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Seismogenic layer, reflective lower crust, surface heat flow and large inland earthquakes

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Abstract

Regional variations in the cutoff depth of seismicity in southwest Japan are derived from more than 60,000 well-determined earthquakes. The thickness of the seismogenic layer is closely related to the strength of the crust and accordingly to the occurrence of large inland earthquakes, since the seismic–aseismic boundary is thought to be related to the brittle–ductile boundary in the crust. Large inland earthquakes are likely to occur in the area where the cutoff depth of seismicity changes abruptly. It is therefore important to survey the regional variations in this depth to evaluate the potential of large inland earthquakes. The cutoff depth of seismicity roughly coincides with a temperature range of 300–400ºC in the crust. In addition, distinct S-wave reflectors as well as a reflective lower crust have generally been observed in some areas in Japan. The depths of the reflector and the top of the reflective lower crust lie several kilometers below the cutoff depth of seismicity and they seem to coincide with a temperature range of about 300–450ºC. Therefore, in those areas where no earthquakes occur but a reflective layer exists, the cutoff depth can be mapped from a survey of reflectivity in the crust. The heterogeneity of the crust is very important for understanding the nature of the crust where large earthquakes are frequent. This paper proposes a model of crust inhomogeneity based on observation results.

Keywords: crustal structure; seismogenic layer; reflective lower crust; intra-plate earthquake; heat flow; seismicity; southwest Japan

1. Introduction

Seismic–aseismic boundaries in the middle crust have been clearly defined from accurate hypocenter determinations in many areas where earthquakes occur only in the upper crust. The cutoff depth strongly depends on the thermal structure of the crust (Kobayashi, 1977; Ito, 1990). Thus, it is interpreted that the seismogenic layer is related to the brittle–ductile boundary in the crust (Brace and Kohlstedt, 1980; Sibson, 1982; Meissner and Strehlau, 1982; Meissner and Wever, 1986), although the detailed connection is still in question. The thickness of the seismogenic layer therefore appears to be related to the strength of the crust and also to the occurrence of large earthquakes (Sibson, 1984; Mizoue et al., 1986; Shimamoto, 1989; Ito, 1992).

In recent years, a reflective lower crust has been detected in Japan (Yoshii, 1990) as well as in the

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United States, Europe and other continents (Mooney and Brochier, 1987). The top of the reflective lower crust also changes with the crustal temperature (Klemperer, 1987). Thus, the cutoff depths can be determined from the crustal reflectivity even in areas where there are no earthquakes. Further, distinct S-wave reflectors have been found in some areas near volcanoes (Mizoue, 1980; Matsumoto and Hasegawa, 1996, 1997). These reflectors seem to be the 'bright spots' found by reflection seismology and can be caused by a magma reservoir (Sanford, 1965; Brown et al., 1980) or some other strong heterogeneity in the crust. Such crustal heterogeneity appears to be very important for the nucleation process of large earthquakes in the crust.

This paper modifies the model for nucleation of large earthquakes proposed by Ito (1992) using new data and evidence. However, the modified model is still tentative and qualitative. We are now conducting observations in the Tohoku district using a dense network of seismological stations to make the model a quantitative one.

2. Cutoff depth of seismicity and large earthquakes in the crust

The cutoff depth of seismicity in the crust was precisely redetermined from careful analyses of microearthquakes observed by a dense network of stations (Ito et al., 1995). Fig. 1 shows the epicenter distribution in southwest Japan. These well-determined events are selected from more than 110,000 hypocenters determined from 1976 to 1991 in this

