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Remote Triggering of the M_w 6.9 Hokkaido Earthquake as a Result of the M_w 6.6 Indonesian Earthquake on September 11, 2008

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ABSTRACT

Only just recently, the phenomenon of earthquakes being triggered by a distant earthquake has been well established. Yet, most of the triggered earthquakes have been limited to small earthquakes (M < 3). Also, the exact triggering mechanism for earthquakes is still not clear. Here I show how one strong earthquake (M_w = 6.6) is capable of triggering another (M_w = 6.9) at a remote distance (~4750 km). On September 11, 2008, two strong earthquakes with magnitudes (M_w) of 6.6 and 6.9 hit respectively in Indonesia and Japan within a short interval of ~21 minutes time. Careful examination of broadband seismograms recorded in Japan shows that the Hokkaido earthquake occurred just as the surface waves generated by the Indonesia earthquake arrived. Although the peak dynamic stress estimated at the focus of the Hokkaido earthquake was just reaching the lower bound for the capability of triggering earthquakes in general, a more plausible mechanism for triggering an earthquake might be attributed to the change of a fault property by fluid infiltration. These observations suggest that the Hokkaido earthquake was likely triggered from a remote distance by the surface waves generated from the Indonesia earthquake. If some more cases can be observed, a temporal warning of possible interaction between strong earthquakes might be concerned in the future.

Key words: Remote trigger, Dynamic stress, Boundary fault

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1. INTRODUCTION

The phenomenon of earthquake triggering is one of the most interesting subjects in seismological studies and can help researchers improve the understanding of how earthquakes occur and may mitigate potential seismic hazards in the future. Previously, it has been observed that some small earthquakes or tremors were triggered by the surface waves of a distant earthquake, particularly around volcanic or geothermal areas (Hill et al. 1993; Gomberg 1996; Gomberg et al. 2001, 2004; Hough and Kanamori 2002; Husen et al. 2004; Prejean 2004; West 2005; Hill and Prejean 2007; Peng and Chao 2008; Peng et al. 2011; Wu et al. 2011). The peak dynamic stresses carried by large surface waves greater than ~0.1 bar (~0.01 MPa) are capable of triggering micro-earthquakes or tremors at remote distances as far as 10000 km (Hill and Prejean 2007). A good example is the powerful California Earthquake that hit the remote Mojave Desert community of Landers, which triggered swarms of smaller quakes as far away as Mount Shasta, Skull Mountain, Idaho and even Yellowstone National Park (bounded by Idaho, Montana, and Wyoming) more than 800 miles away (Hill et al. 1993; Gomberg 1996).

Another earthquake triggering mechanism is the tiny stress caused by daily deviations of the Earth's tides. A lower bound for dynamic stress of ~1 KPa has been suggested by the modulation between the Earth's tides and the occurrence of crustal thrust earthquakes in convergent margins around the Pacific basin (Cochran et al. 2004) and in Japan (Tanaka et al. 2004). Such a lower bound or threshold for initiating an earthquake is consistent with laboratory results showing that cyclical stressing at 1 - 4 KPa level should modulate the occurrence of background seismicity (Lockner and Beeler 1999; Beeler and Lockner 2003). In combination, both earthquakes triggered by seismic waves and the Earth's tide might achieve the lower bound (~1 KPa)

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necessary to provide the peak dynamic stress capable of inducing a triggered response (Hill and Prejean 2007).

Although the phenomenon of earthquakes triggering by the surface waves of a distant earthquake has been well established (Hill and Prejean 2007), the exact mechanism for triggered earthquakes is not yet fully understood. Further, most of the triggered earthquakes are often small (generally M < 3). For example, the widespread triggering of nonvolcanic tremors with small magnitudes at seven sites along the transform plate boundary in California were caused by the 2002 M_w = 7.8 Denali, Alaska earthquake (Gomberg et al. 2008). Although a global statistical study reported an absence of large remotely triggered earthquakes beyond the mainshock region (Parsons and Velasco 2011), there is still no strong evidence to show whether one strong earthquake (M > 6) is capable of triggering another at a remote distance of greater than 1000 km.

In this study, two strong earthquakes (M_w = 6.6 and 6.9) occurred within 21 minutes in Indonesia and Hokkaido, Japan on September 11, 2008 (Fig. 1) and provided an excellent opportunity to examine the possible interaction between the two events. First, temporal correlation between the arrivals of surface waves of the Indonesia earthquake and the occurrence of the Hokkaido earthquake are examined from broadband seismic stations (F-net) in Japan. Second, the peak dynamic stress of the surface waves of the Indonesia earthquake is estimated from the peak particle velocity and the phase velocity observed at broadband seismic stations. Third, tectonic characteristics at the triggered earthquake are discussed for understanding that one strong earthquake (M > 6) might be triggered by oscillatory surface waves generated by another event at remote distances.

