

Repeating earthquakes and quasi-static slip on the plate boundary east off northern Honshu, Japan

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We have investigated spatio-temporal variation in small repeating earthquake activity in the 1989 earthquake swarm and used them to infer quasi-static slip distribution on the plate boundary off Sanriku, northern Honshu, Japan. Seismicity and inferred quasi-static slip accelerations propagated to the west and to the south during the swarm activity to trigger the occurrence of the largest earthquake (M7.1). To explain the migration of the seismicity and inferred quasi-static slip acceleration, we propose a conceptual model named the ‘chain reaction model’ in which large earthquakes generate large afterslips and then the afterslips accelerate the ruptures of the nearby asperities to generate the next earthquakes which are also followed by large afterslips, and so on. The model is applicable to a plate boundary where asperities are located sparsely but the afterslip associated with the rupture of an asperity can reach nearby asperities. Aftershock area expansion, which is conspicuous off Sanriku, is also explained by the model. If we can evaluate the slip deficit of a large asperity correctly, we will be able to issue a warning of large earthquake occurrence in some areas when we detect the acceleration of quasi-static slip near the asperity although the prediction is inevitably probabilistic.

Key words:

1. Introduction

In the last decade, GPS (Global Positioning System) data have provided us with significant information on interplate coupling (e.g., Nishimura *et al.*, 2000). They, as well as crustal movement observation data, have revealed that slow events or silent earthquakes have occurred in many areas around Japan (e.g., Kawasaki *et al.*, 1995; Hirose *et al.*, 1999; Ozawa *et al.*, 2002). Such quasi-static slips including stable sliding probably effect stress concentration and accumulation on seismic patches (asperities) that generate interplate earthquakes. Thus, it is important to investigate the spatio-temporal variation of quasi-static slip in detail to determine its relation to future interplate earthquakes.

To date, GPS stations can be installed on land only; it is hard to estimate detailed variations of quasi-static slips in areas far from the shore. Ellsworth (1995) and Nadeau and McEvilly (1999) showed that the variations of quasi-static slips can be estimated from data of small repeating earthquakes in California. This is because such a repeating earthquake sequence is thought to be caused by repeated slips at a small asperity that is loaded by quasi-static slips in the surrounding area. The cumulative slip at the asperity must coincide with the cumulative quasi-static slip in the surrounding area (Fig. 1). Thus, we can estimate the quasi-static slip history of the aseismic area surrounding the asperity by calculating the cumulative slip of the repeaters occurring at the asperity.

Igarashi *et al.* (2003) found many small repeating earthquakes in the area east off northern Honshu, Japan, and confirmed that most of the repeaters were occurring on the plate boundary using relocated hypocenters and focal mechanisms. From the repeating earthquake data, Igarashi *et al.* (2003) estimated the quasi-static slip distribution on the plate boundary east off northern Honshu and showed that the distribution was consistent with that estimated from GPS data. In addition to their data, Uchida *et al.* (2003a) analyzed smaller and older repeating earthquake data also to obtain the spatio-temporal variation of the quasi-static slip on the plate boundary off Sanriku for the period from 1984 to 2001.

When a large asperity ruptures, however, some parts of the surrounding quasi-statically slipping region and nearby small asperities will slip together seismically to generate a large earthquake. In this case, the cumulative slips at small asperities estimated from repeaters will not include the slips related to large earthquake. Thus, it should be noted that the cumulative slips estimated from repeating earthquake data might be underestimated in some regions close to a large asperity for a period within which a large earthquake occurred at the asperity. Nonetheless, the repeating earthquake data is one of the important tools at present for estimating the quasi-static slip distribution.

In this study, we estimated the quasi-static slip variation on the plate boundary east off northern Honshu during an earthquake swarm using the small repeaters and investigated the relation between the acceleration of the quasi-static slip and earthquake swarm.