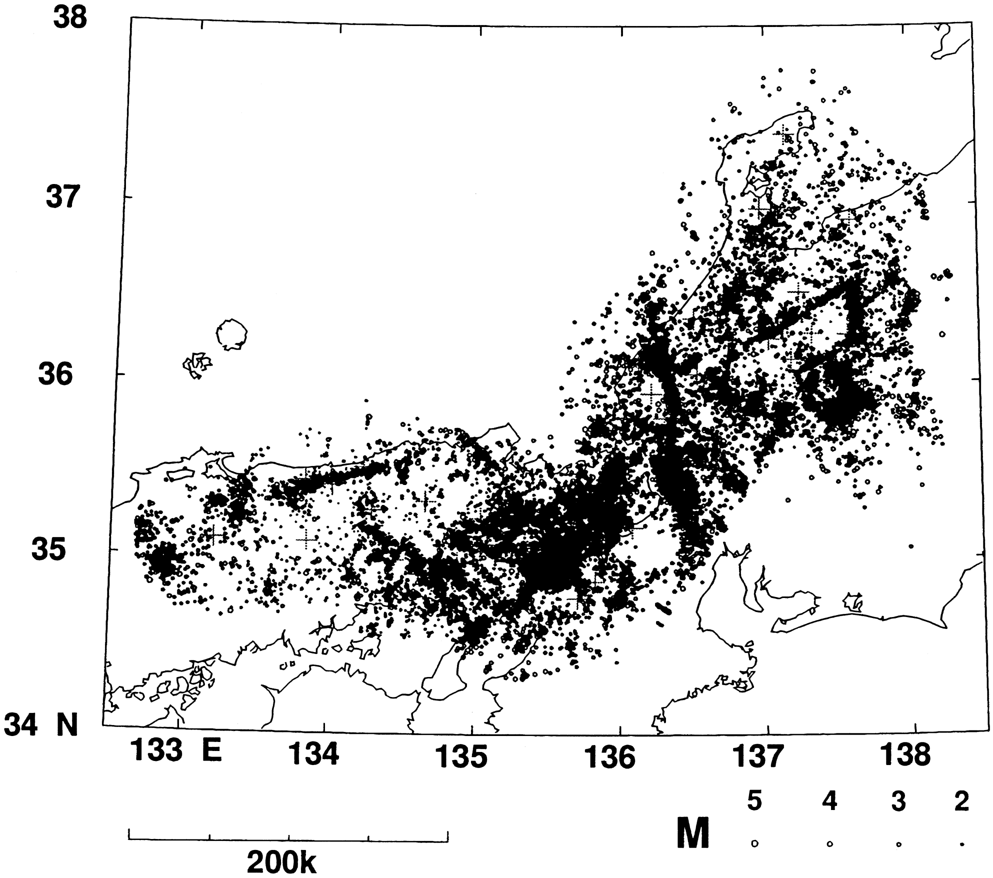

Fig. 1. Epicenter distribution of selected earthquakes from 1976 to 1991 in southwest Japan. About 64,000 events were selected from more than 100,000. Contours of the cutoff depth of seismicity in Fig. 3 are derived from these data.

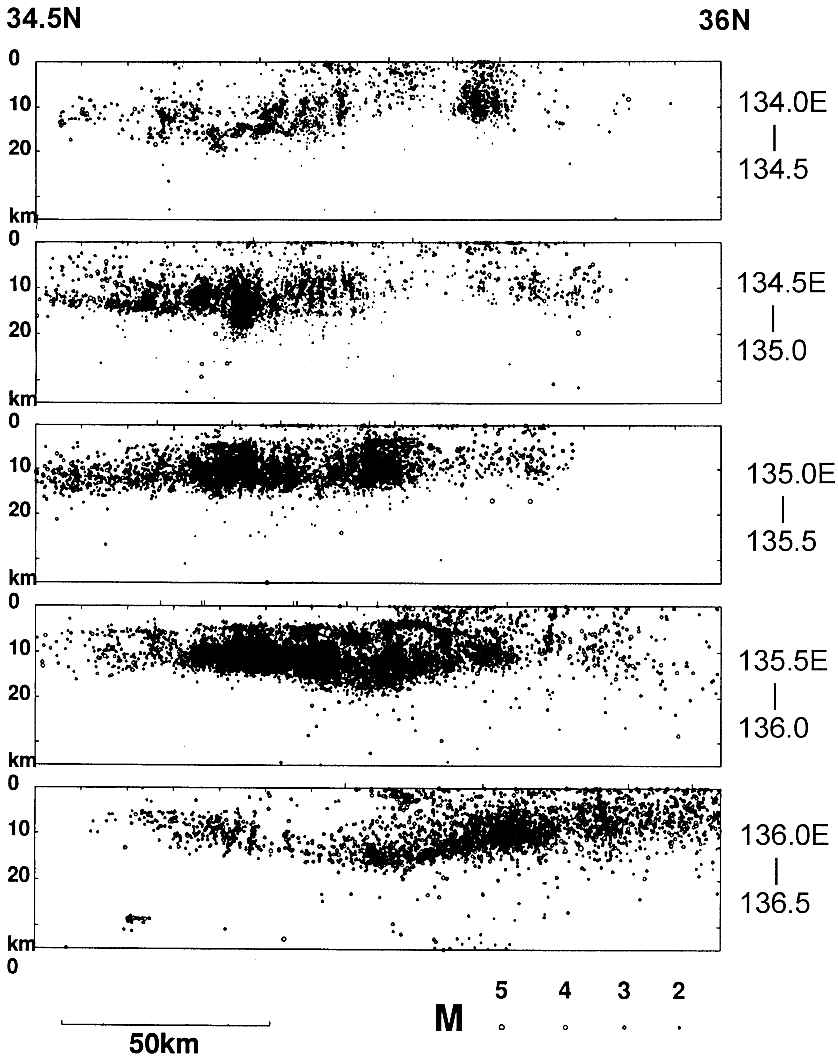

Fig. 2. Examples of focal depth distributions of earthquakes in Fig. 1 projected on the north–south direction.

area by use of high-gain short-period networks (Ito et al., 1995). The focal depths were precisely re-determined from detailed analyses of data recorded by telemetered networks. Some examples of focal depth sections are shown in Fig. 2, in which variations in cutoff depth are quite evident. Fig. 3 shows contours of the variations in cutoff depth of seismicity. Several characteristic features of cutoff depth can be seen. The depths of the seismic–aseimic boundaries vary from place to place within a depth range of 12–25 km with an undulation wavelength of about 30–50 km. The cutoff depth is generally shallow in mountainous areas and particularly shallow in volcanic areas. This shows that the cutoff depth is closely related to the thermal structure in the crust.