2. THE 2008 HOKKAIDO AND INDONESIA EARTHQUAKES

On September 11, 2008, a strong earthquake (M_w = 6.9) occurred at southeast offshore of the Hokkaido island, northern Japan (Fig. 2). This earthquake was located at 41.89°N, 143.75°E, with a depth of 25 km, according to the National Earthquake Information Center (NEIC) of the United States Geological Survey (USGS) (http://neic.usgs.gov/neis/epic/). The focal mechanism based on the Centroid Moment Tensor (CMT) solution shows that the earthquake took place on a low-angle (17°) thrusting fault. This is a typical interplate earthquake between the North American plate and the subducting Pacific plate. The Pacific plate approaches Hokkaido from the east-southeast at a rate of about 8.2 cm per year relative to the North American plate. The subduction slab of the Pacific plate from the Japan trench and Chishima trench to the upper mantle can be clearly delineated by the earthquakes (M > 4) in the past decade (Fig. 2b). It is clear that the earthquake occurred in the Pacific Ocean near the plate boundary subducting toward land

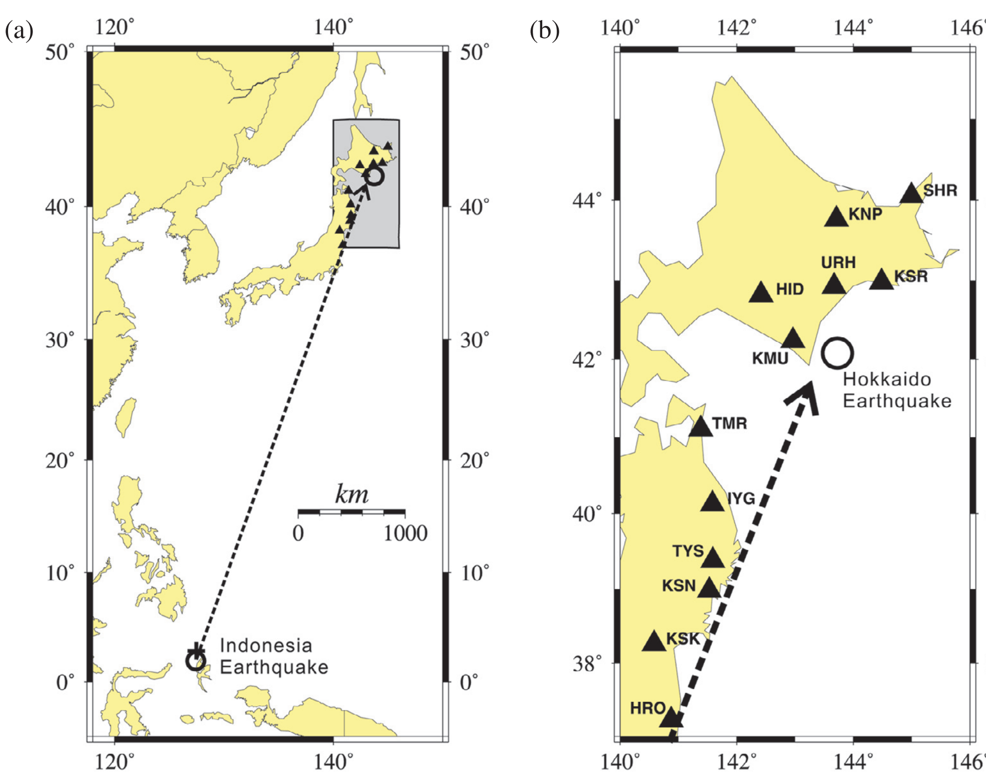

Fig. 1. (a) Locations of the Indonesia and Hokkaido earthquakes (circles) which occurred on September 9, 2008 and (b) Some broadband seismic stations (triangles) of F-net in northern Japan. Dashed lines with an arrow denote the wave propagation direction.

