc basin, the mechanism of occurrence is the same as that of an earthquake occurring at the margin of an inland basin, which is called a direct inland earthquake. What distinguishes them is the size of the basin, which has nothing to do with plate subduction.

The topography reflects the geology and tectonic movements of a place. Since erosion is not as pronounced in marine areas as it is on land, sedimentary landforms such as deep-sea terrace are clear, and landforms reflecting tectonic movements such as earthquakes and faults are easily recognized. The larger the size of the forearc basin or the inland basins, the larger the earthquake is likely to be. Therefore, more research on geomorphology and geology should be incorporated into the future understanding of earthquake generation mechanisms.

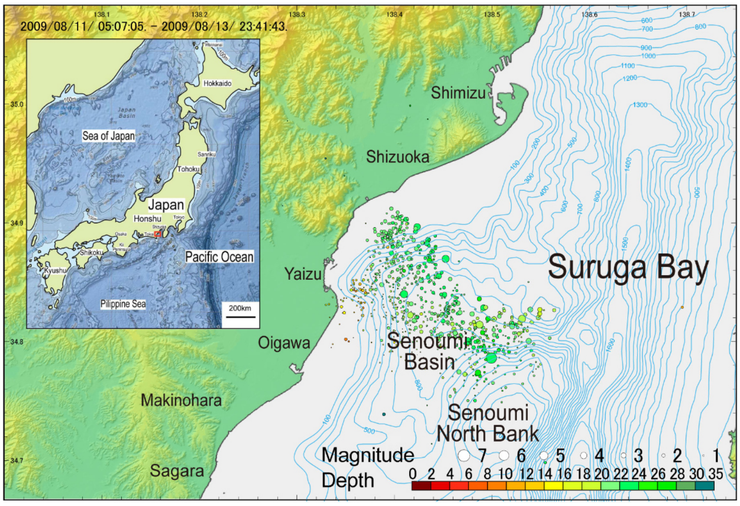

Fig. 11 Distribution of the epicenter of the 2009 Suruga Bay Earthquake (Red box in the index map). The epicenters are limited to the northeastern margin of the Senoumi Basin from Shizuoka to the Senoumi North Bank.

Earthquakes in the Nankai Trough

Fig. 12 shows the distribution of epicenters along the Nankai Trough at depths of 0 to 50 km, and Fig. 13 shows the distribution of hypocenters at depths of 0 to 50 km in four north-south cross sections across the Nankai Trough. Fig. 13 shows that there is no deep seismic surface, and the upper end of the distribution of hypocenters at depths of 20 to 40 km is extended near the coastline and does not coincide with the Nankai Trough axis.

In Fig. 12, there are seismic blank zones in the Akaishi Mountains and the Kii Mountains at a depth of 30 km or less from Shizuoka to the Kii Peninsula, and earthquakes with a depth of 30-50 km are concentrated in the southern part of those mountains. In that sea area, there is a blank zone of earthquakes with a depth of less than 30 km from the Enshu-nada to the Kumano-nada, but the concentration of earthquakes with a depth of 30-50 km is in the southern part of the Kumano-nada (beneath the outer margin of the Kumano Basin) and not in the Enshu-nada. In other words, the concentration of earthquakes with a depth of 30-50 km in this region seems to be distributed along the southern margin of the uplifted massif, including the Akaishi Mountains, the Kii Mountains, and the outer margin of the Kumano Basin (Fig. 12). This suggests that earthquakes in this region are thought to be caused by pushing up the up-