Large earthquakes with magnitudes of *M* 6 (Japan Meteorological Agency scale) or greater which occurred in the area in the period from 1827 to 1995 (Utsu, 1982; Usami, 1987; JMA) are also shown in Fig. 3. The hypocenters of old earthquakes up to 1884 are after Usami (1987) and those from 1885–1925 after Utsu (1982). Since there are many historical records in this area, the epicenters are accurate enough even for historical earthquakes to discuss

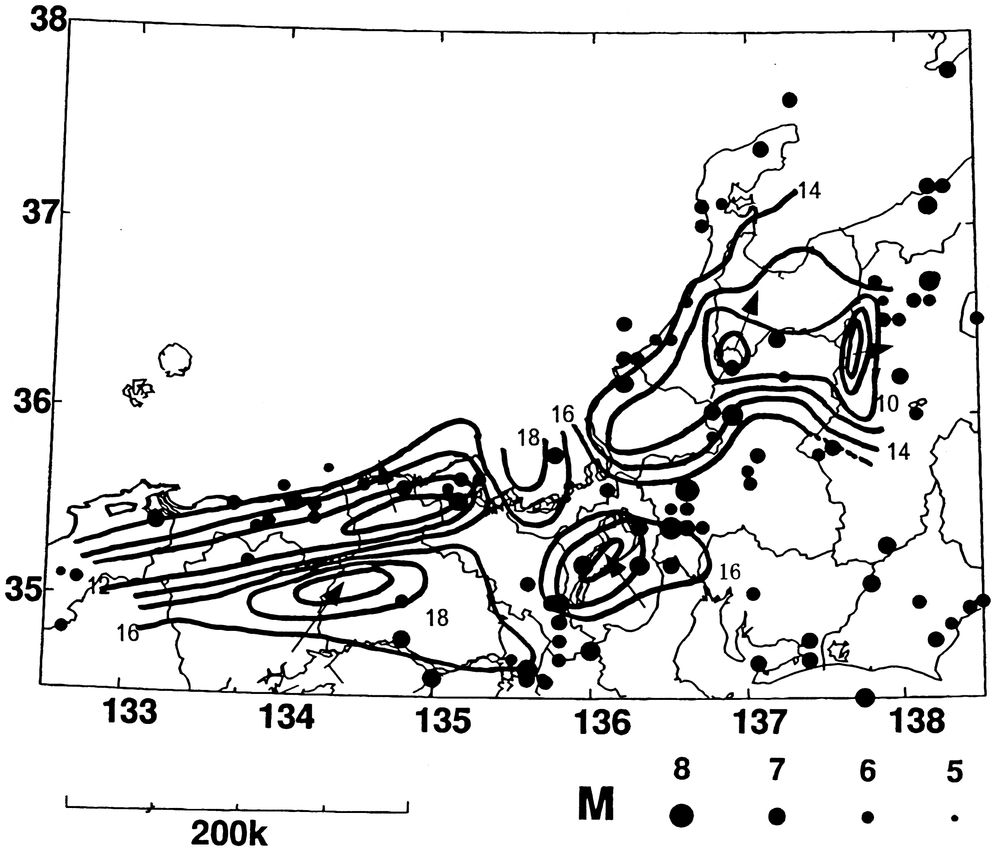

Fig. 3. Contours of cutoff depth of seismicity in southwest Japan. Contour interval is 2 km. Numerals show cutoff depth. Dots indicate large earthquakes with *M* 6 or greater from 715 to 1995.

the following relationship. Events after 1926 are taken from JMA (Japan Meteorological Agency) catalogues. As a result, referring to other distributions of precise focal depth distributions of earthquakes (e.g. Ito, 1990), large shocks seem to occur in areas where the lateral gradients of the cutoff depths are steep. These areas correspond to the boundaries between mountainous areas and lower planes (Ito et al., 1995). Thus, the variations in thickness of the seismogenic layer may be closely related to the occurrence of large earthquakes.