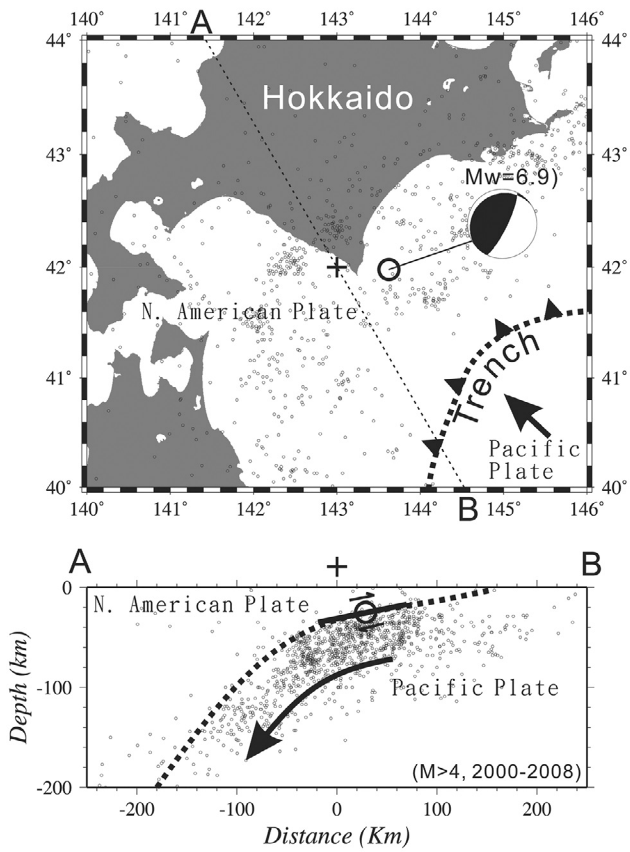

Fig. 2. Locations of background earthquakes (M > 4) and simplified tectonics in and around Hokkaido (the upper panel), and earthquake projection along A - B profile for showing the subducted slab. Arrows show the direction of plate movement.

from the trench. Thus, the hanging wall of the subduction boundary fault belongs to the North American plate, but its footwall is part of the subducted Pacific plate. Historically, some destructive earthquakes with an extremely similar mechanism had repeatedly taken place in the same area, including the earthquakes of March 4, 1952 (M = 8.1), May 16, 1968 (M = 7.9), and September 25, 2003 earthquake (M = 8.3) (NEIC, USGS).

On the same day, September 11, 2008, another strong earthquake (M_w = 6.6) occurred ~21 minutes ahead of the Hokkaido earthquake in Halmahera, Indonesia (Fig. 1a). Based on the report of the NEIC, USGS, this earthquake took place at 120 km North of Ternate (1.88°N, 127.36°E, depth = 96 km), Moluccas, Indonesia. The CMT solution (USGS) shows it was reverse faulting and occurred at the complicated plate boundary between the Pacific and the Indo-Australia plates. It is interesting to note that the Indonesia earthquake occurred (at 00h:00m:02s) 1250 seconds before the Hokkaido earthquake (at 00h:20m:52s); the two earthquakes were separated by a distance of ~4750 km. To discuss a possible connection between both earthquakes, a velocity of about 3.8 km s^{-1} is obtained if one takes the distance divided by the time difference between both earthquakes. This implies a typical surface wave propagating from the Indonesia earthquake to the Hokkaido earthquake might be suitable for explaining the velocity of ~3.8 km s^{-1}.

Since both the Hokkaido and Indonesia earthquakes were large enough (M > 6.5), the seismic data generated by both were well recorded by the global broadband seismic stations as well as the densely broadband seismic array (F-net) in Japan for further investigations.

3. TEMPORAL CORRELATION BETWEEN TWO EARTHQUAKES

Detailed examination of seismograms recorded at the broadband seismic stations (F-net) in Japan shows strong temporal correlation between the 2008 Hokkaido and Indonesia earthquakes. The propagation of major seismic waves, particularly surface (Rayleigh) waves, generated by the Indonesia earthquake (the first event) throughout northern Japan is clearly shown on the vertical seismograms recorded at some broadband seismic stations of F-net in Japan (Fig. 3). Also, the first P-wave arrivals of the Hokkaido earthquake (the second event) can easily be aligned from the impulsive waves with over-scale amplitudes at Fig. 3a. It is remarkable to note that the alignment of the Rayleigh wave arrivals generated by the Indonesia earthquake intersected with the first P-waves generated by the Hokkaido earthquake at Station KMU (Fig. 3b).

