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Influence of Water on Earthquake Generation along Subduction Zones

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Abstract

To understand the physical bases of earthquake generation along subducting plate boundaries, it is important to know the physical properties of rocks, asperity distribution, and presence of water at the plate interface. Two seismic experiments in the Japan Trench and the Izu-Bonin Trench revealed a strong correlation for aseismic zone and intense seismic reflections, and the possibility of a low-temperature phase of serpentine at subducting plate boundaries. Serpentine layer or high water contents in the layer may cause intense seismic reflections. Free water and/or low-temperature serpentine mineral may act as a lubricant at the subducting plate boundary, and large earthquakes may be controlled by the presence of these materials. We propose three types of subduction zone around the Japan arc and the Izu-Bonin arc to characterize earthquake generation in each subduction zone. Earthquake occurrence in three typical subduction zones may be controlled by differences in the free water contents of rocks and hydrous minerals along subduction boundaries. Dehydration of hydrous phases brings other conditions related to earthquake generation.

Key words: water, serpentine, smectite, hydrous minerals, seismic velocity structure

1. Introduction

Along subducting plate boundaries around the Japan arc, past destructive earthquakes mostly occurred along the Kuril- Japan-Nankai- Hyuga-nada -Ryukyu Trenches. However, low seismic activity of large shallow earthquakes and high activity of deep earthquakes characterize the Izu-Bonin-Mariana Trenches. It is a question of what mechanism controls the different characteristics of earthquake generation among various subduction zones. In Fig. 1, we summarize possible important factors governing earthquake generation along subduction zones. Although stress (or strain) and temperature are the common control factors, free water contents, mineral assemblages, and characteristics of asperities at subducting plate boundaries are also very important. This is because free and mineral water contents and mineral assemblages relate to physical properties at a subducting plate boundary.

Kasahara *et al.* (1998) proposed an observational strategy for oceanic surveys to understand the mechanism of large earthquake generation at subducting plate boundaries. They emphasized the use of seismic characterization for the subducting plate boundary to obtain the physical properties of interface rocks. AVO (Amplitude Variation with Offset) technique (e.g., Yilmatz, 2001), which uses the angle dependencies of reflected waves amplitudes related to acoustic impedance contrast at an interface, is an example of seismic characterization. A strongly coupled plate interface may not have large changes of seismic impedance contrast across the interface as clarified by Kasahara *et al.* (1998). However, a weakly coupled interface has a large impedance contrast,

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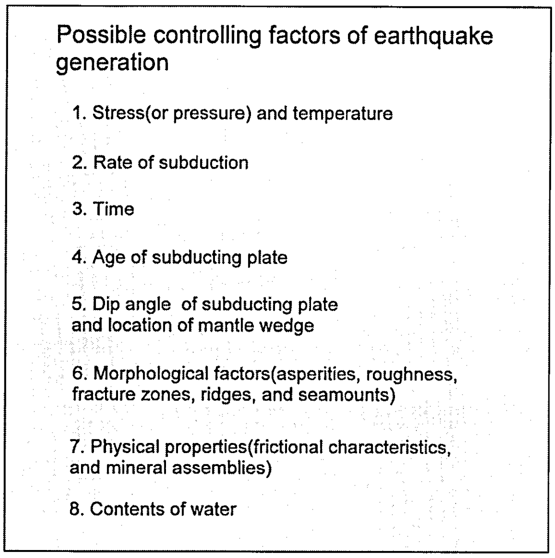


Fig. 1. Summary of factors controlling earthquake generation.

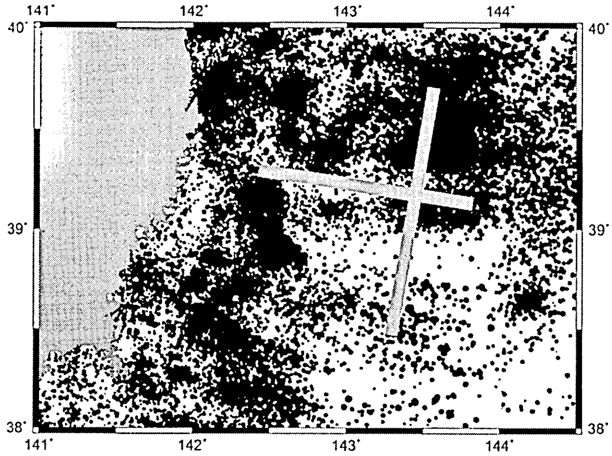


Fig. 2. Earthquake hypocenters shallower than 100 km between 1988 and 1998 observed by Univ. Tohoku. Distinct aseismic zones are seen in the region at 38° 40′ N-39° N. Cross lines show NS and EW survey lines (after Fujie *et al.*, 2000b).

because a weak coupling can be produced by a thin interface layer of a mechanically weak material such as water or hydrous clay minerals.

To understand the physical properties of plate interface rocks, presence of free water, and characteristics of asperities at subducting plate boundaries near Japan, two seismic experiments were carried out in the Japan Trench and the Izu-Bonin Trench (IBT). The survey line of the Japan Trench crossed an aseismic region, which was seen during the past several decades. The survey line in the IBT includes the region of 30° 20′ N-31° 40′ N and 140° 30′ E-142° E.

In this article, we summarize the results obtained by these two experiments, discuss the relation among free water, hydrous minerals and seismic characteristics obtained, and propose three types of the subduction zone to interpret the characteristics of earthquake generation in a shallow part of a subduction zone by means of free water, clay, and serpentine minerals.