3. Cutoff depth of seismicity and thermal structure in crust

Although many factors affect the cutoff depth of seismicity, the thermal structure of the crust in this respect is found to be dominant in most areas. Fig. 4 shows cutoff depths versus surface heat flow values for the world (Ito, 1990). The top-sides of the rectangles indicate the depth above which 90% of the earthquakes occur, while the bottom side denotes the cutoff depth of seismicity. The hatched rectangles show data for Japan. There are not many areas with both accurate focal depth distributions and surface heat flow values. However, the number of measurements has been increasing in recent years. Fig. 4 shows that the cutoff depths are roughly inversely proportional to the surface heat flow. The isotherms shown in Fig. 4 are calculated as in Chapman (1986). Isotherms between 300 and 400°C roughly correspond to the cutoff depth, as has been pointed out by several other studies (Kobayashi, 1977; Sibson, 1982).

Well-determined hypocenter distributions often show that there is an upper cutoff of seismicity near

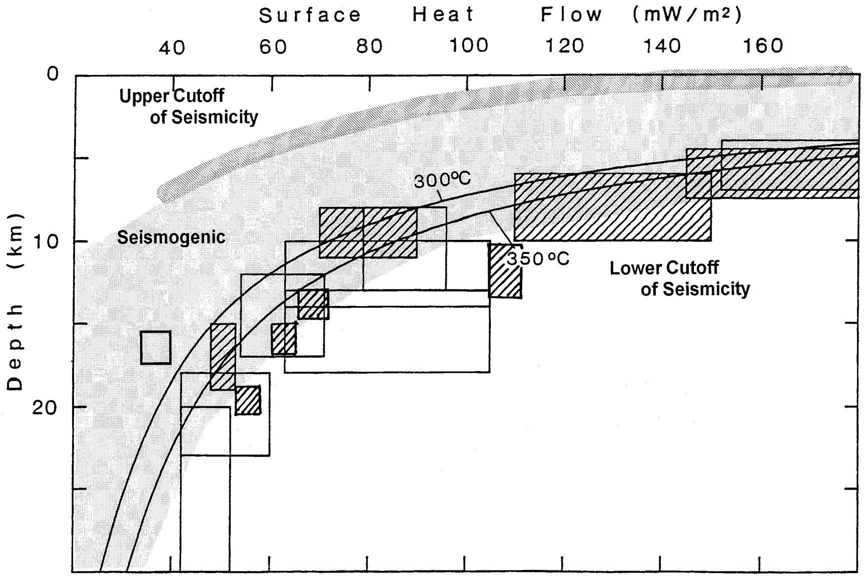

Fig. 4. Upper cutoff of seismicity and seismogenic zone (shaded zone) are drawn in the figure of lower cutoff depth of seismicity and surface heat flow (Ito, 1990). The upper region of the rectangle indicates the depth above which 90% of shocks occur, while the lower region shows the cutoff depth of seismicity. Isotherms of 300 and 350°C are calculated as in Chapman (1986).

the surface of the crust. This feature is seen in some sections of Fig. 2. The upper cutoff depth changes in the same way as the lower cutoff depth in many areas. That is, for a deep upper cutoff depth, there is also a deep lower cutoff depth. The change in the upper cutoff depth is in the range of 0.5–8 km and the accuracy of the focal depths of shallow events is usually not very good, making it very difficult to detect lateral variations. However, the nearly parallel variations in the upper and lower cutoff depths are clearly observed in volcanic areas or in geothermal areas as well as in areas where focal depths are accurately determined. Fig. 4 shows the change in the upper cutoff depth schematically.

If the thermal structure is related to the occurrence of large earthquakes, it is logical to examine earthquakes near volcanoes where the lateral temperature variation is large. Ito (1992) studied the focal depth distributions near active volcanoes: the Izu–Oshima, Unzen, Kirishima, Sakurajima and Aso volcanoes in Japan. All depth sections of earthquakes near active volcanoes show shallow cutoffs under the active crater. The cutoff depth is usually less than 5 km right below the crater, extending to approximately 10 km or more below the flanks of the volcano. The cutoff depths decrease towards the center from both sides of the volcanoes. Hasegawa and Yamamoto (1994) made a composite depth cross-section of earthquakes near several volcanoes in the Tohoku district of northeastern Japan, indicating a similar gradual decrease of the cutoff depth of seismicity towards the craters. Smith et al. (1977) reported similar features of focal depth distributions and thermal structure in the Yellowstone hot spot. Thus, from the collection of well-determined focal depths near volcanoes, it is clear that the cutoff depths decrease from the flanks toward the center of the volcano (Ito, 1992). Shallow cutoff depths of seismicity can also be found in some geothermal areas in Japan. These facts indicate that the changes in the thickness of the seismogenic layer strongly depend on temperature.

