Seeking the Cause of Large Crustal Earthquakes in Japan: Influence of Arc Magma and Fluids

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Abstract. To better understand the generating mechanism of large crustal earthquakes, we have investigated the relationship between the three-dimensional seismic velocity structure and the distribution of large crustal earthquakes (magnitude 5.7–8.0; depth 0–20 km) in Japan during a period of 115 years from 1885 to 1999. We found that most of the large crustal earthquakes occurred in or around zones of low seismic velocity revealed by seismic tomography. The low-velocity zones may represent weak sections of the seismogenic crust. We believe that the crustal weakening is closely related to the subduction processes in this region. Along the volcanic front and in back-arc areas, the crustal weakening may be caused by active volcanoes and arc magma resulting from the convective circulation process in the mantle wedge and dehydration reactions in the subducting slab. In the forearc areas, fluids are detected in the earthquake source zones, which may have contributed to the rupture nucleation. The fluids may have shallow origins such as meteoric water, fluids trapped in pore spaces and from mineral dehydration in the crust, and deep origins such as the dehydration of the subducting slab. Our results indicate that large earthquakes do not strike anywhere, but only anomalous areas that may be detected with geophysical methods. These findings may help to improve our understanding of earthquake dynamics and may also contribute to the mitigation of seismic hazards.

1. INTRODUCTION

Despite the decades of international efforts, seismologists still cannot predict earthquakes. Some researchers have begun to suspect that earthquakes are intrinsically unpredictable (e.g., Geller et al., 1997; Kagan and Jackson, 1996), while some others are still optimistic on earthquake prediction but admit that it is a very difficult task (e.g., Varotsos et al., 1996; Wyss, 1997). In spite of such a debate, it is generally believed that continuous seismological studies are needed for clarifying the mechanism of earthquake generation and for the mitigation of seismic hazards.

Japan is an earthquake country and has suffered heavily from seismic hazards during its long history. Nearly one tenth of the earthquakes on Earth occur in or around the Japan Islands, which are caused by active subduction and collisions among four lithospheric plates in this region (Ishida, 1992; Seno et al., 1993, 1996). The Pacific plate is subducting from the east beneath the North America and Eurasian plates in eastern Japan; the Philippine Sea plate is
descending from the south beneath the Eurasian plate in southwest Japan. Large interplate earthquakes occur along the plate boundaries off the Pacific coast of the Japan Islands. Intraplate earthquakes within the continental plate take place in the upper crust beneath the Japan Islands and along the coast of the Japan Sea. Although the crustal intraplate earthquakes do not occur so frequently as the interplate earthquakes, they generally inflict greater damages because they are shallow and near the densely populated areas. A recent example of inland crustal earthquakes is the 1995 Southern Hyogo Prefecture (Kobe) earthquake (M 7.2) in southwest Japan, which caused over 6400 fatalities and tremendous property losses.

In this work we have investigated the relationship between the three-dimensional (3-D) crustal structure and the distribution of large crustal earthquakes of Japan in recent history. An unexpected correlation between them has been found. Our results indicate that arc magma and fluids in the crust and uppermost mantle may be able to contribute to the generation of large crustal earthquakes in island arc or continental margin regions.

Fig. 1. Distribution of seismic stations of the Japan University Seismic Network (solid squares). Open squares show the temporary stations installed following the January 17, 1995 Kobe earthquake (M 7.2) in southwest Japan. Curved lines show the Japan Trench, Sagami Trough and Suruga Trough, which are the major plate boundaries in the Japanese region.
2. HETEROGENEOUS STRUCTURE OF THE JAPAN ISLANDS

We have improved the 3-D P and S wave velocity models of the Japan subduction zone over our previous work (Zhao et al., 1992a, 1994) by using a large number of arrival times from local, regional and teleseismic events recorded by the updated Japan University Seismic Network (JUSN). The JUSN is operated by eight national universities in Japan and consists of about 300 seismic stations equipped with short-period and broad-band seismographs (Tsuboi et al., 1989). It densely and uniformly covers the entire Japan Islands with an average spacing between stations of 25–40 km (Fig. 1). At present the JUSN data are available for the earthquakes in and around the Japan Islands during July 1985 to December 1993. The data are published in Japan University Network Earthquake Catalog (JUNC) by the Earthquake Research Institute, University of Tokyo (Tsuboi et al., 1989). We used over 150,000 P and S wave arrival times from about 5000 local and regional earthquakes (0 to 650 km depths) selected from JUNC (July 1985–December 1993). In addition to first P and S arrivals, we also picked about 1400 P to S and S to P converted waves at the upper boundary of the subducting Pacific plate and S to P converted waves at the Moho discontinuity (Zhao et al.,