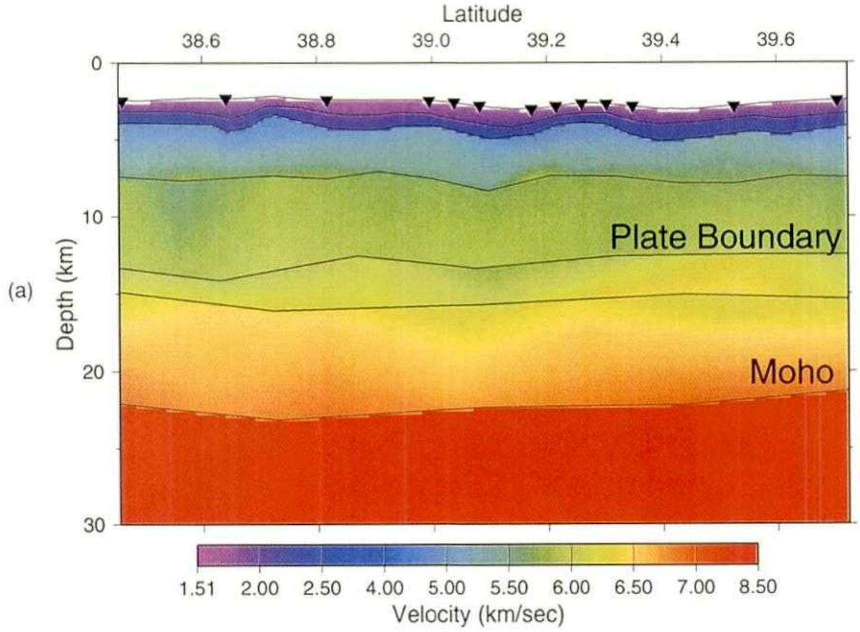
2. Seismic experiments in the Japan Trench and the Izu-Bonin Trench

2. 1. Descriptions of two seismic experiments

Epicenter distribution from 1988 to 1998 obtained by Tohoku University shows the presence of an aseismic zone at 38° 40′ N-39° N and 143° 30′ -144° E (Fig. 2). It seems that this aseismic zone has existed for a long time. Two possibilities can be considered for the aseismic zone: a future focal zone for large earthquakes or an aseismically slipping zone. In previous researches, the aseismic zone has been considered to be as a region with a high potential for future large earthquakes (e.g., Mogi, 1979). However, the second case suggests a continuous slip at subducting plate boundary releasing strain energy and aseismicity due to small elastic strains. As the aseismic zone in the Japan Trench is less sensitive by GPS measurements due to the long distance between it and the coastal area, it is important to clarify the origin of this aseismic zone through seismic refraction/reflection experiments across the aseismic zone.

The second region is characterized by a serpentine seamount called Torishima Serpentine Forearc Seamount (TSFS) and low activities of large shallow earthquakes. Along the Izu-Bonin-Mariana Trenches, an array of serpentine seamounts has been recognized (Fryer et al., 1990) and the TSFS is one of them. Dredges and ODP Leg. 125 drillings at the TSFS brought serpentine mud with serpentinized harzburgite and blueschist rocks (Fryer *et al.*; 1990, Ishii et al., 1992). Harzburgite is characterized by a high Mg/Fe ratio of olivine $(Mg, Fe)_2SiO_4$ and orthopyroxene.

In both experiments, ocean bottom seismometers, airguns shootings, and explosives were used. To determine a structure shallower than approximately 5 km in depth, airgun data were used. Because chemical explosions of 20–40 kg radiate higher energies than airguns, even though explosions are sparse, arrivals from chemical explosions were used to deter-



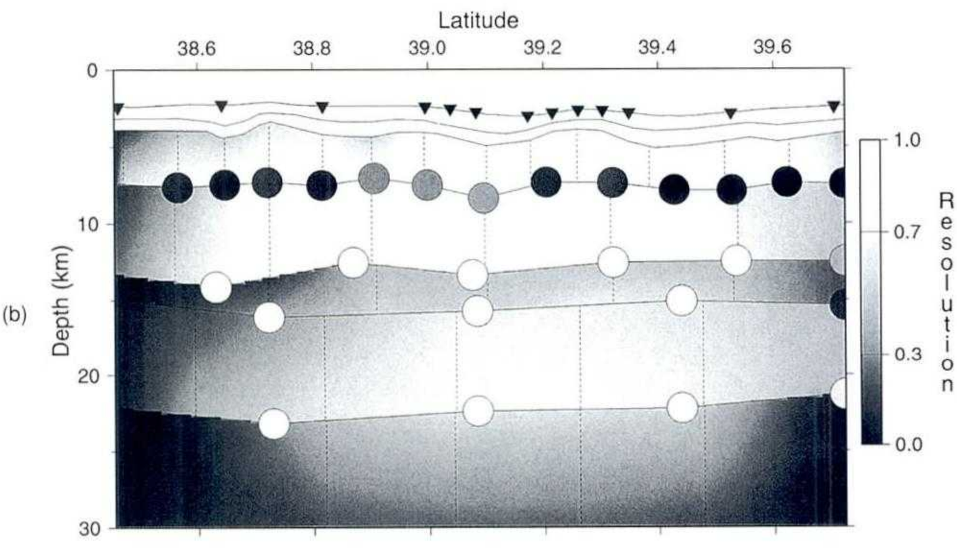


Fig. 3. (a) Velocity structure along the N-S line obtained by a tomographic study shown in Fig. 2 (after Fujie *et al*., 2000b). (b) Resolution for structural model in (a). 1.0 is the best and 0 is the worst. Circles indicate resolution of depth, and background tone shows resolution of velocity. Note the depth resolution at 7km depth seems to be poor due to very small velocity contrast at this layer boundary.

mine structures deeper than 5km. For both analyses, a combination of forward modeling using a ray-tracing technique developed by Zelt and Smith (1992) and a travel-time inversion technique developed by Fujie (1999) and Fujie *et al.* (2000a) were employed. Reflected phases were also included in the inversion. As the travel-time inversion was non-linear, the initial model for inversion was modified to obtain fewer RMS errors than ca. 100 milliseconds using a trial and error approach. Although the improvement achieved by inversion was approximately 30–50 milliseconds in RMS, inversion may give an objective guarantee of the result. During non-linear inversion, ray paths were repeatedly calculated for each linear-inversion process based on a new method (Fujie *et al*., 2000a). Final RMS errors for travel times are approximately 50–70 milliseconds.