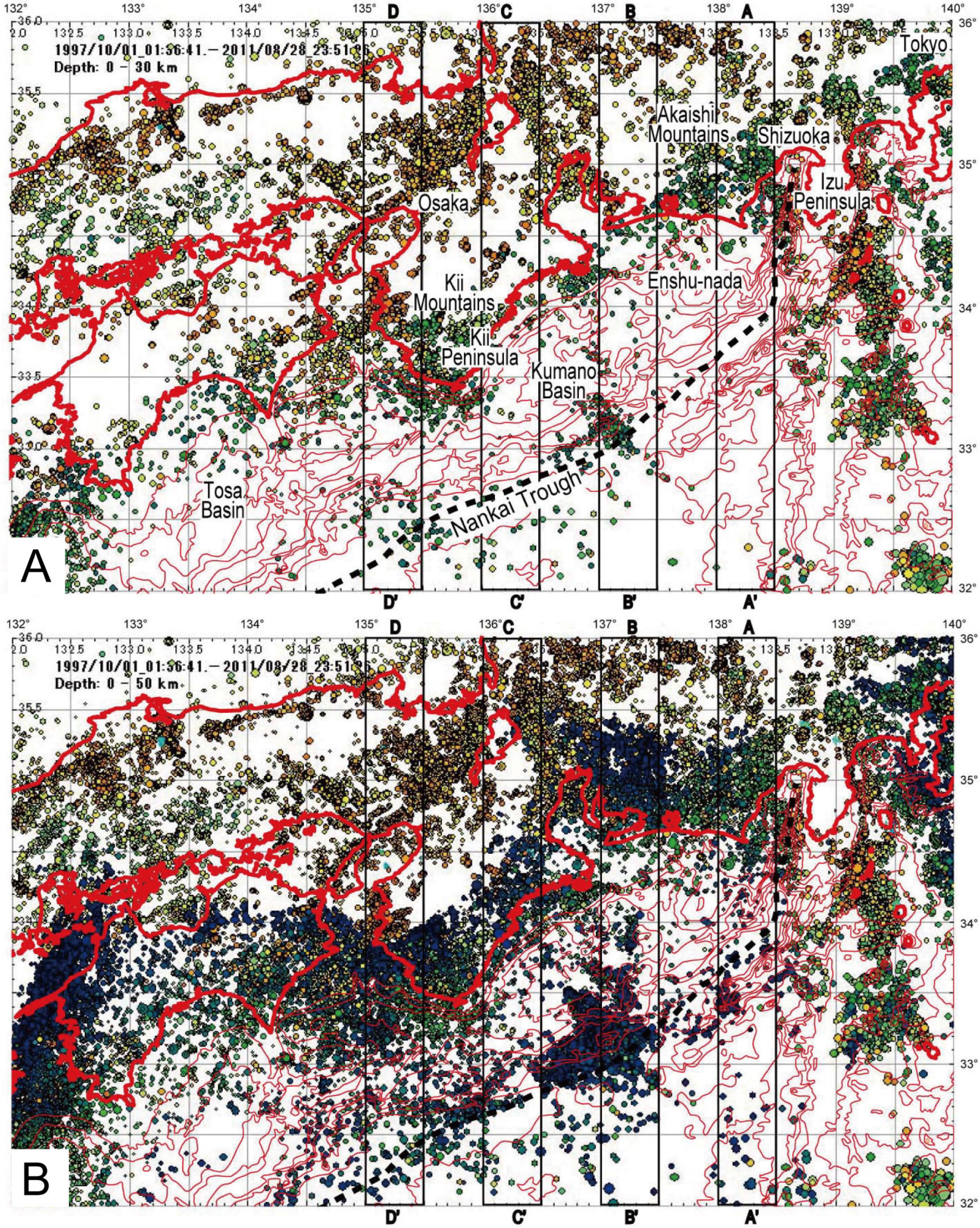

Fig. 12 Distribution of epicenters from 0 to 50 km depth along the Nankai Trough. A: Depth range from 0 to 30 km, B: Depth range from 0 to 50 km.