![Fig. 2. Distribution of active volcanoes (solid triangles) and Quaternary volcanoes (open triangles) on the Japan Islands. Curved lines show the Japan Trench, Sagami Trough and Suruga Trough, which are the major plate boundaries in the Japanese region.](image-url)
Fig. 3. (a) Contour map of heat flow on the Japan Islands (after Yuhara, 1973). Values are in heat flow unit (10^{-3} \text{cal cm}^{-2}\text{s}^{-1}). (b) Vertical geothermal gradient (in °C/100 m) on the Japan Islands (after Okubo et al., 1989).

We also picked 12,759 P wave arrival times from 174 teleseismic events (M 6.0–8.0) with epicentral distances from 30° to 90° (Zhao and Hasegawa, 1994; Zhao et al., 1994, 2000). The picking accuracy is estimated to be 0.05 to 0.15 s for most of the P arrivals, and better than 0.3 s for all the data.
Fig. 4. P-wave velocity image at a depth of 40 km beneath northeast (a) and central Japan (b). Red and blue colors denote low and high velocities, respectively. Circles denote earthquakes (M 5.7–8.0, depths 0–20 km) that occurred during a period of 115 years from 1885 through 1999. Solid triangles denote active volcanoes. Active faults are shown by thick lines. The velocity perturbation scale and the earthquake magnitude scale are shown on the right and at the bottom, respectively. Crosses and open squares in (a) show low-frequency microearthquakes and S-wave reflectors in midcrust, respectively.
We set up a 3-D grid in the study area with a grid spacing of 25 to 33 km in the horizontal direction and 10 to 30 km in depth. Hypocentral parameters and velocities at the grid nodes are taken as unknown parameters. An efficient 3-D ray tracing technique (Zhao et al., 1992a) was used to compute travel times and ray paths. A conjugate gradient algorithm was used to invert the large sparse system of observational equations. Velocity and hypocenter parameters are determined in an iterative inversion process. The complex geometries of the Conrad and Moho discontinuities and the subducting slab boundary (Zhao et al., 1992b, 1997a) were taken into account in the tomographic inversion. The horizontal resolution is 25 to 33 km for the images of the crust and mantle wedge, and 35 to 40 km for the subducting Pacific slab and the mantle below it. The vertical resolution is 10 to 30 km. Although the major features of the structure are
Fig. 6. P-wave velocity image at a depth of (a) 10, (b) 25, and (c) 40 km beneath southwest Japan. Open triangles denote Quaternary volcanoes. Other labelings are the same as Fig. 4.
generally the same as the previous work, their spatial resolution and reliability are improved.

As shown Fig. 2, active arc volcanoes exist in Hokkaido, eastern Honshu and Kyushu (Yokoyama et al., 1987), which are associated with the subduction of the Pacific and the Philippine Sea plates. Quaternary volcanoes exist along the coast of the Japan Sea in Chugoku (Yokoyama et al., 1987). It is thought that the Quaternary volcanoes are also associated with the subduction of the Philippine Sea plate, although some researchers have suggested that they are caused by the upwelling of a mantle plume (Iwamori, 1991). These volcanic areas exhibit high heat flows and large geothermal gradients, indicating that magma chambers exist beneath the volcanoes and so they have high temperatures (Yuhara, 1973; Okubo et al., 1989) (Fig. 3). Our tomographic images show that seismic velocity is very slow in the volcanic areas, which are caused by high temperatures (Figs. 4–6).

In Kii, Shikoku and southern Chugoku (Figs. 2 and 3), there is no volcano and heat flows and geothermal gradients are low, suggesting that those areas have lower temperatures, and magma chambers may not exist there.