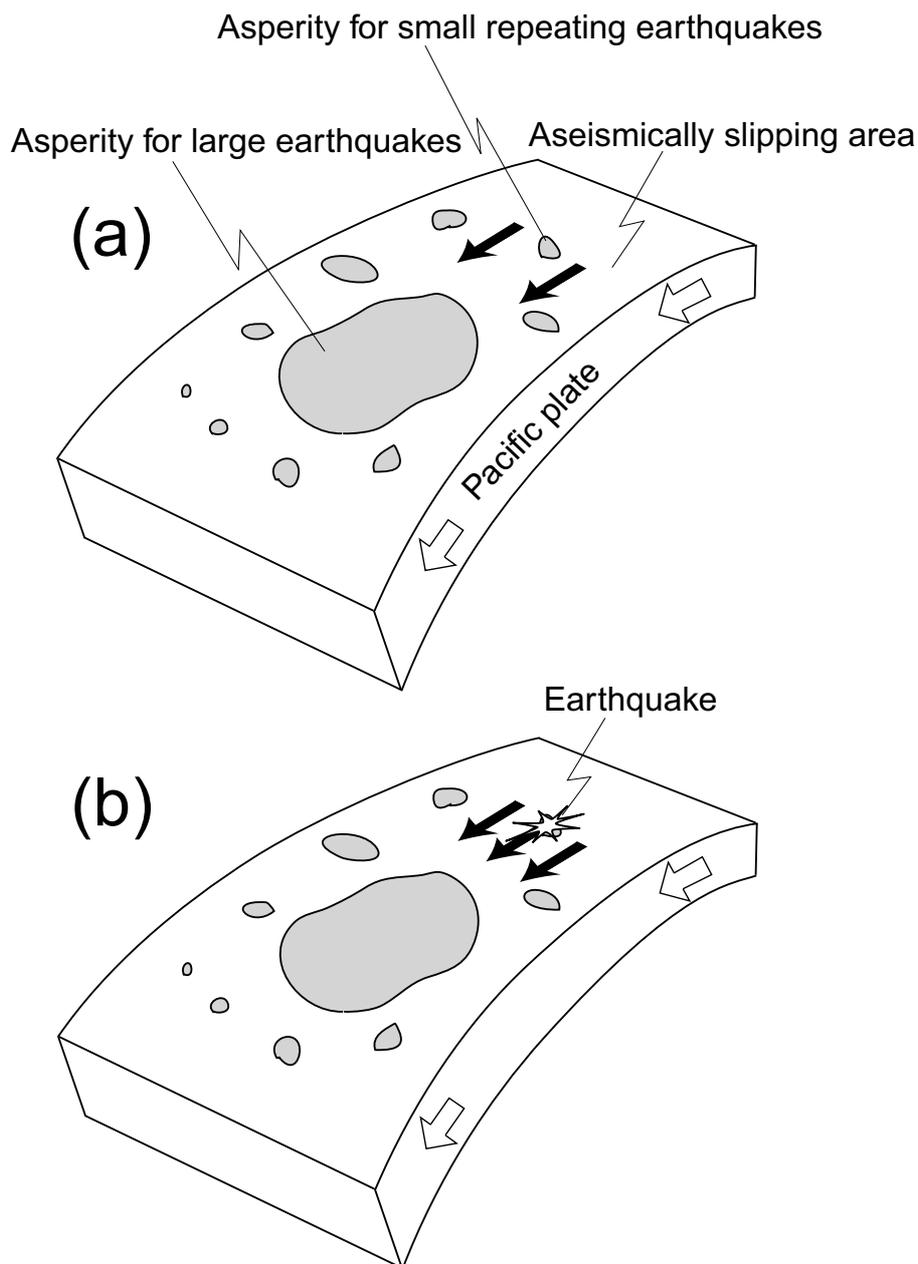


Fig. 1. Schematic illustration showing the relation between slips in the aseismic area and asperities on the plate boundary east off northern Honshu, Japan. Various sizes of asperities are distributed on the plate boundary. (a) Areas other than asperities slip aseismically, and (b) the asperities eventually rupture as earthquakes.

2. Repeating Earthquake Data Analysis

We used digital vertical component waveform data of earthquakes with $M \geq 2.0$ recorded by Tohoku University's microearthquake observation network for the period from July 1984 to October 2001 (Fig. 2). Sampling frequencies of the data were 100 Hz and most of seismometers were of 1 Hz velocity type.

In order to detect repeaters, we used the same method as the one adopted by Igarashi *et al.* (2003) and Uchida *et al.* (2003a). We filtered the vertical component waveforms with a pass-band from 1 Hz to 4 Hz and then cross-correlated the filtered seismograms of earthquakes whose epicentral separation was less than 30 km. The window length for the calculation was 40 s, from 1 s before the P-wave onset to S-wave

coda. If the cross-correlation was equal to 0.95 or greater for two or more stations, we regarded the two earthquakes were belonging to the same repeating earthquake group.

The wavelength of S wave at 4 Hz (cutoff frequency of our filter) is around 1 km at the source depth and its quarter is around 0.3 km. Since most of the analyzed earthquakes are between $M_{2.5}$ and $M_{4.0}$, the source dimension is considered to be around 0.1–0.5 km (based on the model proposed by Nadeau and Johnson (1998)) or around 0.1–0.8 km (10 MPa constant stress drop model). Thus we believe each repeating earthquake group is composed of earthquakes which destroyed the same source area although there might be some exceptions. Okada *et al.* (2003) revealed that the Off-Kamaishi $M_{4.8}$ repeaters ruptured the same source area