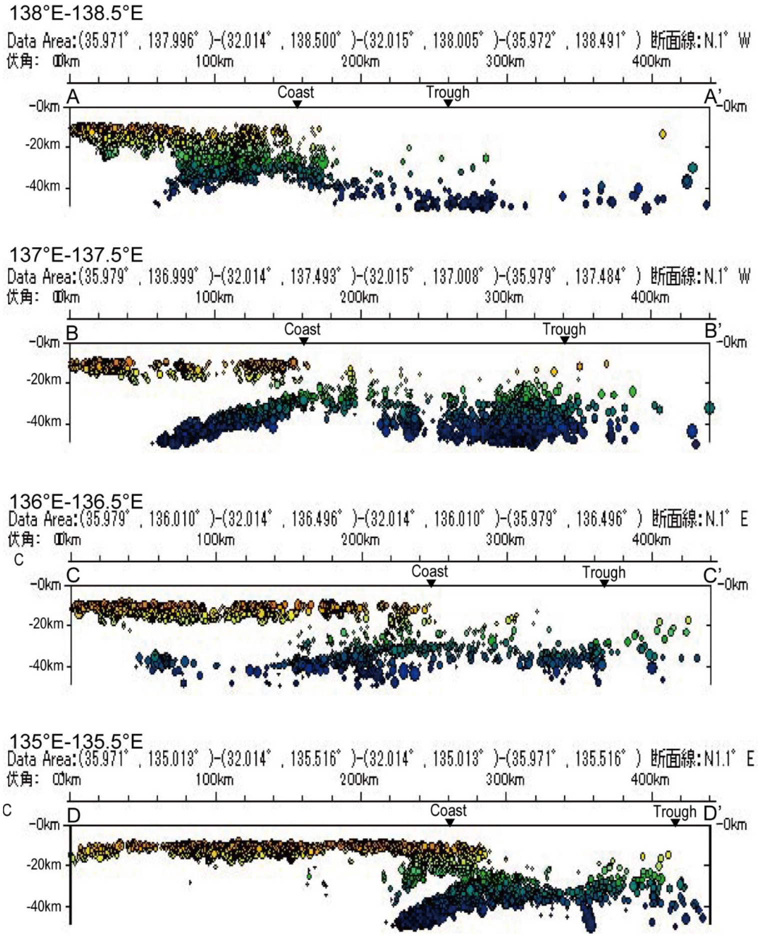

Fig. 13 Distribution of hypocenters from 0 to 50 km depth in four north-south cross sections across the Nankai Trough. Coast is the location of the coastline, and Trough is the location of the deepest axis of the Nankai Trough. No deep seismic surface along the trough is observed in any of the cross sections. In all sections, earthquakes are concentrated below the coast and the landward side. In addition to that, in the B section earthquakes are also concentrated below the landward side of the Nankai Trough (beneath the outer edge of the Kumano Basin).