3. EARTHQUAKES IN VOLCANIC AREAS: INFLUENCE OF ARC MAGMA

3.1 Distribution of large earthquakes and tomography

The obtained velocity images are compared with active faults and 160 earthquakes with magnitudes of 5.7 to 8.0 that occurred in the depth range of 0 to 20 km during a period of 115 years from 1885 through 1999 (Figs. 4–6). Hypocentral locations and magnitudes of the large earthquakes during 1885 to 1980 are taken from Utsu (1982). Those from 1981 through 1999 are from the earthquake reports in Journal of Seismological Society of Japan (SSJ) (Vol. 33–42) and SSJ Newsletters (Vol. 1–10). The earthquakes during 1885 to 1926 were located by Utsu (1982) by referring to the historic records on the damages reported by the local governments and newspapers. Those after 1926 were located by the Japan Meteorological Agency using the data recorded by the seismic networks. This earthquake catalog is complete at the M \( \geq 5.7 \) level (Utsu, 1982). The accuracy of the hypocentral locations is estimated to be about 10 km for the earthquakes until 1960 and about 5 km for the events thereafter. The accuracy of the magnitudes is 0.2–0.3 for the earthquakes until 1960 and 0.1–0.2 for the events thereafter. Because all the large historic earthquakes used in this study occurred beneath the inland areas, their locations and magnitudes were relatively well determined.

Prominent low-velocity (low-V) zones exist beneath the active volcanoes in Tohoku (Fig. 4(a)), Kanto and central Honshu (Fig. 4(b)), Hokkaido (Fig. 5(a)) and northern Kyushu (Fig. 5(b)) and the Quaternary volcanoes in northern Chugoku (Fig. 6(c)). Among the tomographic images of all depth levels, the images at 40 km depth (Figs. 4, 5, 6(c)) have the best resolution because this depth slice was most densely sampled by both the horizontally propagating Pn waves (refracted at the Moho discontinuity) from the crustal events and the vertically
traveling rays from the events in the subducting slab. Note that the Moho discontinuity is shallower than 40 km beneath the Japan Islands (Zhao et al., 1992b). In addition, we believe that the horizontal variations of seismic velocity and temperature in the crust are caused mainly by the upward intrusion of mantle diapirs and magma chambers into the crust in volcanic areas, as discussed in the following. In the volcanic areas, the crustal images are actually very similar to the Pn velocity image at 40 km depth. Hence we prefer to use the Pn velocity images (Figs. 4, 5, 6(c)) to represent the 3-D velocity structure of the crust and uppermost mantle beneath the volcanic areas.

We computed P-velocity perturbations ($\Delta V/V$) in the crust and uppermost mantle at the epicenters of the 160 large historic earthquakes in Japan and found that for 70% of the earthquakes, $-3\% < \Delta V/V < 0\%$, and 11% of them having $\Delta V/V < -3\%$. For the remaining 19% of the large earthquakes, $0\% < \Delta V/V < 1.5\%$. These results indicate that the large historic earthquakes generally occurred at the edge portion of low-V zones or along the boundary between low and high velocity bodies (Figs. 4–6). Only some smaller events (M 5.7–5.8) are located in the central part of the low-V zones. It was noticed earlier that large earthquakes (M > 6.0) do not occur within 10 km of a volcano (Ito, 1993). In northern Kyushu, large earthquakes occurred right along the volcanic front (Fig. 5(b)). A few of the earthquakes are located in high velocity (high-V) areas (Figs. 4–6); those events are generally smaller than M 6.0. Note that the resolution of our tomographic images is 25 to 33 km in the horizontal direction and 10–15 km at depths in the crust and uppermost mantle. There is a possibility that some low-V and high-V zones smaller than the resolution scale are not detected in our current tomographic maps.

3.2 Geophysical indicators of arc magma

In Tohoku (Fig. 4(a)), low-frequency microearthquakes occur in or around the low-V zones, which are caused by the upward intrusion of magma chambers (Hasegawa and Zhao, 1994). A total of 153 low-frequency microearthquakes during July 1976 to July 1991 were detected in the depth range of 22 to 47 km around the Moho discontinuity. These events have anomalously low predominant frequencies (1–5.5 Hz) for both P and S waves, in contrast to those (8–20 Hz) of normal crustal events (depths 0–15 km) in the brittle seismogenic layer. The magnitudes of these events are small (M ≤ 2.2). The proximity of these events to the active volcanoes and low-V zones in the uppermost mantle suggests that these deep, low-frequency microearthquakes are generated by magmatic activity of mantle diapirs (Hasegawa and Zhao, 1994).

S-wave reflectors are detected in the crust and they are also located in or around the low-V zones in volcanic areas (Matsumoto and Hasegawa, 1996; Horiuchi et al., 1997) (Fig. 4(a)). The reflectors with a thickness of only about 100 m were detected in the midcrust below the brittle seismogenic layer. They generated reflected S waves with anomalously large amplitudes, which can be explained by a large velocity contrast across a discontinuity underlain by very
low-rigidity materials, such as magma or water in a state of super critical fluids (Matsumoto and Hasegawa, 1996).