Sholtz (1998) reviewed the upper and lower cutoff depth of seismicity in relation to thermal structure. On the basis of the constitutive law of frictional resistance, he showed that the upper cutoff depth might be caused by loosely consolidated material. However, he also showed that the parameters of the constitutive law depend on temperature, and it may be hard for earthquakes to occur in low-temperature areas as well as in high-temperature areas. There is an aseismic layer in the shallow depth of a few km in the subduction zone. This shallow transition from seismic to aseismic is interpreted as a thermal effect (Hyndman and Wang, 1993). According to their result, very few earthquakes occur in the low-temperature zone of less than 100–150°C. The temperature dependence of upper cutoff depths shown in Fig. 4 may be evidence of the thermal effect of the seismic–aseismic boundary in the crust.

4. Large earthquakes near volcanoes

The distances from large earthquakes to the nearest volcano are calculated and plotted in Fig. 5 (Ito, 1992). This shows that no large shocks occurred within 8–10 km of a volcano. Taking into account the accuracy of the hypocenters of old events during the period 1885–1925, large shallow events with magnitudes equal to or greater than 6.5 were selected. Large shallow earthquakes (depth less than 30 km) in the period 1926–1987 with magnitudes equal to or greater than 6.0 were obtained from the JMA catalog. The accuracy of the former epicenters is less reliable than that of the latter, whose hypocenters were determined from the data of the improved observation system. Since surface ruptures and/or damage reports were also considered when determining the locations of most of the former earthquakes, the locations can be used for the present analyses (Ito, 1992).

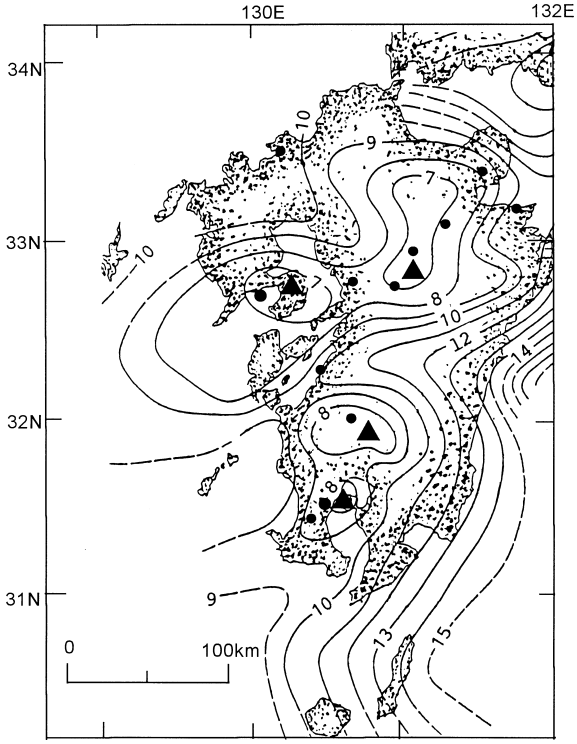

Fig. 6. Contours of Curie depth in km (solid line after Okubo et al., 1989), volcanoes (triangles) and large earthquakes of M 6 or greater from 1885 to 1987 (dots) in Kyushu, Japan.

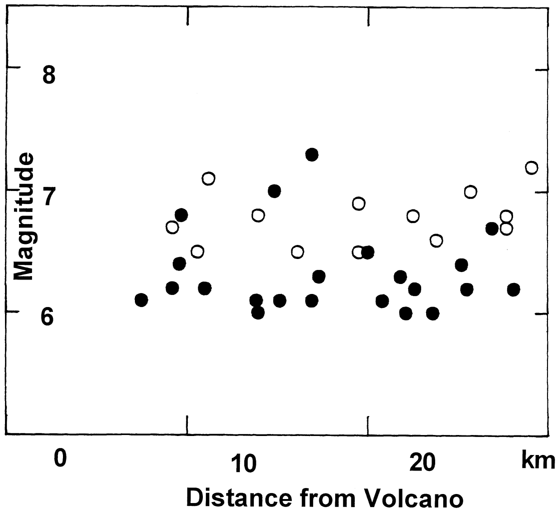

Fig. 5. Magnitudes of large earthquakes near active volcanoes as a function of distance from the craters of volcanoes. Circles indicate seismic events from 1885 to 1925 and dots those from 1926 to 1987. It should be noted that large earthquakes occur at distances of about 8–10 km or greater from the volcanoes.

Fig. 6 shows the contours of Curie depth points (Okubo et al., 1989), active volcanoes (triangles) and large earthquakes of magnitude 6 or greater (solid circles) in Kyushu Island. Although there are some problems with the absolute values of the Curie point depth because of the many assumptions, the variations in relative values of the Curie point depth indicate well the thermal structure of the crust. As shown in Fig. 6, Curie depth points are shallow near volcanoes and also outline the volcanic areas. Some large seismic events occurred near but not very near volcanoes. Most large shocks occur at distances of more than 8–10 km from volcanoes (Fig. 6). Nearly the same distributions are obtained in other volcanic areas, such as the Tohoku, Kanto and Chubu districts in Japan. Thus, large earthquakes are likely to occur in regions with large lateral variations in temperature gradient.