2. 2. Results in the Japan Trench

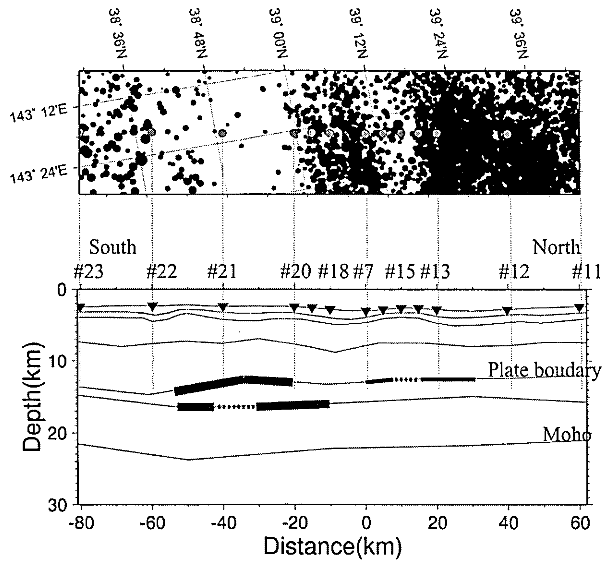


Fig. 4. Comparison of intensity of reflected phases at subducting plate boundaries and seismic activity. Note that there is a good correlation between seismicity and intensity of seismic reflections (after Fujie *et al.*, 2000b, 2002).

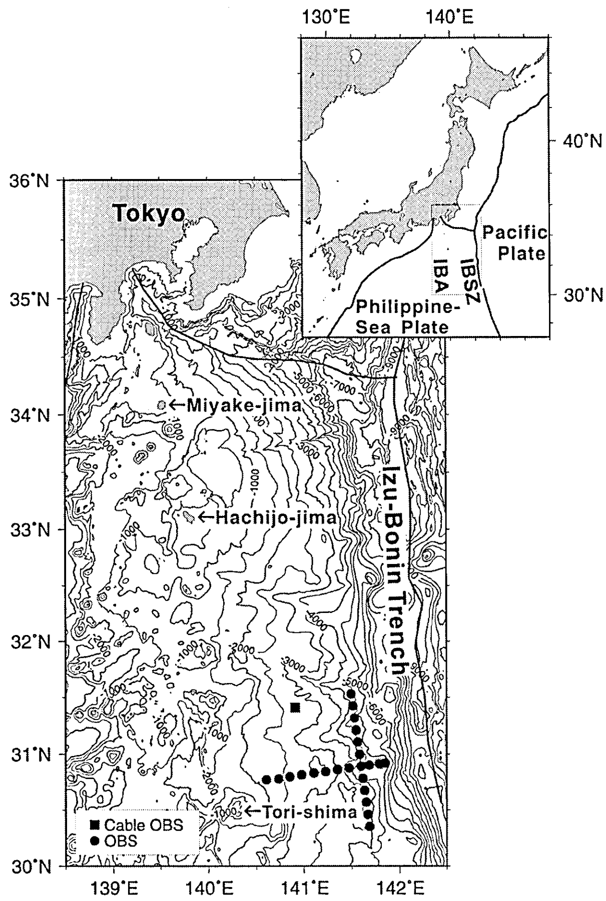


Fig. 5. Survey lines in the Izu-Bonin Trench shown by two crossed dots (OBSs).

In 1996, we carried out a seismic refraction/reflection experiment in the Japan Trench. The aims of this study were to understand the heterogeneous crustal structure across and parallel to the Japan Trench, and to study the relations among aseismic zone, crustal structure, and characteristics of seismic waves on subducting plate boundary.

The survey lines are shown in Fig. 2. Fig. 3a shows velocity structures along the N-S line in Fig. 2, parallel to the Japan Trench obtained by the seismic experiment (Fujie *et al.*, 2000b, 2002). The resolution of the structural model is shown in Fig. 3b. Circles show depth reliability. This suggests that the result is well resolved in the central part and is poor in the south and the north due to few rays. The subducting plate boundary was interpreted at 13 km in depth from the sea surface for this line. The depth of the subducting oceanic Moho was obtained to be 22–23 km. The thickness of the subducting oceanic crust was estimated to be 9 km, which seems a little thick. As only a subtle change is identified in the velocity structure along the line parallel to the trench axis, an aseismic zone existing in 38°40′ N-39° N seems not to be related to structural heterogeneity. In contrast to the rather homogeneous seismic velocity structure, reflected seismic waves have a large amplitude on some OBS #20-22, which were located between 38°40′ N-39° N, but do not have large amplitudes on other OBSs (Fujie, 1999). These phases were interpreted as reflected phases at a subducting plate boundary (Fujie *et al.*, 2000b, 2002). Fig. 4 summarizes the locations of intensive seismic reflections in comparison to earthquakes epicenter distributions along the survey line 40 km-wide in longitude (Fujie *et al.*, 2000b, 2002). It was concluded that intense seismic reflections appear beneath the aseismic zone at 38°40′ N-39° N and beneath 39 °15′ N - 39°-18′ N. In some OBSs, double reflections are identified. The deeper reflection was interpreted to be a reflection in the subduction oceanic crust.

2. 3. Seismic structures of the forearc slope of the IBT and seismic velocity at the subducting plate boundary

A seismic refraction/reflection study crossing the TSFS was carried out in 1998. The aims of this study were to study the characteristics of the Izu-Bonin subduction zone and reveal the relation be-

(a)

(b)