Attenuation tomography imaged high attenuation (low-Q) zones in the crust and mantle wedge beneath active volcanoes (Sekiguchi, 1991; Tsumura et al., 1996). The Q images have a resolution of about 40 km. The low-Q zones coincide with the low-V zones (Fig. 4) in both location and spatial extent. In addition, seismic waves passing through the mantle wedge low-V/low-Q zones show strong shear wave splitting, indicating that the low-V/low-Q zones are very anisotropic (Okada et al., 1995; Hiramatsu et al., 1998). The origin of anisotropy in the low-V/low-Q zones is thought to be partial melting. The fraction of melts is estimated to be 2% from the degree of anisotropy and the velocity reduction.

Taking into account the coincidence of the active volcanoes, low-V/low-Q and anisotropic zones, low-frequency microearthquakes and crustal S-wave reflectors, the low-V zones in the uppermost mantle (Figs. 4, 5, 6(c)) are interpreted to represent the magma bodies that form the source zone of the arc magmatism and volcanism (Zhao et al., 1992a, 1994; Hasegawa and Zhao, 1994). The volcanic areas underlain by the low-V zones generally have high topography and larger contractional crustal strain (>10^-5) in the plate convergence directions (Hasegawa et al., 2000). Many microearthquakes in the crust also occurred in those low-V volcanic areas (Figs. 7 and 8).

There are large lateral variations in the temperature of the crust and the cutoff depth of microearthquakes (Matsuo, 1985; Ito, 1993; Hasegawa et al., 2000) (Figs. 7 and 8). The temperature distribution in the crust is estimated by applying the method of Sato et al. (1989) to the seismic velocity data determined by seismic tomography (Zhao et al., 1992a) and temperature derivatives with respect to velocity measured in laboratory (Hasegawa et al., 2000; Zhao et al., 2000). The cutoff depth coincides with the 400°C isotherm and becomes shallower by 5 to 7 km beneath active volcanoes (Fig. 8). Two large crustal earthquakes occurred between two groups of volcanoes in Tohoku. Beneath Unzen Volcano in northern Kyushu, the cutoff depth of crustal microearthquakes shallows clearly toward the crater of the volcano (Fig. 7), indicating the thinning of the brittle seismogenic layer beneath the volcano (Ito, 1993).
3.3 Arc magma and large crustal earthquakes

A qualitative model is proposed to explain these observations for the volcanic areas (Fig. 13). The low-V zones in the uppermost mantle (Figs. 4–6) may be the manifestation of mantle diapirs associated with the ascending flow of subduction-induced convection in the mantle wedge and dehydration reactions in the subducting slab (Zhao et al., 1992a, 1997b). As mentioned above, magma further rising from the mantle diapirs to the crust may cause low-frequency microearthquakes at levels of the lower crust and uppermost mantle, and make their appearance as S-wave reflectors at midcrustal levels. Their upward intrusion raises the temperature and reduces the seismic velocity of crustal materials around them, causing the brittle seismogenic layer above them to become locally thinner and weaker.
Subject to the horizontally compressional stress field in the plate convergence direction, contractive deformations will take place mainly in the low-V, low-Q areas because of the thinner brittle seismogenic layer and the weaker crust and uppermost mantle there due to the higher temperature and the existence of magma- or fluid-filled, thin, inclined reflectors that are incapable of sustaining the applied shear stress. The deformation proceeds partially in small earthquakes but mainly in plastic deformation, causing the crustal shortening, upheaval and mountain building there (Hasegawa et al., 2000). Large crustal earthquakes cannot occur within the weak low-V zones but in their edge portions where the mechanical strength of materials is stronger than those of the low-V zones but still weaker than the normal sections of the seismogenic layer. Thus the edge portion of the low-V areas becomes the ideal locations to generate large earthquakes that produce faults reaching to the Earth’s surface or blind faults within the brittle upper crust (Fig. 13).