It is obvious that no large earthquakes occurred near the center of volcanoes in the Japanese Islands from 1885–1987 (Figs. 5 and 6). It may be inferred from these observations that the seismogenic layer, being so thin close to the craters, cannot accumulate enough stress to cause a large earthquake. However, at the base or outside the area of the volcano, the seismogenic layer is thick enough to accumulate sufficient stress for a large earthquake.

5. Top of reflective lower crust and thermal structure

The 'reflective lower crust' has been found in the United States, Europe and Australia by the reflection technique (Mooney and Brochier, 1987). In Japan there are only a few reflection sections that probe the entire crust. However, some wide-angle reflection records from refraction seismic surveys clearly show the reflective lower crust. Fig. 7 shows an example of a record section of an explosion seismic survey in the northern Kinki district (RGES, 1995). The large amplitudes indicate the waves reflected from the middle and lower crust. Reflected waves of this kind have been observed in several areas of the Japanese Islands (Yoshii, 1990). This suggests that there is a reflective lower crust below the Japanese Islands.

Fig. 8 shows the focal depths of microearthquakes and the top of the reflective lower crust in the Kinki district. The broken lines in the lower crust indicate schematically the depth range for reflected waves with large amplitudes. The top of the reflective lower crust seems to have nearly the same depth variation as the cutoff depth of seismicity, although the former is 3–5 km deeper.

Klemperer (1987) indicated a relationship between the top to the reflective lower crust and the surface heat flow. Hyndman and Shearer (1989) pointed out a similar relationship between the top of the low-resistivity area and the surface heat flow. Both relationships are very similar to that displayed in Fig. 4 between the cutoff depths and the surface heat flow. The temperature of the top of the reflective lower crust and the low electrical resistivity regions is about 300–450°C in the continental crust, which is about equal to that of the cutoff depth. The top of the reflective lower crust determined in the Kinki

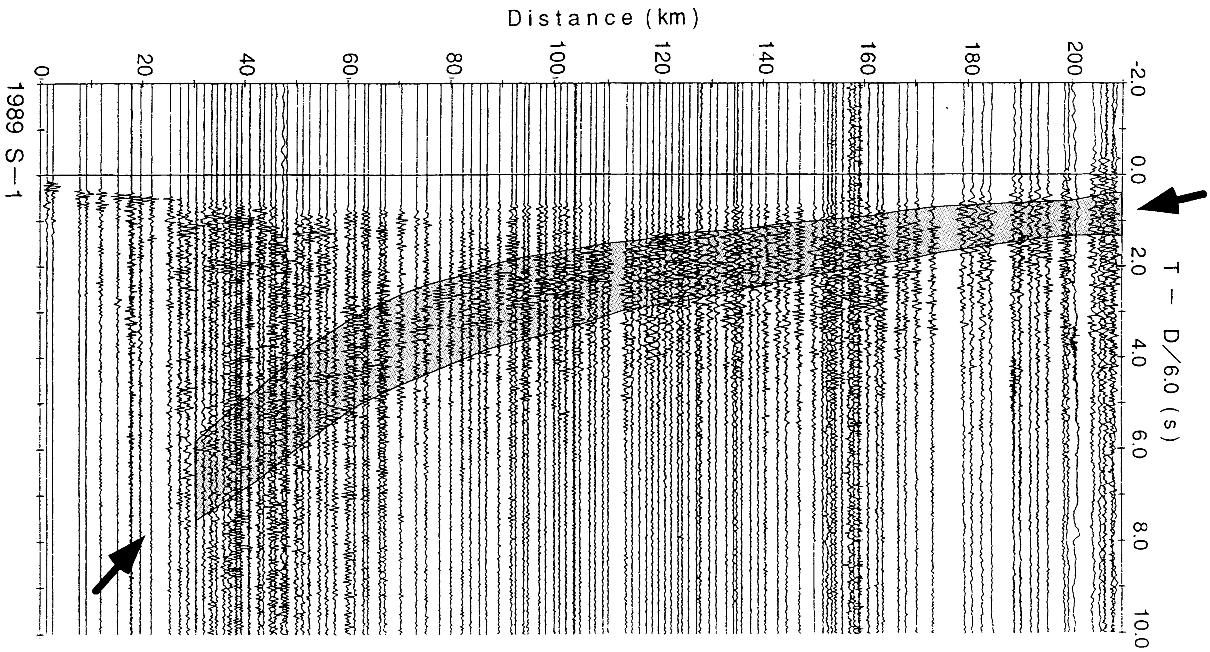

Fig. 7. Record section of an explosion survey in the northern Kinki district, Japan. Later arrivals with large amplitude (shaded area) indicate reflection from middle to lower crust.