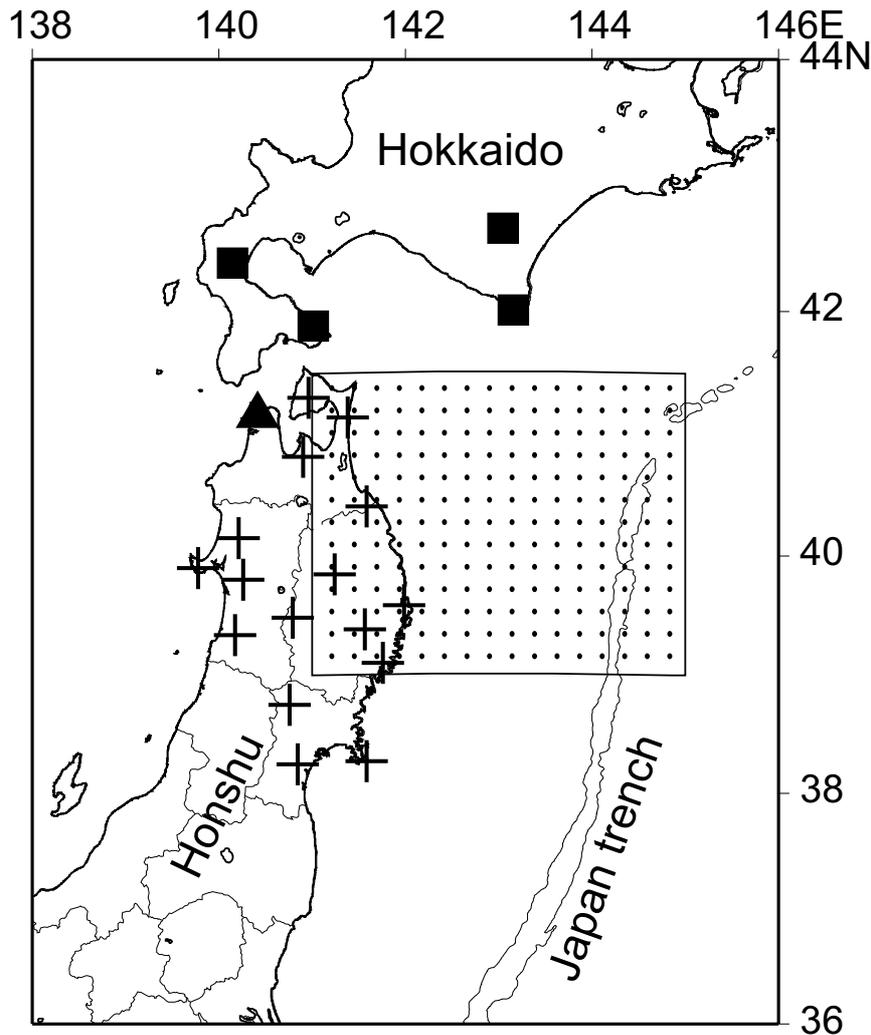


Fig. 2. Seismic stations used for the repeating earthquake data analyses in this study. Cross, triangle and square respectively denote the stations belonging to Tohoku University, Hirosaki University and Hokkaido University. Study area is indicated by hatch.

but the hypocenters (rupture initiation points) were different. Thus, we did not use a filter with higher cut-off frequency because the use of such a filter might exclude the earthquake pairs that destroyed the same area but initiated at different points. Stations used in the analyses were the same as Uchida *et al.* (2003a) and are shown in Fig. 2. We selected the stations that had operated throughout the analyzed period and had good S/N ratios. Their azimuthal coverage was also taken into account.

From the comparison with the hypocenters determined using both the OBS (ocean bottom seismograph) and land network data, Hino *et al.* (1996) showed that the epicenters in the Tohoku University's catalogue were biased about 10–40 km to the east for the events east of around 143.5E. Standard errors of the epicenters in the Tohoku University's catalogue are 0.01–0.03 degrees in latitude and 0.04–0.12 degrees in longitude for most of the earthquakes in the area east of 143E. This implies that the relative location errors are typically around 10 km and occasionally as large as 30 km for the regions close to the trench. Thus, we adopted the criteria of 30 km for the epicenter separations in searching for the repeaters.

Slip amount of each detected repeater was estimated using the scaling relationship proposed by Nadeau and Johnson (1998). Then, we made a slip history for each repeating earthquake group by calculating the cumulative sum of the slips. It is still controversial whether the asperity can also slip aseismically in the interseismic period. For example, Beeler *et al.* (2001) proposed a model in which asperity surrounded by aseismic zones could creep in the interseismic period. However, all we have to know here is the cumulative slip at each asperity irrespective of whether the slip is seismic or aseismic. Even if we use the Beeler's model, the sum of the obtained seismic and aseismic slips at the asperity is almost the same as the seismic slip estimated from Nadeau and Johnson's model (Igarashi *et al.*, 2003). Thus we believe that the cumulative slips estimated here are reliable although there is an uncertainty of a factor of about 2 (Igarashi *et al.*, 2003). Note that the slip amount estimated here is not thought to represent the slip averaged over the source area but probably corresponds to the maximum slip on the area. The stress drops for very small repeaters may become as large as (but do not exceed) those observed in rock fracture experiments (Johnson and Nadeau, 2002; Seno, 2003).