Among seismic data recorded at F-net, seismograms at Station KMU show that the inception time of the Hokkaido earthquake corresponds very well to the arrivals of the Rayleigh waves generated by the Indonesia earthquake (Fig. 4). Although Station KMU is about 100 km away from the epicenter of the Hokkaido earthquake, the arrivals of Rayleigh wave to both epicenter of the Hokkaido earthquake and Station KMU were almost the same in that they were located almost at the same distance from the Indonesia earthquake (Fig. 1). As a result, the occurrence time of the Hokkaido earthquake was well correlated to the arrivals of the Rayleigh waves from the Indonesia earthquake, even though the Hokkaido earthquake occurred about 15 seconds earlier than the first P-wave arrival at Station KMU. For two stations (KSR and SHR) north to the Hokkaido earthquake (Fig. 1), the P-waves of the Hokkaido earthquake clearly arrived earlier than Rayleigh waves generated by the Indonesia earthquake (Fig. 5).

4. PEAK DYNAMIC STRESS

Since the Hokkaido earthquake occurred right at the arrivals of Rayleigh waves generated by the Indonesia earthquake, it is interesting to ask whether they occurred as a coincidence or the 2nd earthquake was associated with the dynamic stress carried by seismic waves by the 1st one. Although it can not be totally excluded that such a temporal correlation between two strong earthquakes might be just a coincident, the probability of two strong earthquakes (M_w > 6.5) took place at different places within 20 minutes is extremely low (< 0.01) based on the available earthquake catalogue information (NEIC, USGS).

The peak dynamic stress carried by seismic waves can be estimated from the peak particle and phase velocities (i.e., Hill et al. 1993; Hill and Prejean 2007; Peng and Chao 2008; Lin 2010). Based on the assumption of plane wave propagation, the peak dynamic stress associated with surface waves is proportional to $G\ u/v_s$ (Jaeger and Cook 1979), where G is the shear modulus, u is the peak particle velocity and v_s is the phase velocity. Using the peak particle velocity of 0.08 mm s^{-1} (Fig. 6), the phase velocity of 3.8 km s^{-1} (Fig. 3) and nominal G values between 20 and 50 Gpa in crust (Turcotte and Schubert 1982), we estimate the amplitude of the stress associated with the Rayleigh waves to range from 0.42 to 1.05 KPa. The maxima value of 1.05 KPa just reached the