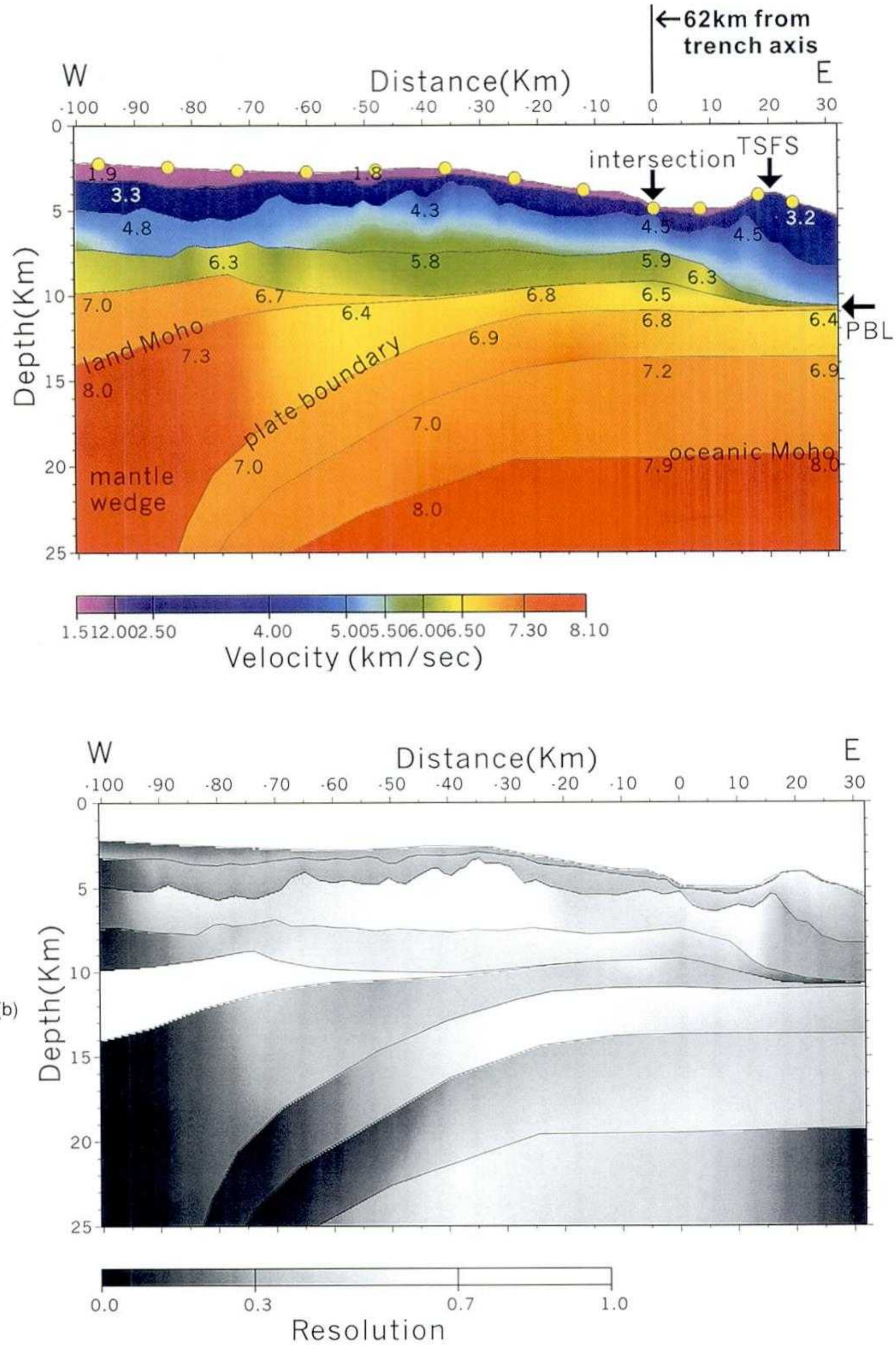


Fig. 6. (a) Velocity structure for E-W line perpendicular to the IBT obtained by a tomographic study. PBL: Plate boundary layer. TSFS is located 20 km from the intersection (0 km). IBT axis is located 62 km east of the intersection (after Kamimura *et al.*, 2002). (b) Resolution of the velocity model in (a).

tween serpentine diapiring and subduction process. The E-W line of the IBT seismic study crossed the TSFS at the eastern edge, and the N-S line was parallel to the IBT axis and approximately 60 km from the trench axis (Fig. 5). Both lines were approximately 130 km long.

From a tomographic analysis of airgun and explosion data obtained by the above survey, two seismic velocity profiles, perpendicular to and parallel to the trench axis, were obtained. Fig. 6a shows the P-wave velocity structure perpendicular to the IBT (E-W line) (Kamimura *et al.*, 2000, 2002). The resolution for the velocity structure is shown in Fig. 6b. Kamimura *et al.* (2002) obtained the following results. In the velocity structure along the subducting plate, a low-velocity (approximately 6.5 km/s) material appears just beneath the serpentine diapir, forms a sill-shape with thickening and increasing velocity from the diapir toward the west, and connects to the wedge mantle. The velocity of the wedge mantle is less than 7.9–8.0 km/s, which is the typical velocity for a normal oceanic mantle. Seismic waves passing through beneath the seamount weakened their amplitude.

Fig. 7a shows results for P-wave velocity structure parallel to the IBT (N-S line) (Kamimura *et al.*, 2002). The resolution for the velocity structure is shown in Fig. 7b. The velocities and the depths at the intersection of the N-S and the E-W are slightly different. This is explained by differences between the two data sets, because velocities and depths at the intersection for one profile were optimally determined using various ray path data along one particular profile. If we place a strong constraint of exactly the same structure at the intersection, a strange irregularity on each profile will appear at the intersection. On this N-S line, the reflected arrivals from the Moho of the wedge mantle, the subducting plate interface, and the Moho of the subducting oceanic plate were clearly identified. Combining the reflecting and refracting results, it is obvious that a thin layer of 6.5 km/s is present between island arc crust and subducting oceanic plate, as shown in Fig. 8. This layer was also interpreted as serpentinized peridotite judging from the presence of the serpentine diapir near the intersection of the two survey lines. In contrast to the E-W line, the crustal structure along the N-S line was found to be homogeneous.

3. Interpretation of results in the Japan Trench and the Izu-Bonin Trench from the viewpoint of free water in boundary rocks and serpentinization

3. 1. A possible interpretation of seismic characteristics in the Japan Trench

The experiment crossing the aseismic zone in the Japan Trench showed a strong correlation between seismic reflection intensity and location of aseismic zone. As indicated by Fujie *et al.* (2002), the intensive seismic reflection phases should correspond to a high seismic impedance contrast across the boundary as mentioned before. From the constraints of the travel time tomography, the constraint for the high seismic contract layer requires that the velocities of the layer below the reflected interface with 2–3 km thickness may not be as slow as 3–4 km/s or as fast as 8 km/s to create the contrast. A possible case is the presence of a thin layer of less than hundred meters in thickness with a low velocity at the subducting plate boundary (Fujie *et al.*, 2002). Such a layer can be interpreted from the presence of free water or a layer with hydrated minerals as serpentine.