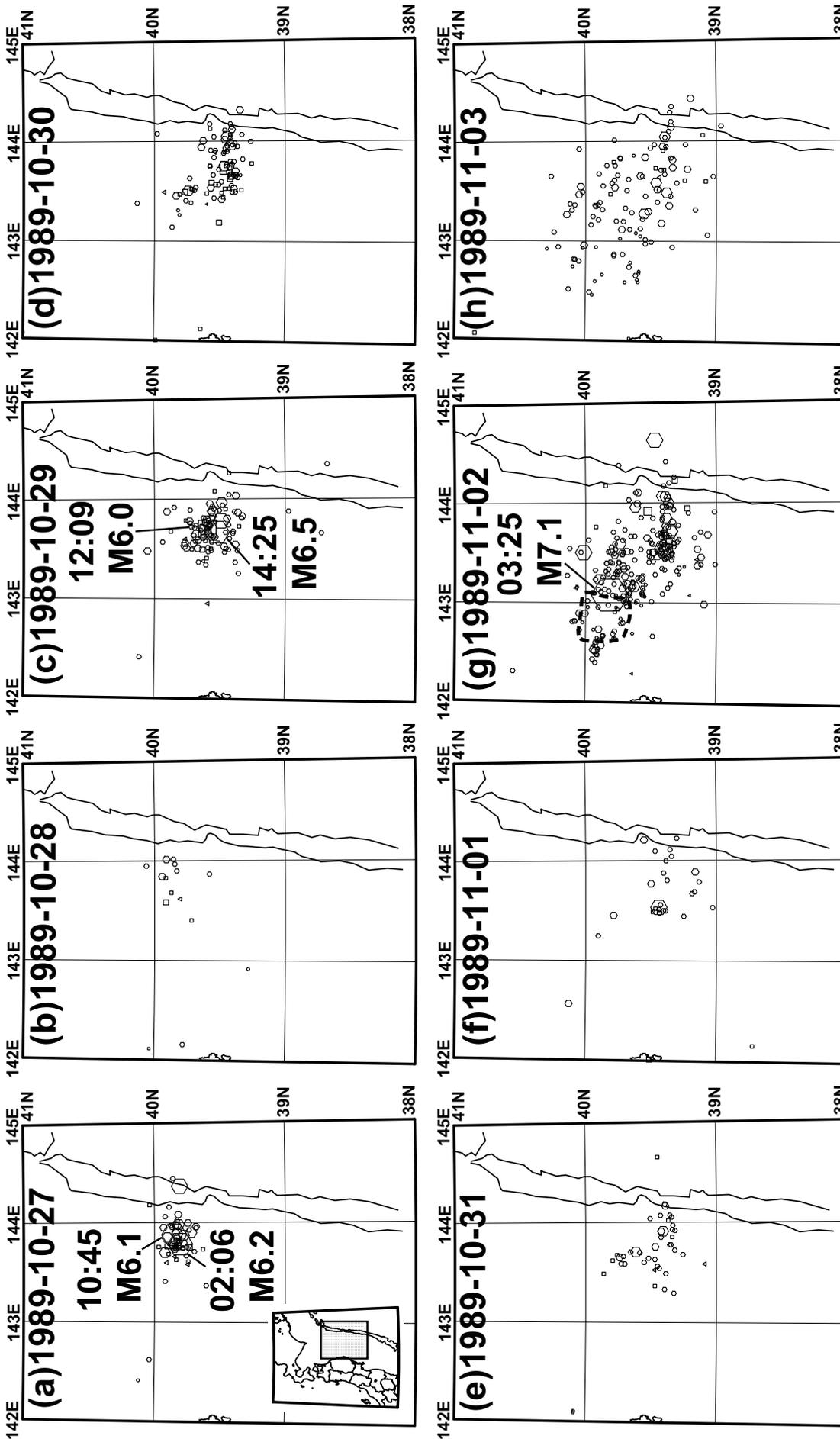


Fig. 3. Daily epicenter maps for the 1989 earthquake swarm for the period from October 27 to November 3, 1989. Main source area for the largest earthquake of M7.1 estimated by Yamanaka and Kikuchi (2004) is indicated by dashed line in Fig. 3(g).