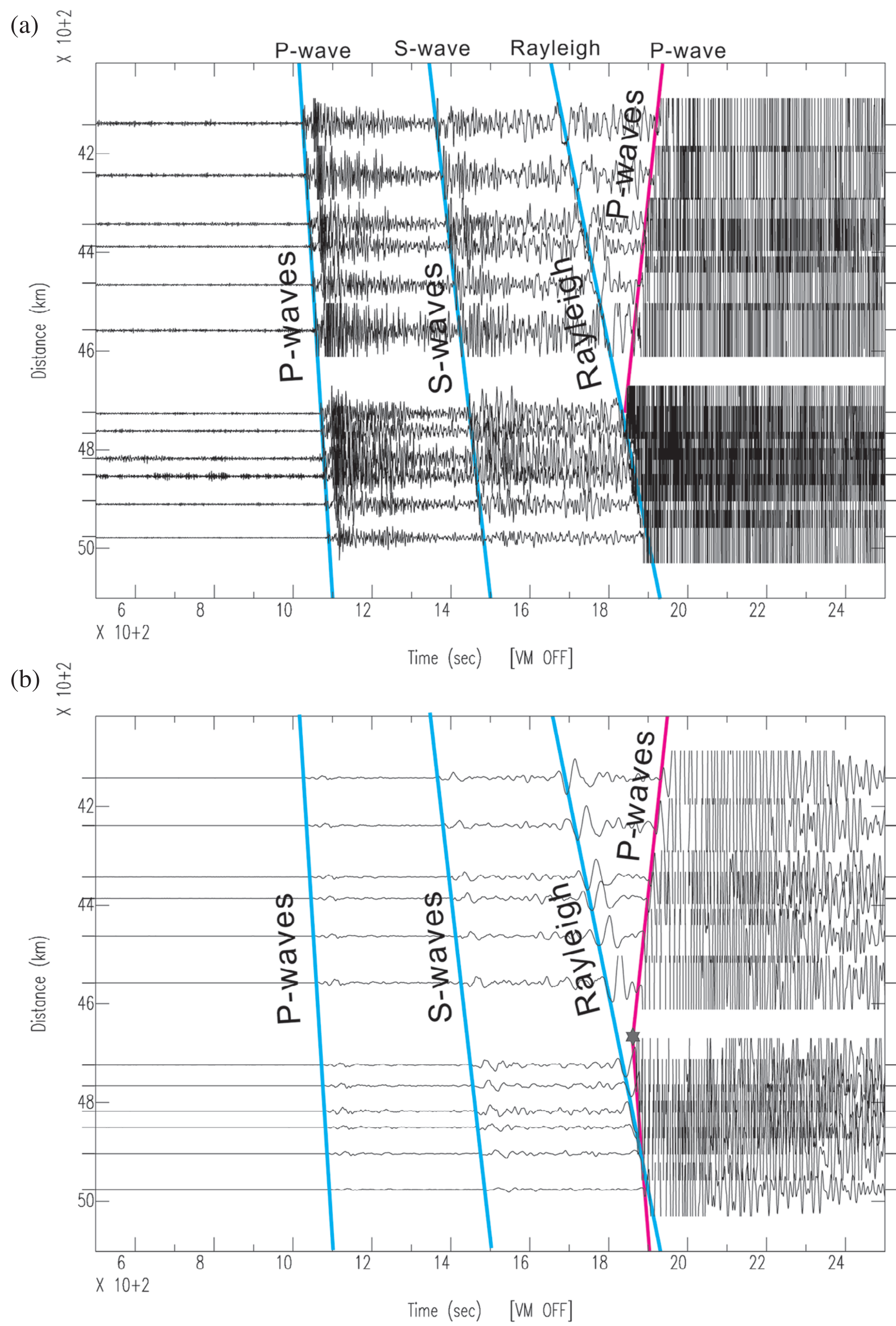

Fig. 3. (a) Vertical seismograms and (b) those filtered by 0.01 - 0.03 Hz showing major arrivals generated by the Indonesia and Hokkaido earthquakes. Arrivals of P- and S-waves as well as Rayleigh waves are aligned by coloured lines, respectively.

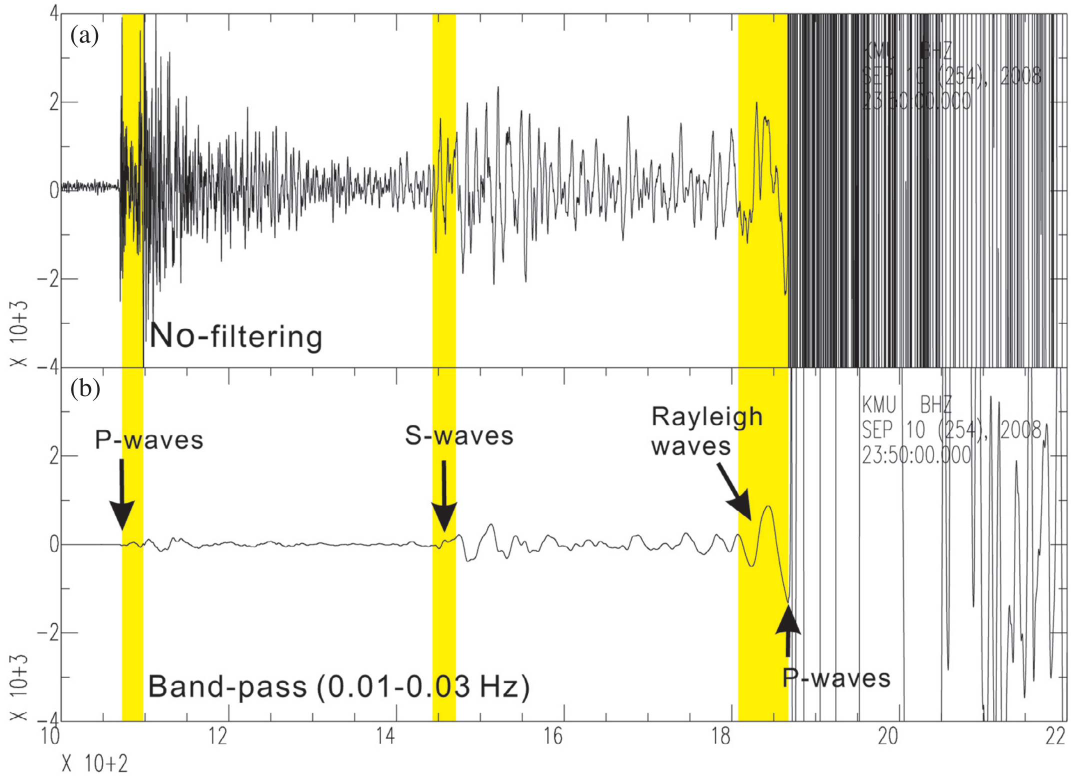

Fig. 4. (a) Vertical seismogram and (b) that filtered by 0.01 - 0.03 Hz recorded at Station KMU of the F-net in Japan. Clear arrivals of P- and S-waves as well as the Rayleigh waves are marked by arrows.