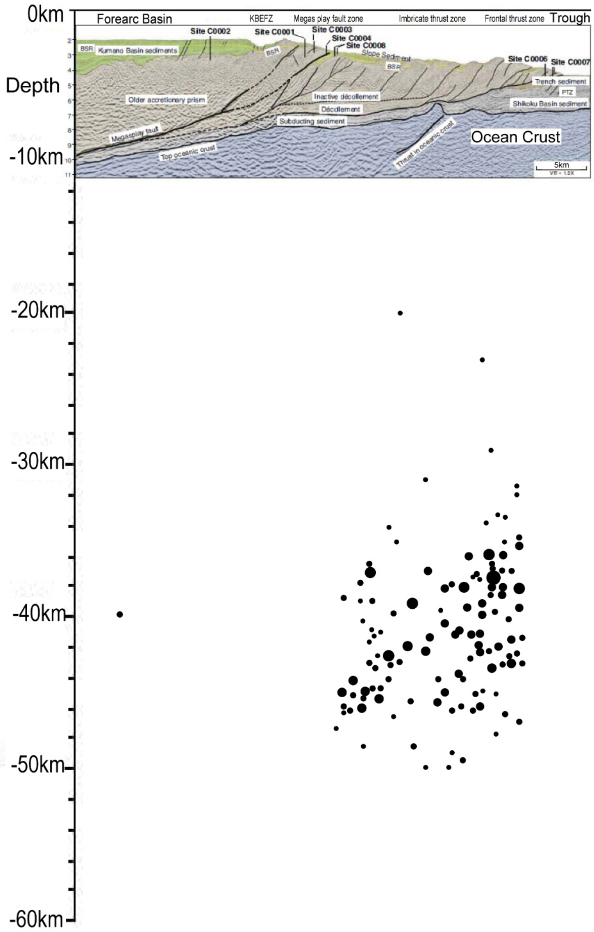

Fig. 14 Distribution of earthquakes beneath the Kumano Basin. Most earthquakes do not occur on the top surface of the ocean crust (the Philippine Sea Plate). Black circles are hypocenters. In fact, the hypocenters are much deeper, at depths of 20 to 50 km, and the earthquakes occur independently of the upper surface of the plate. The top of this figure is the geological cross section of the Nankai Trough from Saffer et al. (2010).

lifted land mass from below.

The hypocenters of earthquakes concentrated in the southern part of the Kumano-nada are located at 30-50 km, and there are almost no earthquakes at depths of 0-10 km, which is the subduction zone of the Philippine Sea Plate (Fig. 14). In other words, there is no relationship between plate subduction zones and the occurrence of earthquakes.

Mountains are uplifted, while basins are relatively subsided. For example, the boundary between Osaka Bay-Osaka Plain region and the rising the Rokko Mountains has been subject to continuous uplift and relative subsidence (sea level rise) caused by the Rokko Movement. Similarly, the Akashi Mountains, the Kii Mountains, the outer ridge of the landward side of the Nankai Trough that formed the deep-sea terrace (forearc basin), and the upper continental slope of the landward side of the trench have been actively uplifted since the Quaternary. The mechanism of uplift movement of mountainous and continental slopes relative to the basin seems to be closely related to the occurrence of earthquakes.

The island arc-trench system is characterized by island arc uplift, volcanic activity, trenches, and earthquakes. The island arc is thought to have been formed by uplift since the late Miocene, especially since about 430 Ka (Shiba, 2017a, 2017b, 2021), and volcanic and seismic activities are thought to be associated with this. Therefore, it is necessary to study earthquakes in relation to the uplift movements and magmatic activities that formed the island arc, rather than considering plate subduction alone as the cause of earthquakes.

Mechanism of earthquake occurrence

In conclusion, I believe that earthquakes are not caused by a simple mechanism of the plate tectonics, as is commonly believed, in which the landward side of a plate is pushed by a subducting oceanic plate, causing the landward side to spring up due to accumulated strain.

Hosoi (1996) argued that the "destruction" of individual parts of the crust can be considered when it progresses gradually at a very low speed, but it is questionable what kind of "reality" of destruction exists in the crust where there is no surrounding space when instantaneous energy is released, such as in an earthquake. He believes that the fluid (water) itself, which can flow explosively, plays a major role in the occurrence of instantaneous ruptures such as earthquakes.

As for the mechanism of earthquake occurrence, I believe that one of the most likely causes of earthquakes is the shock proposed by Hosoi (1996), which is an explosive flow of high-pressure water from an anomalous high-pressure block to the adjacent layer, breaking through a weak part of the fault wall. Especially in the case of earthquake swarm occurring in hot spring areas, the increase in ground heat or steam pressure and the change in groundwater flow are consider to be closely related to the occurrence of earthquake swarm. Therefore, the interrelationship between regional uplift zones and basins, as well as the stress and heat increase and changes within the crustal interior and the upper mantle that cause the uplift, are important in understanding the cause of earthquakes.

However, I am not able to predict where and when the next earthquake will occur. Even for earthquakes that have occurred in the past, nobody is not possible to clearly explain the specific mechanism that caused them. However, since most earthquakes occur at the boundary between uplift zone and basin, something must be causing the uplift of the crust. The causes of earthquakes are probably closely related to changes in the low-velocity layers at the lower crust, magmatic activity, and resulting changes in vapor pressure, such as heat and hydrothermal fluids in the crust or strata.

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