A subducting slab has sediment layers, oceanic crust, and oceanic mantle. Sediment layers contain abundant clay minerals represented by smectite. The oceanic crust is considered to be a basalt-gabbro layer. The oceanic mantle seems to comprise peridotite. Smectite contains a huge amount of water. It seems natural to think that some minerals of oceanic crust (MORB) may also be hydrated like that found by oceanic floor alternation. MORB may partly change to the greenschist facies and the blueschist facies rocks (e.g., Takahashi, 2000). MORB composition plus H_2O change the phase as chlorite−>amphibole−>chloritoid+zoisite−>lawsonite+chloritoid at low temperature (<600℃) and high pressure (1 GPa–3 GPa) (Schmidt and Poli, 1998). These phases contain water in a crystaline structure. Hydrated minerals in greenschist facies rocks are chlorite, epidote, and actinolite. Blueschist facies rocks includes glaucophene (a kind of amphibole group). These minerals should dehydrate around 1–3 GPa and 400℃–500℃ (Takahashi, 2000). Dehydration of hydrous minerals in the MORB releases water to the subducting plate boundary. This water should play important role in the physical process of the earthquake generation mechanism. Iwamori (1998, 2001) suggested that dehydration of hydrous minerals in the hydrated oceanic crust produces a fountain at depth of 30–60 km for subduction of an old plate such as the Pacific Pate.

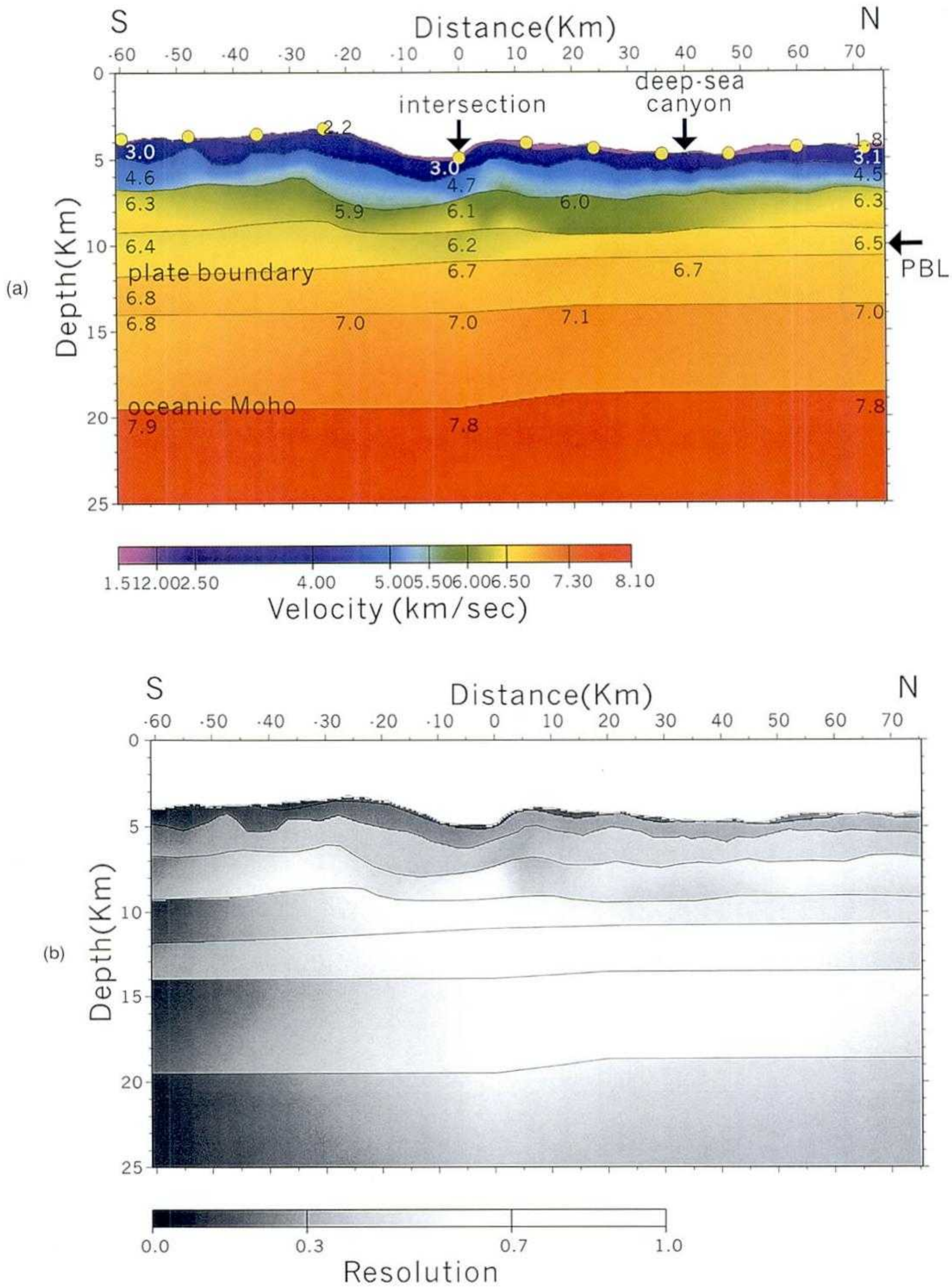


Fig. 7. (a) Velocity structure for N-S line parallel to the IBT obtained by a tomographic study (after Kamimura *et al*., 2002). (b) Resolution of the velocity model in (a).