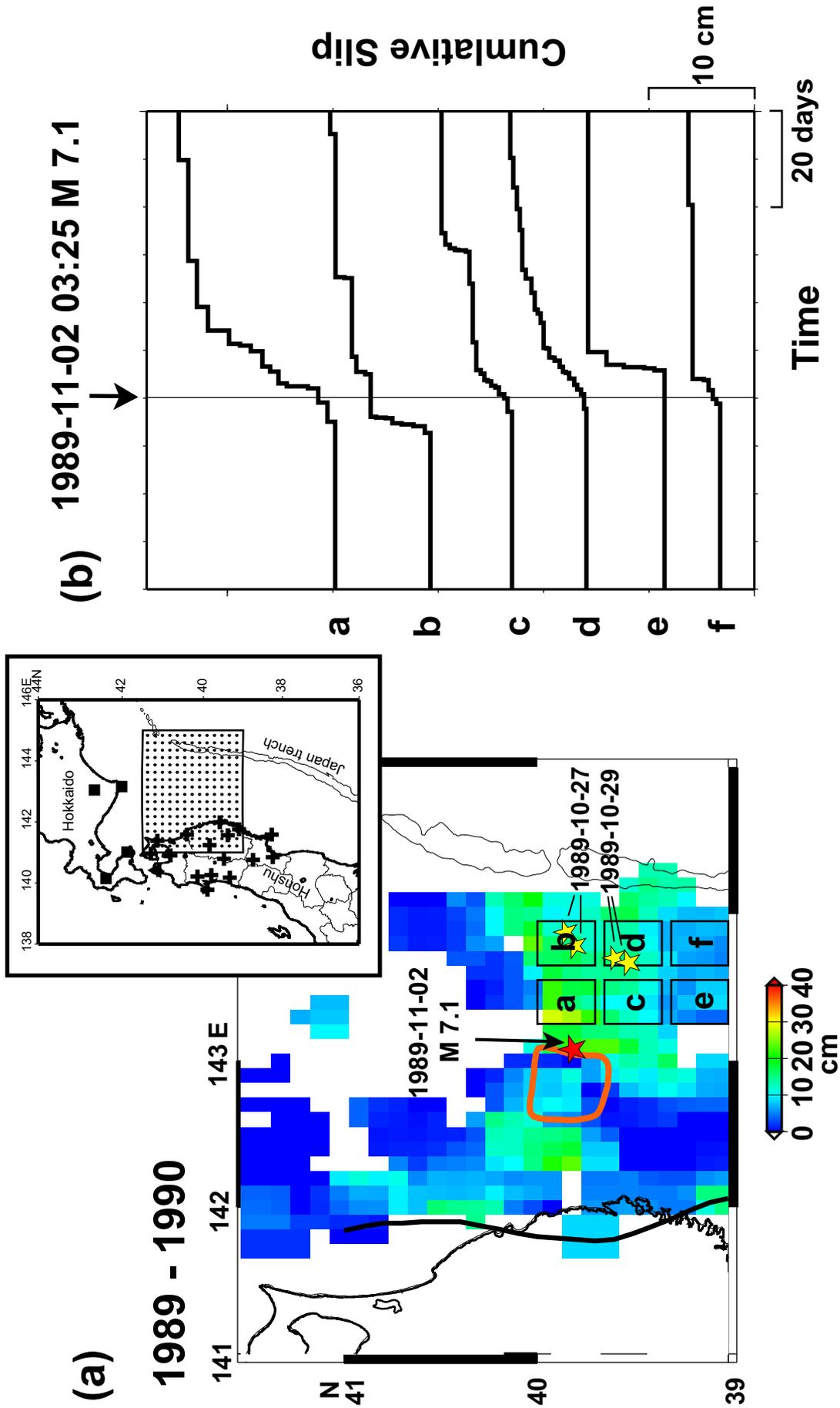


Fig. 4. Spatio-temporal variation of quasi-static slips related to the 1989 earthquake swarm inferred from repeating earthquake data. (a) Slip distribution on the plate boundary for the period from 1989 to 1990 estimated from repeating earthquake data analysis. Slip amount averaged over spatial window of 0.3 by 0.3 degrees are shown by the color pixel of the 0.1 by 0.1 degrees located at the center of each window. Red and yellow stars, respectively, denote earthquakes with M7 and M6. Orange contour represents the main source area of the largest earthquake (M7.1) estimated by Yamanaka and Kikuchi (2004). Heavy line near the coast denotes western limit of the interplate earthquake occurrence (Igarashi *et al.*, 2001). (b) Cumulative slips in the regions labeled from 'a' to 'f' in Fig. 4(a). Each trace is arbitrarily shifted vertically. Vertical line indicates the occurrence time of the largest earthquake of M7.1.

In order to obtain more reliable histories, we calculated spatial moving averages of the histories with a window of 0.3 by 0.3 degrees; the moving step was 0.1 degrees. The averaged (stacked) histories are thought to express the quasi-static slips on the plate boundary. We used hypocenter and magnitude data in the Tohoku University's catalogue in the analysis. When we explicitly show the magnitudes of large earthquakes which were not used in the analysis, however, the values represent the magnitudes determined by JMA (Japan Meteorological Agency). This is just for the convenience of the readers.

The spatio-temporal distribution of the inferred quasi-static slip on the plate boundary has already been reported by Uchida *et al.* (2003a, 2004). Here we focus on the earthquake swarm activity in 1989. Figure 3 shows daily epicenter maps for the 1989 earthquake swarm. The activity started on October 27, 1989. Then the activity migrated to the south and to the west and eventually the largest earthquake of M7.1 occurred on November 2. Note that the 'aftershock' area for the largest earthquake has a diameter of around 100 km which is too large for the M7.1 earthquake and is actually much larger than its main source area estimated by Yamanaka and Kikuchi (2004) as shown in Fig. 3(g).

Figure 4(a) shows the estimated slip distribution on the plate boundary for the period from 1989 to 1990. On November 2, 1989, the largest earthquake (M7.1) in the swarm occurred. The figure shows that large slips occurred in the period of 1989–1990 to the southeast of the M7.1 earthquake. Cumulative slips for the regions labeled from 'a' to 'f' in the figure are shown in Fig. 4(b).

Figure 4(b) indicates that quasi-static slip accelerated first in region 'b' and then the initiation of the acceleration propagated to the south and to the west and reached regions 'a', 'c', 'd' and 'f'. The largest earthquake (M7.1) then occurred to the west of the region 'a'. Finally, slip accelerated in region 'e'. The acceleration started prior to the occurrence of the largest earthquake. This preceding acceleration probably corresponds to the afterslips of M6 earthquakes occurring prior to the largest earthquake. Note that the propagation pattern of the acceleration is very similar to the seismicity migration shown in Fig. 3.