4. EARTHQUAKES IN NON-VOLCANIC AREAS: INFLUENCE OF FLUIDS

Figure 6 shows the comparison of the distribution of large crustal earthquakes with the velocity images of the crust (10 and 25 km depths) and the uppermost mantle (40 km depth) in southwest Japan. The velocity images in the upper crust (Fig. 6(a)) are consistent with the surface geology. The high-velocity zones in Kii Peninsula at 25 km depth (Fig. 6(b)) and those in Shikoku at 40 km depth (Fig. 6(c)) are associated with the subducting Philippine Sea slab. We can see that many of the large earthquakes occurred along the Japan Sea coast of Chugoku, where Quaternary volcanoes exist and seismic velocities are lower (Fig. 6(c)). Those large earthquakes may have the same cause as that in the active volcanic regions (Figs. 4, 5, 13). In Kii, Shikoku and southern Chugoku, prominent low-V zones are visible, and large crustal earthquakes occurred also in or around the low-V zones. But it is hard to attribute those low-V zones to high temperature because no volcano exists there and heat flows and geothermal gradients are low in those non-volcanic areas (Figs. 2 and 3).

4.1 Fluids in the earthquake source zone

In order to unravel the cause of large earthquakes in the non-volcanic areas, we have made detailed investigations of the 1995 Kobe earthquake (M 7.2), which may be representative of large crustal earthquakes in southwest Japan. Zhao et al. (1996) and Zhao and Negishi (1998) determined high-resolution 3-D P and S wave velocity and Poisson’s ratio structures in the Kobe source area, and relocated the aftershocks with the obtained 3-D velocity model. They used 64,337 P and 49,200 S wave high-quality arrival times from 3634 Kobe aftershocks and local microearthquakes recorded by over 100 JUSN permanent stations and 30 portable stations that were set up following the Kobe mainshock (Fig. 9). The velocity models have a spatial resolution of 4–5 km in the Kobe fault zone.

Significant velocity variations of up to 6% are revealed in the aftershock area. The Kobe mainshock hypocenter is located in a distinctive zone characterized
by low P and S wave velocities and high Poisson’s ratio (Fig. 10). This anomaly exists in the depth range of 16 to 21 km, and extends 15 to 20 km laterally. This anomaly is interpreted to be a fluid-filled, fractured rock matrix that contributed to the initiation of the Kobe earthquake. This interpretation has been supported by many pieces of evidence from hydrological, geochemical, seismological and geophysical investigations conducted at the Kobe earthquake region (for details, see Zhao and Negishi, 1998).

There may be two origins of fluids in the Kobe fault zone: one is shallow origins such as meteoric water, pore fluids and mineral dehydration in the crust (Kerrick et al., 1984); the other is deep origins such as the dehydration of the subducting oceanic plate. The evidence for them is shown below.

4.2 Shallow origins of fluids

Zhao and Mizuno (1999) estimated the crack density and saturation rate in the Kobe fault zone by applying the partial saturation crack model of O’Connell and Budiansky (1974) to the 3-D P and S velocity and Poisson’s ratio data obtained from the tomographic inversions by Zhao and Negishi (1998). The crack density parameter ($\varepsilon$) is defined as the product of the number of circular cracks
Fig. 10. (a) Distribution of aftershocks (dots) of the 1995 Kobe earthquake within a 5-km width from the line A–B in Fig. 9. (b) P-wave velocity (Vp), (c) S-wave velocity (Vs), and (d) Poisson’s ratio images along the line A–B. Slow velocity and high Poisson’s ratio are shown in circles; fast velocity and low Poisson’s ratio are shown in crosses. The star symbol shows the Kobe mainshock hypocenter. Vp and Vs perturbations range from -6% to 6% from the 1-D velocity model. Poisson’s ratio ranges from 0.225 to 0.27 (-10% to 8% from the average value). The vertical exaggeration is 2:1.

per unit volume and the cube of the average radius of the cracks. The saturation rate (\(\xi\)) is defined as the ratio of the number of cracks filled with fluids to the total number of cracks (O’Connell and Budiansky, 1974). Their results show that \(\varepsilon\) is in the range of 0.02 to 0.15, and \(\xi\) is from 20 to 90% in the Kobe area. At the mainshock hypocenter \(\varepsilon\) exhibits its maximum value of 0.15 and \(\xi\) reaches to
90%, which are 5–10 times greater than those of the surrounding areas off the fault zone.