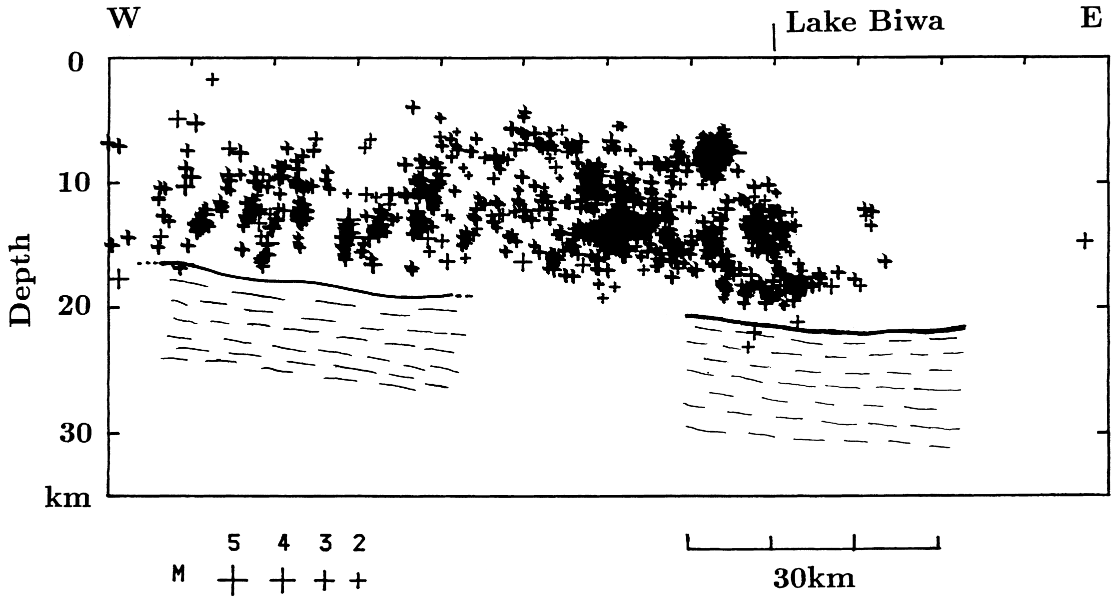

Fig. 8. Cross-section of focal depths of earthquakes and top of reflective lower crust in the northern Kinki district, Japan. Broken lines schematically indicate the depth range of the reflective lower crust.

district and other areas in Japan roughly corresponds to the relationship by Klemperer (1987). Only a few low-resistivity layers in the mid-crust of Japan have been obtained in the same manner as Hyndman and Shearer (1989) pointed out. However, Fujita et al. (1997) reported a clear low-resistivity layer corresponding to a seismic reflection in the middle crust in the Kii Peninsula, central Japan.

6. Distinct reflection of S-waves

Clear reflections of S-waves at the mid-crust have been observed in some areas in Japan (Mizoue, 1980; Matsumoto and Hasegawa, 1996, 1997). The reflected waves with large amplitude are thought to be the same kind of waves as those discovered in the Soccoro Rio-Grande region, New Mexico (Sanford, 1965; Brown et al., 1980), which were interpreted as SxP and SxS. The wave reflectors were found mainly near volcanoes, but not right below the craters. In some areas, the depths of the reflection points are determined from detailed analyses of the waves. The depths of the reflection points decrease towards the volcano as does the cutoff depth of seismicity, forming a half of an inverted-cone-shaped reflection plane around the volcano (Matsumoto and Hasegawa, 1996, 1997). This kind of reflection was found in some areas, where the cutoff depth of seismicity seems to go along with a similar change in the reflection depths (Nishiwaki et al., 1989; Inamori et al., 1992).

The relation of this layer to the reflective lower crust is not clear. However, reflective layers are common in the plastic regime not only in the lower crust (15–30 km) but also in the upper crust, with a very shallow seismogenic layer. Thus, the reflective layers in the crust might be caused by ductile deformation. As a consequence, the cutoff depths and the reflective layers seem to be related through the thermal structure. Moreover, strong reflections of S-waves might be caused by magma or fluid in the crust and may play an important role in the nucleation of large earthquakes (Zhao et al., 1996; Zhao and Negishi, 1998).