Yamanaka *et al*. (2000) obtained the asperity distribution for past large earthquakes. They think that the area among asperities generates small earthquakes and a large amount of strain energy is released by viscoelastic slip. If Iwamori's simulation of the hydration-dehydration process at the old plate subduction (Iwamori, 1998) is correct, water released by the dehydration of hydrated MORB may flow through non-asperity parts, and the fluid flow releases strain energy at these portions. This may

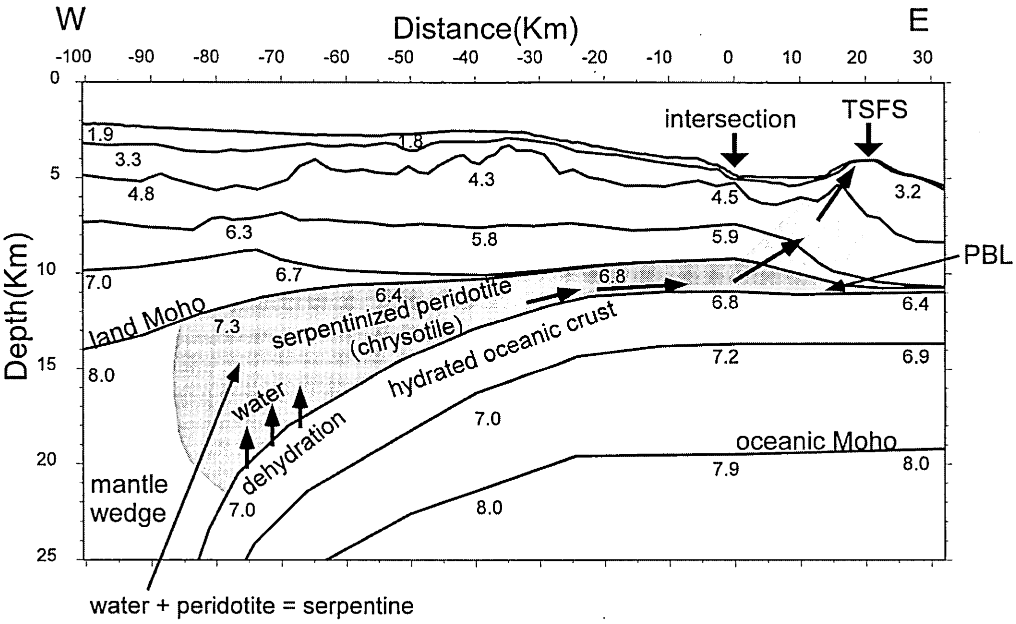


Fig. 8. Schematic representation of the velocity structure of the Izu-Bonin cross section.

cause small earthquakes. In the aseismic zone in 38°40N′-39°N, the entire region may continue to slip due to the presence of water in rocks or clay minerals at the subducting plate boundary and release strain energy continuously.

The island-arc crustal materials above the subducting Pacific Plate have an extremely low seismic velocity (1.5–3 km/s) at water depths greater than 4,000 m on the forearc slope of the Japan Trench (Tsuru *et al.*, 2000). The low seismic velocity materials may have similar characteristics as decollement seen in Nankai and Barbados accretionary prisms, because they have almost the same low mechanical strength. Such low-velocity materials are unlikely seismic sources of large earthquakes, but like a decollement are possible tsunami sources.

3. 2. Izu-Bonin-Mariana Trench type subduction zone

The velocity structure obtained by the seismic experiment in the Izu-Bonin subduction zone suggests serpentinized peridotite along the shallow part of subducting plate and it may continue to the serpentine seamount (Fig. 8). Serpentines are formed of hydration minerals of olivine ($(Mg, Fe)_2SiO_4$) (forsterite - fayalite) under the low-temperature conditions. When peridotites are hydrated by water, they become serpentines ($Mg_3Si_2O_5(OH)_4$) in many cases.

According to Fryer *et al.* (1990), serpentine minerals found at serpentine seamounts at Izu-Bonin-Mariana forearc were probably derived from the island-arc wedge mantle. However, there are some arguments about the origin of serpentinites exposed at the forearc slope. Although Fryer *et al.* (1990) think that serpentinites came along the subducting slab, Ishii *et al.*, (2000) proposed the tectonic erosion process after diapir of serpentinites to the forearc. Although they proposed the exposure of serpentine seamounts approaching the trench axis, we think that the locations of serpentine seamounts show the extent of ease of exposure at the ocean bottom, because the area near the trench axis is the easiest place for an upwelling to the ocean bottom.

Water in hydrate wedge mantle peridotites can be supplied by a dehydration of the hydrated oceanic crust as suggested by Iwamori (1998). The hydration of olivine makes serpentine minerals. There are three serpentine minerals: chrysotile, lizardite, and antigorite (O'Hanley, 1996). Chrysotile is the low-temperature phase below 250℃, and it may correspond to the temperature conditions at the uppermost interface of the wedge mantle and subducted slab of old and cold plate subduction (Iwamori, 1998). The density of chrysotile is low and the chrysotile rocks possibly migrate to shallow parts along the plate boundary. The downward drag force to the slab due to the high dip angle of the Wadati-Benioff zone may assist upwelling along the plate boundary, because the plate boundary may become tensional in this case. Moore *et al.* (1997) showed the frictional strengths of three phases of the serpentine group by the fault gouge experiments. Chrysotile gauge showed a very low frictional coefficient of $\mu = 0.2$, and those of lizardite and antigorite were $\mu > 0.4$. Chrysotile gauge showed stable sliding, but lizardite and antigorite showed a stick slip. Chrysotile is not a swelling clay, but can anomalously absorb water similar to smectite (Young and Healey, 1954). Due to these differences in frictional coefficients, the chrysotile rocks have low-frictional coefficient properties; they may act as a lubricant if they exist at the subducting plate boundary, suggesting rare occurrences of large earthquakes at a shallow boundary.

It is extremely difficult to conclude the presence of serpentinized peridotite in a subducting plate boundary using seismic velocity alone. One reason is that serpentinization occurs gradually. Measurements of seismic velocities in the laboratory show that velocities and densities of serpentinized peridotites vary from 4.9 km/s to 7.4 km/s for 2,513 kg/m^3 and 3,172 kg/m^3, respectively (Gebrande, 1982). The Vp/Vs for serpentinized peridotites with lower velocity specimens show a slightly higher ratio (c.a. 2.0), and the method using Vp/Vs might give serpentinization, although there are many explanations for high Vp/Vs. However, if the mantle has a velocity lower than c.a. 7.8 km/s, it is highly probable that there is serpentinized peridotite in the upper portion of wedge mantle.