A significant discrepancy between $\varepsilon$ and $\zeta$ exists beneath Osaka Bay where the crack density is low but saturation rate is high (see the color figures in Zhao and Mizuno, 1999). $\zeta$ is generally high beneath seas but low beneath land areas. The reason for this difference is not clear. An apparent explanation is that sea waters could permeate down to the deep crust during the long geological history. Note that Osaka Bay and the present sea/land distribution in southwest Japan have existed for 2 millions years (Taira and Nakamura, 1986). This period is long enough for the sea water to permeate down to the deep crust through many active faults there, such as the Osaka Bay fault and Nojima fault that would have been ruptured during many earthquakes cycles in the past 2 millions years. Note that the crustal earthquake cycle is 1000–2000 years in the Kobe region (Taira and Nakamura, 1986).

4.3 Fluids from slab dehydration

Kobe is located in the forearc region of the Nankai subduction zone (Fig. 11). The young Philippine Sea plate is descending beneath the Eurasian plate in southwest Japan, causing intermediate-depth earthquakes that occur actively down to a depth of about 70 km beneath Shikoku and to about 140 km beneath Kyushu (Yamazaki and Ooida, 1985; Ishida, 1992). To unravel the structure of the subducting Philippine Sea slab and its possible effect to the Kobe earthquake,
Fig. 12. (a) Vertical cross section of P-wave velocity structure down to 100 km depth along line AB in the insert map. This result is obtained with the data from 793 microearthquakes that occurred in 1993 and 412 Kobe aftershocks in 1995. Crosses and circles denote fast and slow velocities, respectively. Star shows the hypocenter of the 1995 Kobe mainshock (M 7.2). Dots show the microearthquakes within a 20-km width from the line AB, which occurred during 1985 to 1993. The thick lines on the top show the land areas, the Chugoku District and Awaji Island. The open triangle denotes the Kannabe Quaternary volcano in Chugoku. (b) The same as (a) but only the data from the 793 events that occurred in 1993 were used, so it shows the structure before the 1995 Kobe earthquake. The velocity perturbation scale is shown at the bottom.

we applied the tomographic method (Zhao et al., 1992a) to about 40,000 P and S wave arrival times from 1205 shallow and intermediate-depth earthquakes to determine a detailed 3-D velocity structure of the crust and upper mantle under Shikoku and Chugoku. The data set includes 793 microearthquakes collected from JUNEC (January to December, 1993) and from 412 Kobe aftershocks in
Figure 13. Schematic illustration on the influence of arc magma and slab dehydration on the generation of large crustal earthquakes in a subduction zone region. See the text for details.

January to June 1995 (Fig. 9). The result of this inversion shows the subducting Philippine Sea slab clearly (Fig. 12(a)). The slab has a thickness of 30–35 km and a P-wave velocity 4–6% higher than that of the normal mantle. Intermediate-depth earthquakes occur within the high-velocity slab. Slow velocity anomalies are visible in the crust and mantle wedge beneath the Quaternary volcanoes and above the subducting slab (Figs. 6 and 12(a)), indicating that the Chugoku Quaternary volcanoes are caused by the dehydration of the Philippine Sea slab and convective circulation process in the mantle wedge, similar to the active arc volcanoes in northeast Japan.

A prominent low-V zone exists in the lower crust (16–30 km depth) beneath Kii Channel and Awaji Island, right above the subducted Philippine Sea slab (Fig. 12(a)). This low-V zone has properties as the anomaly at the Kobe hypocenter that we detected in the high-resolution imaging, which shows low Vp, low Vs and high Poisson's ratio (Zhao et al., 1996; Zhao and Negishi, 1998) (Fig. 10). To unravel whether the low-V zone under Awaji Island in Fig. 12(a) was caused by the 1995 Kobe earthquake or it had existed there before 1995, we conducted an inversion using only the data from the 793 microearthquakes in 1993. The result (Fig. 12(b)) clearly shows the same low-V anomaly under the Awaji Island and above the Philippine Sea slab, indicating that the anomaly has already existed there since before the 1995 Kobe earthquake. We also determined Vs and Poisson’s ratio structures in this region and found that the low Vp zone under Awaji Island and above the slab also shows low Vs and high Poisson’s ratio.
These results suggest that the fluids that may have contributed to the initiation of the 1995 Kobe earthquake (Zhao et al., 1996) may be also related to the dehydration process of the subducted Philippine Sea slab, in addition to the shallow origins such as meteoric water, pore fluids and mineral dehydration in the crust (Kerrich et al., 1984; Zhao and Mizuno, 1999). The Philippine Sea plate is descending at a very small dip angle in Shikoku and eastern Kii Peninsula, and the subducting slab is located right under the crust (Fig. 11), thus the fluids from the slab dehydration may easily rise to the crust. When the fluids enter the active faults in the crust (such as the Nojima Fault which generated the 1995 Kobe earthquake), fault zone frictions will decrease, and thus fault ruptures may be triggered to generate the large crustal earthquakes (Fig. 13).