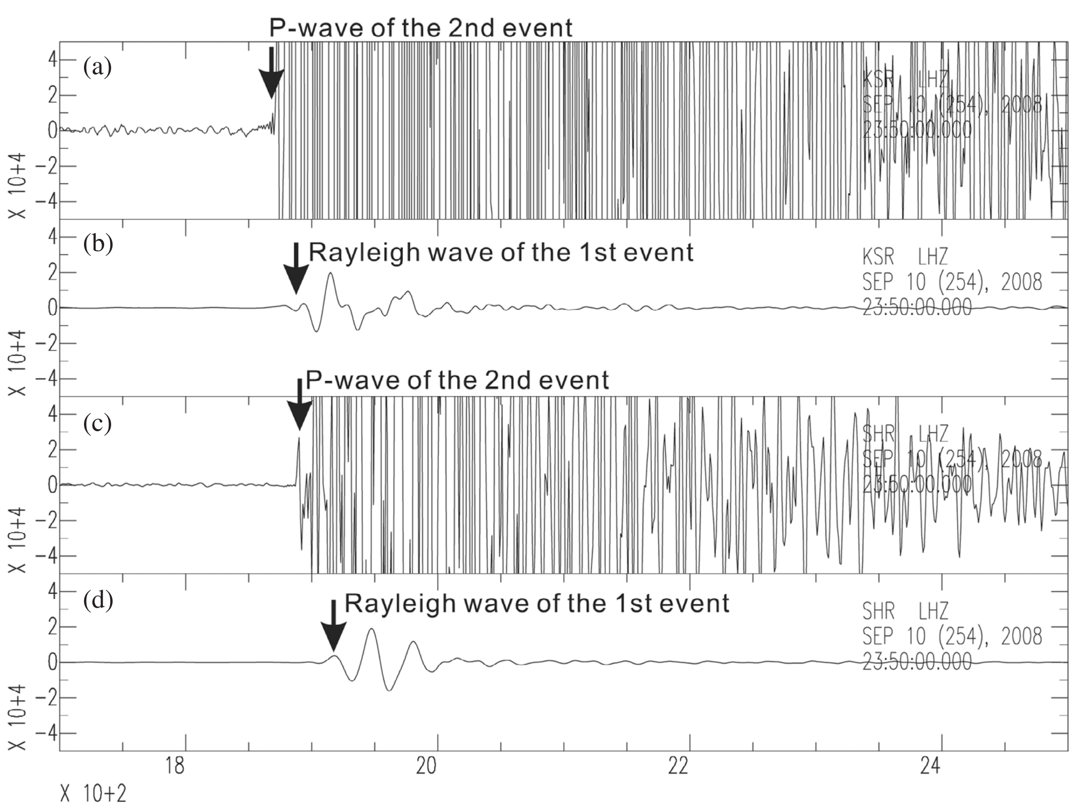

Fig. 5. Horizontal seismograms recorded at Stations KSR and SHR. The P-waves generated by the Hokkaido earthquake (2nd event) were identified directly from the broadband seismograms (a) and (c), and the Rayleigh waves generated by the Indonesia earthquake (1st event) were obtained clearly after applying a band-pass filter between 0.01 and 0.03 Hz (b) and (d).