3. 'Chain Reaction Model' for Earthquake Swarms

In order to explain the migration pattern of seismicity as shown in Fig. 3 and slip acceleration propagation shown in Fig. 4(b), we propose a conceptual model that we refer to as the 'chain reaction model' and show schematically in Fig. 5. We propose that various sizes of asperities exist on the plate boundary; large asperities are responsible for the occurrences of large earthquakes while small asperities generate small repeating earthquakes as shown in Fig. 5(a). Areas other than asperities slip aseismically, increasing the stress on nearby asperities. One of the asperities is eventually loaded to failure, and ruptures as shown in Fig. 5(b). Uchida *et al.* (2003a) showed that large ($M \geq 6$) interplate earthquakes off Sanriku are always followed by large afterslips that trigger the activity of small repeating earthquakes (Fig. 5(b)). The afterslip will also build up stress on other nearby large asperities. One of these will then fail, in turn generating large

afterslip (Fig. 5(c)). As the afterslip areas and slip amounts increase, the stresses on the asperities located at the edge of the afterslip area become large enough to rupture them even if their sizes are large. In this way, a rupture of an asperity (earthquake) generates its afterslip and the afterslip triggers the next earthquake (Fig. 5(d)). When no loaded asperities are left or the stress increase due to the afterslip is not enough to destroy further asperities, the 'chain reaction' stops.

In this paper, we used the term 'asperity' as an area where seismic slip is dominated. In other words, quasi-static or aseismic slip is predominant in the regions other than asperities. Our model is almost the same as the 'coupled asperity model' proposed by Boatwright and Cocco (1996) based on the rate- and state-dependent frictional constitutive law. The 'coupled asperity model' shows that an asperity (strong seismic area) is loaded by the surrounding velocity-hardening region and afterslip mainly occurs just outside the asperity. In the model, the seismic slip at the asperity and aseismic slip in the surrounding region are strongly coupled. Thus, our 'chain reaction model' is a natural consequence of the 'coupled asperity model'.

Other than 1989 seismic activity, earthquake swarms or foreshock-mainshock-aftershock activities frequently occur east off northern Honshu. For example, the 1981 swarm activity off Miyagi prefecture began with M6.1 earthquake about nine hours before the largest earthquake of M7.0 (03:17 JST, January 19, 1981). The 1982 M7.0 earthquake (23:23 JST, July 23, 1982) off Ibaraki prefecture was preceded by four M5 earthquakes starting from 28 hours before the main shock. In the 1992 swarm off Sanriku, the first earthquake was of M6.1 two days prior to the two largest earthquakes of M6.9 (17:36 and 17:39 JST, July 18, 1992). These events all share the same characteristic that aftershock areas are much larger than the source areas of their largest earthquakes.

Even in the mainshock-aftershock activities without foreshocks, epicenters (rupture initiation points) are usually located outside the main source areas (Yamanaka and Kikuchi, 2004) for earthquakes east of northern Honshu, and expansions of the aftershock areas are conspicuous (Tajima and Kanamori, 1985). These activities also indicate that the plate boundary east of northern Honshu is very heterogeneous and coupling of seismic and aseismic slips controls the complicated earthquake activities; i.e., rupture of an asperity causes its afterslip and the afterslip triggers rupture of a nearby asperity, and the large afterslip of a large earthquake is responsible for the aftershock area expansion.

Figure 4 indicates that the propagation speed of the quasi-static slip acceleration was an order of 10 km/day. This value seems to be larger than the speed for the usual afterslip which is an order of 10 km/month (e.g., Nishimura *et al.*, 2000). We think this discrepancy is due to the regionality of the frictional parameters and/or normal stress on the plate boundary. Most of the afterslips or slow events detected by GPS observation are located close to the shore. The nature of the afterslip for the regions close to the trench is still uncertain because of the poor resolution in the GPS data as we mentioned before. On the other hand, Seno (2003) proposed a model in which the frictional property of velocity strengthening becomes extremely weak in a quasi-statically