5. DISCUSSION AND CONCLUSIONS

Many researchers have suggested that fluids widely exist in the crust and uppermost mantle in the forearc regions of subduction zones (Tatsumi, 1989; Peacock, 1990; Iwamori, 1998). The existence of fluids beneath the seismogenic layer may affect the long-term structural and compositional evolution of the fault zone, change the strength of the fault zone, and alter the local stress regime (Sibson, 1992; Hickman et al., 1995). These influences may enhance the stress concentration in the seismogenic layer leading to mechanical failure. Spatial and temporal variations in the crustal stress field have been reported for the source areas of the Kobe earthquake (Katao et al., 1997) and the 1994 Northridge earthquake (M 6.7) in southern California (Zhao et al., 1997c), which have been associated with fluids in the fault zones.

As described above, we attributed the seismic velocity variations mainly to temperature changes in the volcanic areas and to fluids in the forearc regions in southwest Japan. In the forearc areas of Hokkaido and eastern Honshu where the Pacific plate is subducting, there may also be the effects of fluids from the dehydration of the Pacific slab. Heat flow and geothermal gradient are lower in the Pacific coast areas, and so lower temperatures are expected there. Lithological variations in the crust may also contribute to the heterogeneity in the material property and stress field and cause the slow seismic velocity and the weakening of the seismogenic layer (Magistrale and Zhou, 1996). To distinguish the effects of magma, fluids, and lithological changes on the seismic velocity, much future work is needed by using and combining different geophysical imaging methods (such as gravity, magnetotelluric, geoelectric, geothermal and seismic investigations), numerical simulations and laboratory experiments. Future theoretical and experimental work of seismology should pay more attention to the inelastic structure and processes (magma, fluids and their migrations) in the Earth’s interior.

Hauksson and Haase (1997) found that four earthquakes (M > 5.9) in the Los Angeles basin area occurred in or adjacent to high-velocity zones. They interpreted that the high-velocity zones form the upper block of a thrust fault or a thin skinned structure, i.e., the earthquake ruptures actually happened at the boundary between
high and low velocity zones as shown in their figure 13. Hence their results for Southern California do not contradict our observations in Japan. The tectonic background is very different between Japan and California (e.g., there is no active volcano in California), which would also cause differences in the earthquake dynamics and in the relationship between tomography and earthquake distribution.

The 1995 Kobe earthquake has a right-lateral strike-slip focal mechanism caused by east-west compressional stress field, and so it is generally considered that the subduction of the Philippine Sea plate makes little contribution to the generation of the Kobe earthquake. However, our present work shows that the Philippine Sea slab may have contributed to the Kobe earthquake through chemical and mechanical processes such as dehydration and fluid flow, instead of providing the driving stress. If this is true, it is important from the viewpoint of hazard mitigation, to detect the fluid-related anomalies in the fault zones in forearc areas of subduction regions.

These many pieces of evidence mentioned above suggest that the generation of a large crustal earthquake is closely related to the surrounding tectonic environment, such as plate subduction, and physical/chemical properties of crustal materials, such as magma, fluids, etc. The rupture nucleation zone should have a three-dimensional spatial extent, not just limited to the two-dimensional surface of a fault, as suggested earlier by Tsuboi (1956) in the concept of earthquake volume. Complex physical and chemical reactions may take place in the source zone of a future earthquake, causing heterogeneities in the material property and stress field, which may be detected with seismic tomography and other geophysical methods. The source zone of a M 6 to 8 earthquake extends from about 10 km to over 100 km (Kanamori and Anderson, 1975). The resolution of our tomographic imaging is close to that scale of the earthquake sources, which may have enabled us to image the earthquake-related heterogeneities (i.e., earthquake volumes) in the crust and uppermost mantle in Japan.

These results indicate that large earthquakes do not strike anywhere, but only anomalous areas that may be detected with geophysical methods. Higher-resolution seismic imaging and combining seismological studies with geological, geochemical and geophysical investigations would certainly provide us with a better understanding of the earthquake generating process and would also contribute to the mitigation of earthquake hazards.

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