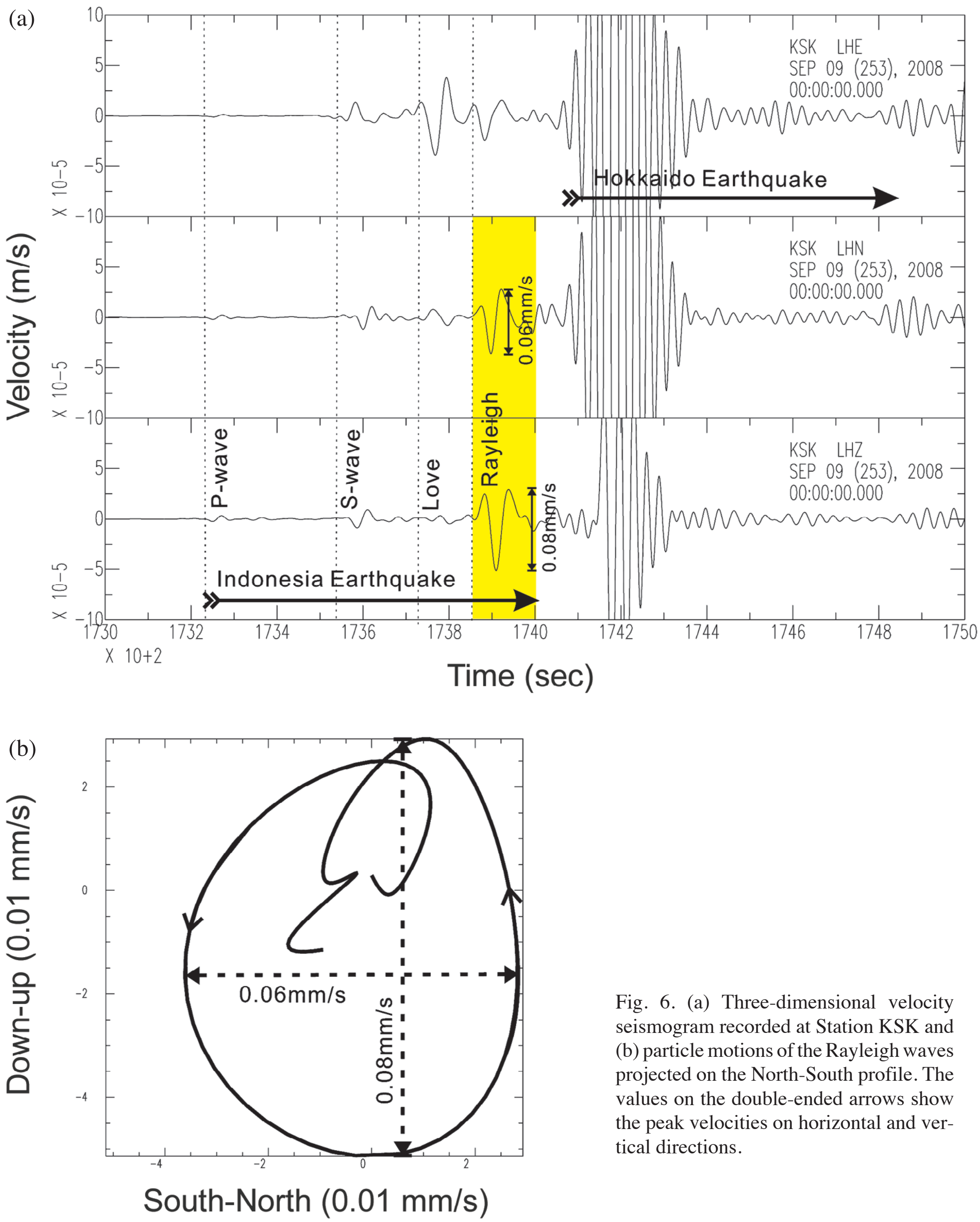

Fig. 6. (a) Three-dimensional velocity seismogram recorded at Station KSK and (b) particle motions of the Rayleigh waves projected on the North-South profile. The values on the double-ended arrows show the peak velocities on horizontal and vertical directions.

observed lower bound (1 - 4 KPa or 0.01 - 0.04 bar) of dynamic stress capable of triggering earthquakes (Lockner and Beeler 1999; Beeler and Lockner 2003; Cochran et al. 2004; Tanaka et al. 2004; Hill and Prejean 2007).

5. DISCUSSION

Although the dynamic stress carried by the Rayleigh waves might just reach the observed lower bound for triggering an earthquake in the past, another plausible trigger mechanism is that the boundary fault at a depth of 25 km which might be both sheared and opened by the depth variation of dynamic stresses of the Rayleigh waves. According to theoretical calculations (Fig. 4.6, Lay and Wallace 2005), displacements of Rayleigh waves vary with depth. At first, retrograde particle motion is observed at depths less than one-fifth of the wavelength, but a prograde feature is shown at deeper layers. Given the observations of the phase velocity of 3.8 km s^{-1} and a period of 33 seconds for Rayleigh waves, horizontal displacements above and below 25 km would move in opposite directions (Fig. 7a). Such a horizontal boundary is extremely close to the focal depth (25 km)