4. Another type of subduction zone: Nankai-Barbados

Nankai Trough and Barbados accretionary prism seem to form a very different subduction zone from the Japan Trench and the Izu-Bonin Trench from the viewpoints of earthquake occurrence, dip angle of Wadati-Benioff zone, and age of subducting slab. The Philippine Sea plate subducts beneath the southwestern Japan and the dip angle is c.a. 7° (GSI, 1994). The Philippine Sea Plate is considered to be 15-20 my (Halbouty, 1992). In the Nankai accretionary prisms, a number of 2D and 3D seismic studies and ODP drillings were carried out (Kuramoto *et al.*, 2000, Moore *et al.* 1998, Moore, 2000, Shipley *et al.*, 1994). In both accretionary prisms, clear decollements were identified by seismic reflection profiles beneath the accretionary prisms. ODP drillings Leg. 171A in the Barbados accretionary prism found high contents of smectite just above the decollement zone (Moore, 2000). In the Nankai Trough, there are slight changes in mineral assemblages, but smectite is also found near the decollement (Moore and Shipley, 1993). In these regions, it was found that the decollement acted as a pathway for fluid. The thickness of the decollement is in the order of 20 meters by LWD (Logging While Drilling) data (Moore, 2000). Upper and lower layers of decollement do not have large contrasts of density and seismic velocity to the decollement zone. As the decollement zone is thought to be a tectonically decoupled zone between two plates, large earthquakes should occur deeper than the decollement zone. Therefore, it is important to study physical state and physical properties in deeper structures than the decollement zone. The decollement zone may be a tsunami source region induced by slip at a tightly coupled plate boundary. In this case, the tsunami source should not be the same as the source region of a large moment release region.

Smectite is a kind of hydrous clay mineral and absorbs a large amount of water as inter-layer water. This property shows itself as swelling with water (swelling clay) with the presence of cations near the inter layer (Kawamura *et al.*, 1997). Montmorillonite is one member of the smectite group. Smectite changes to illite and chlorite through the mixed phase of layer minerals in the dehydration process (Kanagawa, 1998). A fault gauge experiment demonstrated that smectite showed stable sliding, but illite showed stick slip (Moore *et al.*, 1989). Shimamoto and Logan (1981) suggested that ten percent of montmorillonite, as a fault gauge, led to stable sliding. Due to this property of smectite, the presence of this clay mineral at a subducting plate boundary may produce a decoupling of stress as suggested by Vrolijk (1990), and Hyndman *et al.* (1998). In addition to the mechanical properties of smectite, the characteristics of absorbing water are important. Absorption of water is translated as impermeability. The smectite rich layer behaves like an impermeable zone to water, and fluid may flow along it. The combination of a smectite rich layer and a fluid layer may comprise a slip zone.

Smectite may not be stable at deeper parts of a subduction zone. Due to the conversion of smectite to illite, the plate interface with an illite rich layer may be mechanically tightly coupled. This may generate a few large asperities along the Nankai subduction zone. Barbados subduction zones are also classified as this type. Because the dip angle of these subduction zones is small, the wedge mantle is far from the trough (or trench) axis. At the Nankai Trough, the Philippine Sea plate is relatively young and subduction of a young and warm plate may disturb serpentinization of the wedge mantle. Dip angle, location of the wedge mantle, age, and temperature of subducting plate determine the conditions for the decomposition of smectite and serpentinization of wedge mantle peridotite.

5. Three typical cases explaining differences in earthquake generation

5. 1. Classification of subduction zones by characteristics of earthquake generation and subduction zone petrology

As discussed in the previous sections, the Japan Trench, the Izu-Bonin Trench, and the Nankai Trough have their own characteristics in terms of earthquake occurrence and mineral assemblage during subduction. We would like to propose three types of subduction zone related to earthquake occurrence: Nankai-Barbados type, Japan- Hyuga-nada-Kuril type, and Izu-Bonin-Mariana type (Fig. 9). The first type is controlled by smectite (a clay mineral), which acts as a lubricant at a subducting plate boundary. The second type is controlled by water and/or serpentine. Hyuga-nada and Kuril can be included in this type. The third type is controlled by serpentine. Serpentine seamounts have not been seen in places other than Izu-Bonin-Mariana subduction zones. These are classified as diagenesis and metamorphisms (Fig. 10). With plate subduction, unconsolidated sediments are compacted by diagenesis, and they suffer from low-grade metamorphism. Successive high-pressure and high- temperature metamorphisms must produce large amounts of water due to metamorphic reactions.

Water in the crust and the mantle are possibly present in fractures, grain boundary, inter-layer water, crystal structure, and inclusions in crystal. Interlayer water occurs typically in clay minerals as seen in smectite. The behavior of clay minerals is very important at the decollement zone. Water in hydrous minerals is the most significant under high-