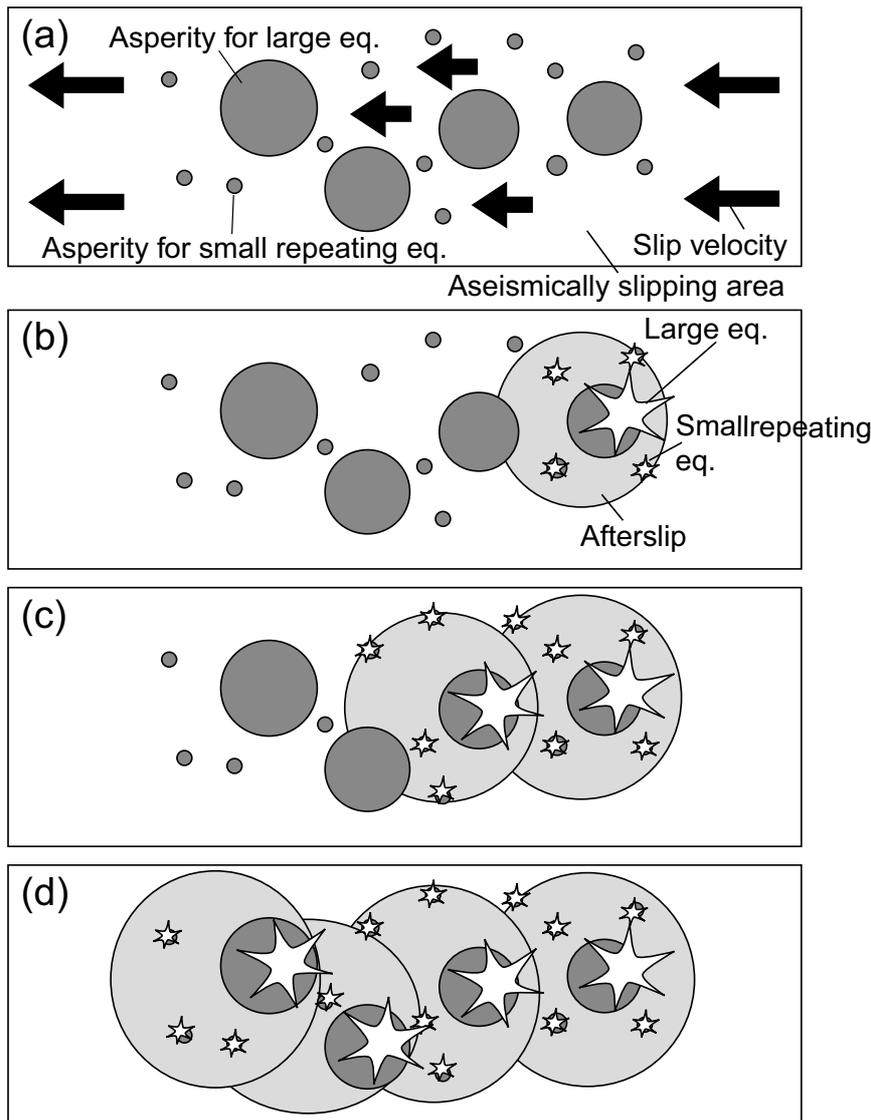


Fig. 5. Schematic illustration of the 'chain reaction model' proposed in this study. See text for further detail.

slipping region due to the elevation of pore fluid pressure. Another major difference between Seno's model and ours is that Seno's model has hierarchical structure inside the asperity while the asperity has its own size in our model. In order to ascertain which model is more suitable, further analyses of afterslips and slow events as well as investigations of the seismic velocity structure around the plate boundary are important.

One may think that such a swarm and aftershock activity can be explained by the stress changes due to large earthquakes. Actually such stress change will also foster the occurrence of nearby earthquakes (e.g., Stein, 1999). In terms of a rate- and state-friction law, Dieterich (1994) showed that seismicity rate would reflect the stressing history and a simple stress step caused by a large earthquake would generate a seismicity rate change following the characteristic Omori aftershock decay law. However, it should be noted that such a simple stress step cannot generate an earthquake swarm activity.

On the other hand, Schaff *et al.* (1998) proposed another mechanism to explain the Omori's law. They analyzed re-

peating earthquakes in the aftershock activity of the 1989 Loma Prieta earthquake and showed that their recurrence intervals followed $1/t$ law. They also showed the nature could be explained by the repeated slips on isolated patches surrounded by postseismic creep caused by the sudden stress step due to the mainshock.

Toda *et al.* (2002) clearly showed that the 2000 Izu islands earthquake swarm activity was also governed by the stressing rate as predicted by Dieterich (1994). Their results indicate that a sustained increase in stressing rate due to such as an intrusion or creep event is necessary for the occurrence of an earthquake swarm. Thus, both Schaff *et al.* (1998) and Toda *et al.* (2002) indicate that the quasi-static slip plays an important role in the earthquake swarm activity as well as aftershocks.

4. Implications for Earthquake Prediction

Frictional constitutive laws (slip dependent law and rate- and state-dependent law) predict that there is a nucleation process for earthquake generation; a slow pre-slip is expected to occur prior to the occurrence of an earthquake (e.g.,

Tse and Rice, 1986; Kato and Hirasawa, 1997; Shibazaki and Matsu'ura, 1998). If we detect the pre-slip, we can predict an earthquake. The size of the pre-slip related to the nucleation process, however, is expected to be very small: for example, Shibazaki and Matsu'ura (1998) proposed a scaling relationship in which the nucleation length is around $1/10$ – $1/20$ of the source size. Johnston and Linde (2002) also concluded that the greatest possible preseismic moment in the nucleation process is less than 0.1% of the final seismic or geodetic moment. Thus, we have to detect a very small strain change to predict an earthquake. For an offshore earthquake, its epicenter is far from strainmeters which are installed in land area. Thus, it is quite difficult to carry out a short-term earthquake prediction for a large offshore earthquake by detecting the pre-slips related to the nucleation process.

Moreover, the strategy of earthquake prediction relying on the nucleation process assumes that the source area of a large earthquake is almost homogenous. If the source area is heterogeneous and a small earthquake (i.e., rupture of a small asperity) immediately triggers the rupture of a nearby large asperity corresponding to the main source area, the nucleation size would be much smaller than the total source area even if the nucleation size is proportional to the source size. Thus, the earthquake prediction strategy based on the nucleation process seems to be hopeless for the offshore large earthquake in the heterogeneous areas unless very sensitive and reliable ocean bottom strainmeters or tiltmeters are developed.