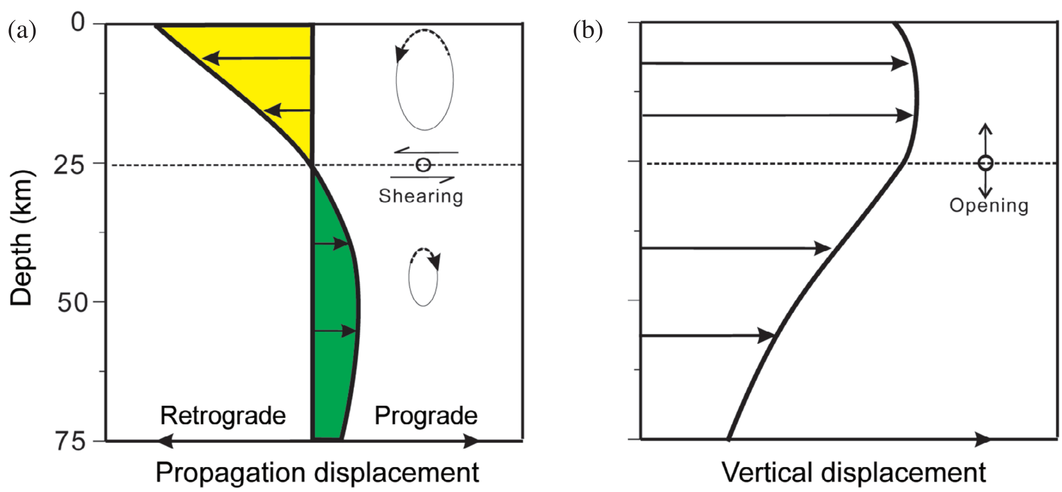

Fig. 7. Schematic plot of particle movements of Rayleigh waves along (a) the wave propagation and (b) vertical directions (modified from Lay and Wallace 2005). The horizontal displacements above and below 25 km move in opposite directions by the observations of the phase velocity of 3.8 km s^{-1} and period of 33 seconds for Rayleigh waves.

of the Hokkaido earthquake, which occurred at the boundary fault between two plates. That means the strong shear stress applied on the fault plane continually oscillated in that the hanging-wall and footwall always move toward opposite directions as Rayleigh wave arrived. Further, the fault plane might be slightly opened by the vertical amplitude variations of Rayleigh waves because the vertical amplitudes of Rayleigh wave at the hanging wall were always greater than those at the footwall (Fig. 7b). In other words, normal stress applied on the fault plane might be reduced to trigger the earthquake.

In addition to dynamic stress carried directly by Rayleigh waves, the boundary fault strength might become significantly weakened after opening and sheared by the oscillations of Rayleigh waves due to fluid infiltration. Although the dynamic stress added on the fault alone might just reach the lower bound to trigger the earthquake, amplitude variations of Rayleigh waves might open the fault to allow fluids to infiltrate into the fault and hence weaken it. Since the Hokkaido earthquake occurred at the subduction boundary between the Pacific plate and the North American plate, some fluids might be released from the subducted Pacific plate. When the boundary fault was slightly opened by the oscillations of Rayleigh waves, fluid would infiltrate into the fault. As a result, the fault slip might be taken place due to both dynamic stress and fluid infiltration into the fault.

It is interesting to note that the Hokkaido earthquake (M_w = 6.9) was not triggered by other larger and closer earthquakes, e.g., the Wenchuan earthquake (M_w = 7.9) on May 12 in China and another earthquake (M_w = 7.0) on July 19 in Japan occurred before the Indonesia earthquake (M_w = 6.6). It is obvious that the dynamic stress carried by those larger and closer earthquakes was larger than that by the Indonesia earthquake. The possible explanations for answering why the previous earthquakes did not trigger the Indonesia earthquake might include the critical stress and incident azimuth of Rayleigh waves. At first, the critical stress might not reach the point of failure when the previous earthquakes occurred. Second, the earthquake triggering might depend on the incident azimuth of the Rayleigh waves.

6. CONCLUSION

It is worthy of note that two strong earthquakes with magnitudes (M_w) of 6.6 and 6.9 respectively struck Indonesia and Japan within a short interval of ~21 minutes time on September 11, 2008. Examinations of broadband seismograms recorded in F-net stations in Japan show that the Hokkaido earthquake occurred just as the Rayleigh waves generated by the Indonesia earthquake arrived. Although the peak dynamic stress estimated at the focus of the Hokkaido earthquake was just reaching the lower bound to be capable of triggering earthquakes, a more plausible mechanism for earthquake triggering might be attributed to the change of the fault property by the fluid infiltration. These observations suggest that the Hokkaido earthquake was likely triggered by the surface waves generated from the Indonesia earthquake. If some other cases can be observed in the future, a temporal warning of possible interaction between strong earthquakes might lead to still further study.

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