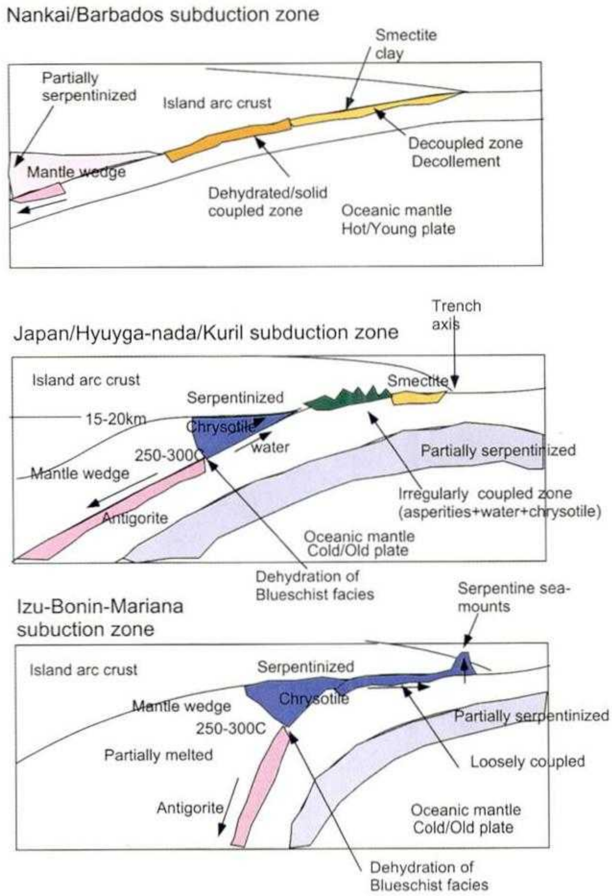


Fig. 9. Three types of earthquake generation at subduction zones. (a) Nankai-Barbados type, (b) Japan -Huyga-nada-Kuril type, (c) Izu-Bonin and Mariana type. In (a), smectite contributes to decollement and it may change to smectite + illite + chlorite phase upon making solid contact with the plate boundary. In (b), smectite and chrysotile, and water may contribute to earthquake generation. In (c), free water generated by the dehydration of hydrated-MORB serpentinizes peridotite in the wedge mantle. Low-temperature phase of serpentine (chrysotile) moves upward along the plate boundary and behaves like a lubricant to decrease large shallow earthquakes. The oceanic mantle may be partially serpentinized.

pressure and high-temperature conditions. Free water released by the dehydration of hydrous minerals moving along or staying at grain boundaries is controlled by dihedral angles of surface energies. A hot plate subducts at the Cascadia subduction zone, and Zhao *et al.* (2001) proposed the presence of a serpentinized mantle wedge at this subduction zone using a tomographic study. This result suggests that the Cascadia subduction zone may be classified as an intermediate type between the Nankai-Barbados

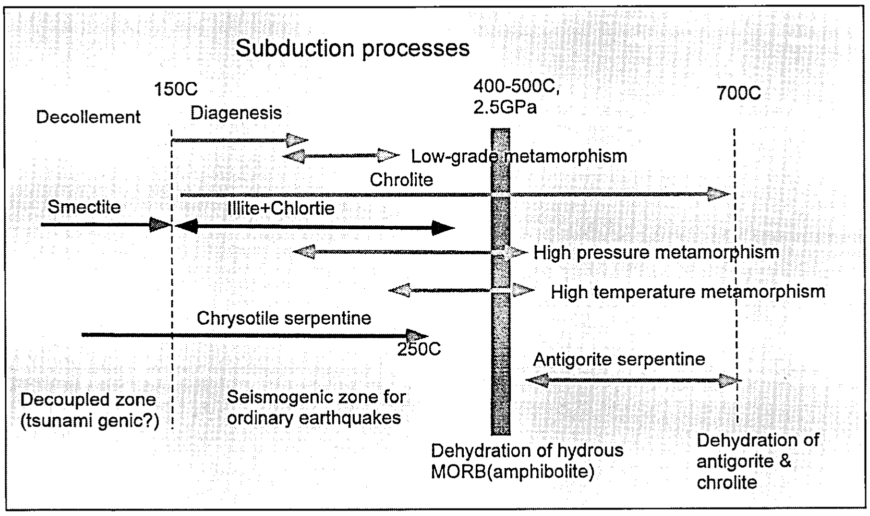


Fig. 10. Summary of physical processes during subduction. Smectite and chrysotile are important factors of earthquake generation at subducting plate boundaries. Dehydration of hydrated-MORB may occur around 400–500℃ at 2.5 GPa.

type and the Japan- Hyuga-nada-Kuril type.

Another important factor for earthquake generation is the deformation rate. It is necessary to separately treat seismic source, tsunami source, and slow movement source detected by GPS. The seismic source region is considered to be a seismic moment release region, and radiates seismic waves shorter than a few hundred seconds. A tsunami source region may or may not be the same as the seismic source region, because a tsunami is caused by rather slow deformation, namely several minutes of characteristic periods. Crustal deformation measured by GPS is not necessarily the same as the seismic source.

5. 2. Water in the island arc crust and some additional effects of water

Zhao *et al.* (1998) proposed the possibility of water triggering Hanshin-Kobe earthquakes using the tomographic method. Takeda (2001) found intense seismic reflection at the subducting plate boundary beneath Kii Peninsula, which has a good correlation with low seismic activity. This can be interpreted as free water at the subducting plate boundary.

Some free water generated by dehydration of hydrated MORB and carried by subduction slab, may hydrate wedge mantle peridotite, and may produce antigorite, but not chrysotile because of the relatively high temperature. Ulmer *et al.* (1995) showed that antigorite dehydrates at around 700℃. Schmidt and Poli (1998) obtained 700℃ at 2 GPa for the dehydration reaction of serpentine to orthopyroxene+olivine+H_2O. According to Iwamori (1998), the temperature corresponds to 150 km–200 km in depth for the old and cold slab subduction. Through the dehydration of antigorite, free water is also released to the subducting plate boundary and it may strongly affect earthquake generation. If the inter-granular water stays in the subducting plate boundary, it may have an embrittlement effect as suggested by Raleigh and Patterson (1965). On the other hand, if free water migrates quickly, embitterment may not occur as suggested by Brodie and Rutter (1987). The low seismicity around 150–200 km may suggest the latter case.

6. Conclusions and summary

To understand physical properties, physical state, and presence of water at the interface, two seismic experiments were carried out in the Japan Trench and the Izu-Bonin Trench.

They revealed a strong correlation between aseismic zone and intense seismic reflections, and the possibility of a low-temperature phase of serpentine at a subducting plate boundary. Earthquake occurrence at subduction zones may be controlled by differences in water contents and hydrous minerals along subduction boundaries. We propose three types of subduction zone from the viewpoint of earthquake occurrence and mineral assemblage. Nankai-Barbados type subduction is mainly controlled by decollement and clay minerals such as smectite. The Izu-Bonin type may be mainly controlled by the low-temperature phase of serpentine (chrysotilte). The Japan-Hyuga-nada-Kuril type may be controlled by water and/or chrysotile and antigorite. Serpentine layer or high contents of water in the layer may cause intense seismic reflections. Water and/or chrysotile may act as a lubricant at the subducting plate boundary and large earthquakes may be controlled by the presence of these materials. Dehydration of hydrous phases brings about other conditions related to earthquake generation.

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