Let us consider the rupture process in the heterogeneous plate boundary. Boatwright and Cocco (1996) proposed that a heterogeneous plate boundary or fault can be thought of as consisting of four kinds of areas: strong seismic, weak seismic, compliant and viscous areas. Strong and weak seismic areas respectively show strong and weak velocity-weakening behaviors. Viscous and compliant areas correspond to strong and weak velocity-strengthening sections, respectively. The viscous areas slip aseismically while the strong seismic areas show large seismic slips. The weak seismic areas slip seismically or aseismically depending on the critical slip distance. The compliant areas slip aseismically but can slip seismically when they are sufficiently loaded by an abrupt stress increase due to such as seismic rupture propagation from an adjacent velocity-weakening area. Afterslips are thought to be prominent in the compliant areas.

However, the boundaries among the four areas are not so clear. Even if a patch has a strong velocity-weakening nature, it would slip aseismically as an episodic creep if the critical slip distance is very large. Thus, we simply refer to the areas where seismic slips surpass aseismic slips as 'asperities' in the present paper. Note that some parts of the 'aseismically slipping area' close to the asperities shown in Figs. 1 and 5 also slip seismically when the asperities rupture (Boatwright and Cocco, 1996; Kato and Hirasawa, 1997).

If two asperities are closely located and are separated by a weak velocity-strengthening area, an earthquake initiated on one of them will propagate seismically even in the velocity-strengthening area, and the other asperity will also rupture easily. In this case, the earthquake will be observed as a 'multiple-shock'. For example, the 1994 Sanriku-Haruka-Oki earthquake (M7.6) is known as a multiple-

shock. Nakayama and Takeo (1997) found that the rupture velocity in the area between the initial event and the main source area was quite slow (1.8 km/s) and moment release in this area was very small. Thus, the area is thought to have the velocity-strengthening nature. The characteristics of the 1994 earthquake mentioned above indicate that the 'chain reaction model' shown in Fig. 5 is probably applicable to some of large interplate earthquakes of multiple-shock type as well as earthquake swarms east off northern Honshu although the area between the asperities may slip seismically.

If this is the case, the short-term prediction would be possible to some extent if we know the precise slip deficits of major asperities. When M5 or M6 earthquakes occur and their large afterslips are detected close to a larger asperity which has been evaluated to have a large slip deficit, we can warn that the probability of a larger earthquake occurrence is very high although the time interval between the first earthquake and main shock occurrences might be as short as several tens of seconds in some cases such as the 1994 earthquake. Slip deficits can be estimated from GPS data and/or small repeating earthquake data analyses. For the areas far from the shore with no small repeating earthquakes, ocean bottom geodetic and/or crustal movement observations (e.g., Spiess *et al.*, 1998; Araki *et al.*, 2004) become quite important to estimate the slip deficit and to evaluate sizes of afterslips.

If the asperity is isolated from other asperities, it is hard to make a short-term prediction in the way we described above. In this case, however, the earthquake occurrence is expected to be periodic and thus the long-term earthquake prediction based on the recurrence interval will be reliable. The most typical periodic earthquake sequence is the M4.8 sequence off Kamaishi (Matsuzawa *et al.*, 2002). There had repeatedly occurred eight similar earthquakes of $M4.8 \pm 0.1$ since 1957 till 1995 with recurrence intervals of 5.35 ± 0.53 years. There have been no other large earthquakes near the M4.8 earthquakes indicating that the asperity for the M4.8 earthquake is isolated from other asperities. Based on the regularity, Matsuzawa *et al.* (1999) predicted that the next $M4.8 \pm 0.1$ earthquake would occur by the end of January 2001 with 68% probability and by the end of November 2001 with 99% probability assuming that the recurrence interval would follow the normal distribution. The expected earthquake of M4.7 really occurred on November 13, 2001 (Matsuzawa *et al.*, 2002).

Okada *et al.* (2003) investigated the source areas of the 2001 earthquake and the previous 1995 earthquake using regional broadband seismograph network data. Their results show that the source areas of the two earthquakes are almost identical and they concluded that the sequence was caused by repeated slips on the same asperity.

Although the time intervals between the earthquakes show some fluctuations, Uchida *et al.* (2003b) pointed out that the fluctuation might have been caused by the slip rate fluctuation in the area surrounding the asperity. If this is the case, the accuracy of the long-term prediction will be improved by monitoring the spatio-temporal variations of the slip rate on the plate boundary. Thus, the reliable estimation of slip-rate variations is quite important both for the short-term and long-term earthquake predictions.

5. Conclusions

We have investigated spatio-temporal variations of small repeating earthquakes within the 1989 earthquake swarm on the plate boundary east off northern Honshu, Japan, and used them to infer variation in quasi-static slip. Obtained distribution of quasi-static slip shows that the quasi-static slip was propagated from northeast to southwest and triggered the largest earthquake of M7.1. The propagation pattern is similar to the migration of seismicity. Based on these observations, we have proposed a conceptual model named the ‘chain reaction model’ in which large earthquakes generate large afterslips and the afterslips foster the ruptures of nearby asperities.

Earthquake prediction strategy relying on the nucleation process might be inapplicable to the offshore earthquakes because pre-slips related to the nucleation would be too small to be detected. On the other hand, if the asperities are located with spacing so that the ‘chain reaction model’ is applicable, we can forecast the occurrences of the largest earthquakes to some extent. For the prediction, we have to evaluate the slip deficit of each asperity and monitor the quasi-static slip variations in real time. Repeating earthquake data as well as GPS and ocean bottom crustal movement observation data will be helpful for this purpose.

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