7. Model of crustal structure for large inland earthquake

Fig. 9 shows a schematic model for the occurrences of large earthquakes in the crust. The cutoff depth of seismicity and the top of the reflective layer

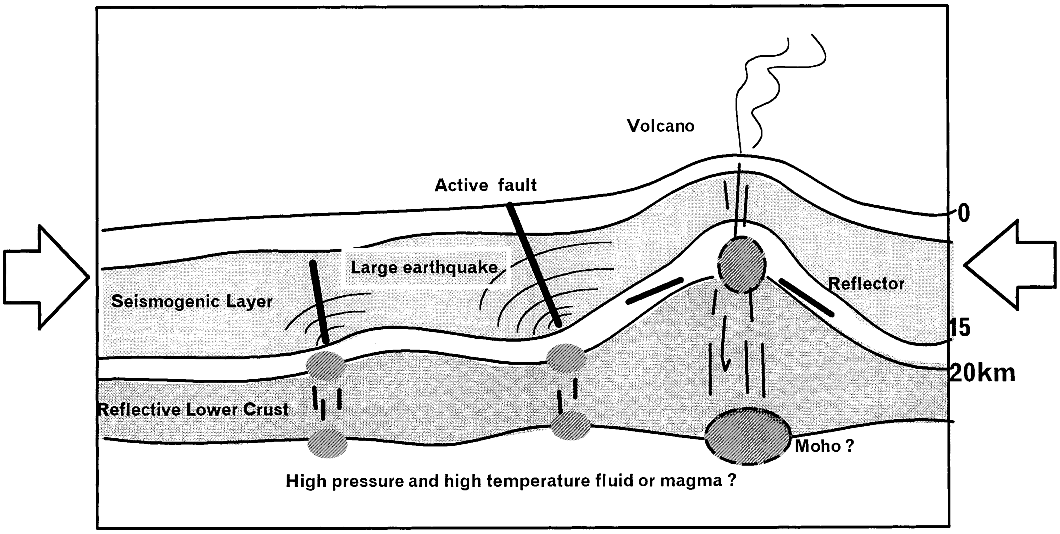

Fig. 9. Schematic model of change in seismogenic layer in the crust, reflective lower crust, S-wave reflectors and inland large earthquakes.

vary from place to place depending mainly on the thermal regime. Plastic lower crust can be deformed in terms of ductile flow by global tectonic stress due to plate motions. The layered structure in the reflective lower crust and also in the upper crust where the seismogenic layer is not thick, may be formed through ductile flow. Since the thickness of the seismogenic layer is an indication of the crust strength, thickness variations may indicate an inhomogeneous stress regime in the crust. Thus, the deformation in the lower crust builds up stress in areas with abrupt lateral variations in the cutoff depths of seismicity. Additional stress caused by thermal activity, such as change in fluid pressure or pore pressure, also plays an important role in stress concentration (Sibson, 1992). However, the detailed process is still unknown. A phenomenon similar to fault-valve behavior (Sibson, 1992) must occur frequently near the cutoff depth of seismicity. Over-pressurized fluid-filled fractures may play a role in the process of fault-valve behavior and eventually in the occurrence of large earthquakes. Earthquake swarms are likely to occur near volcanoes and in geothermal areas. However, no large seismic events occur in volcanic areas, because of the thin seismogenic layer. Instead, small shocks occur as earthquake swarms. The locations of earthquake swarms usually change for some time. This may be caused by the buoyancy-driven movement of fluids.

Where there is a large lateral change in the seismogenic layer thickness, large shocks are repeated many times for a long time, since the thermal structure remains the same for a long time. Thus, since the thickness of the seismogenic layer is correlated to temperature, active faults must be formed in areas with large lateral temperature gradients as a result of repeated large events at nearly the same place. Once a fracture is formed, it may be easily reactivated by the next event. This is a rough sketch of how large earthquakes may nucleate in the crust.

It is not clear that the stress is easily concentrated in areas of large lateral variations in the thickness of the seismogenic layer. However, Shibazaki (1997) reported from numerical model calculations that stress concentrates at large lateral thickness variations in the brittle–ductile boundary. Therefore, considering all observational facts, it seems that large earthquakes may occur in areas of steep lateral changes in the seismogenic layer.

8. Concluding remarks

This paper has presented a heterogeneous crustal model for large inland earthquakes. Earthquakes are closely related to the change in the depth of the seismogenic layer in the crust. The thickness of the seismogenic layer is mainly dominated by the thermal structure of the crust. A reflective lower crust and a distinctive S-wave reflector are also found to be related to the thermal structure of the crust. Therefore, the cutoff depth of seismicity and reflectors in the crust are very important for evaluating the earthquake potential of the crust. Moreover, large seismic events are likely to recur at large lateral changes in the lower cutoff depth of the seismogenic layer in the crust. Active faults are well developed in these areas. This suggests that variations in the thickness of the seismogenic layers must be closely related to the nucleation of large inland earthquakes.

S-wave reflectors have been reported just under the main shock of some large earthquakes. The reflector may be related to a magma body or fluid-filled rocks in the crust. Since earthquake-generating stress is supplied basically from global plate motions, additional stress due to, for example, thermal activity would also affect the earthquake occurrence in the inland area. Over-pressurized fluid-filled fractured rocks in the crust seem to play an important role in the nucleation process of earthquakes. Studies on the nature of the crust based on the thermal structure, including the role of fluids as well as heterogeneous structure, are necessary to determine the locations of future earthquakes.

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