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Abstract

A continuous observation of shear wave splitting for 17 years reveals a unique temporal variation in seismic anisotropy in the shallow crust induced by a larger earthquake (M_W5.7) beneath the Tokai region, Japan. The delay time between the fast and slow wavelets coseismically increased and then decreased back to the pre-event value. The duration of the decreasing stage is about two years. The decrease may indicate crack healing in the upper 10 km of the crust. We approximate the temporal variation in the delay time as a function of logarithm of time, which is concordant with healing phenomena of cracks reported by laboratory experiments. The observation indicates that healing of cracks in crustal rocks is complete in approximately two years.

Introduction

A large earthquake damages rocks in and around its rupture zone, generating defects such as small faults and cracks. A change in static stress or dynamic stress associated with a large earthquake triggers small earthquakes around the rupture zone (Reasenberg and Simpson, 1992; Kilb et al., 2000). It causes a coseismic decrease of seismic wave velocities due to opening or enlargement of cracks (Schaff and Beroza, 2004), and enhances also small scale heterogeneity in the crust (Hiramatsu et al., 2000). The rock properties modified by the coseismic damage are expected to recover with time through healing of the defects. The healing process in the crust in and around the rupture zone have been monitored by various active or passive methods as repeating explosions in a fault zone (Li and Vidale, 2001), water injection into a rupture zone (Nishigami et al., 2001), and observations of seismic waves from natural earthquakes (Marone et al., 1995; Baisch and Bokelmann, 2001; Tadokoro and Ando, 2002).

A recovery phenomenon is one of the most important factors to understand the process of earthquake recurrence. In particular, the time constant associated with the healing is a key parameter. In order to study a fine temporal feature of the healing process, it is desirable to analyze signals from non-expensive and frequent sources for a long time. Shear wave splitting of natural earthquakes is one of the most useful phenomena for the purpose because it is very sensitive to changes in features of cracks. When shear wave enters an anisotropic medium, it splits into two orthogonal wavelets, one traveling faster than the other. The shear wave polarization anisotropy in the shallow crust mainly results from the preferred alignment of cracks, which is controlled by the differential stress and the pore pressure (Zatsepin and Crampin, 1997). The direction of the faster polarized shear-wave, ϕ, is parallel to the preferred orientation of cracks. The delay time, δt, or the time difference between two split shear waves, depends on both the aspect ratio and the crack density. The azimuth of the fast wave and the delay time, therefore, provide information on the features of cracks in the crust. Then a crack healing process as well as opening and enlargement of cracks can be monitored by tracing temporal changes in the splitting parameters ϕ and δt.

Data and Method

In the Tokai region, central Japan, a seismic network of Nagoya University has been operated for more than 20 years. The seismic data allow us to monitor changes in the anisotropy in crust of the region for the period using the shear wave splitting. In a previous study, we found a significant increase in δt at the station STN (Shintoyone) following one of the largest earthquakes in a 20 year period. The Aichi-Ken-Tobu earthquake (M_W5.7) occurred on 16 March 1997 at a depth of 39km (Saiga et al, 2003). This event provides an invaluable opportunity to study the fine recovery process of the enhanced anisotropy. In this paper, we build upon the previous results, investigating further the shear wave splitting after the interval analyzed in the previous paper (Saiga et al, 2003). We report here that cracks in the crust heal over a period of about two years and suggest a logarithmic fit to the recovery as a function of the time elapsed since the earthquake.

We use waveform data of two stations, STN and INU (Inuyama) of the network (Figure 1). The period of the analysis covers the years from 1986 to 2003. As shown on cross-sections in Figure 1b and 1c, we observe numerous earthquakes in the crust (shallower than 25km) and on the upper plane of the subducting Philippine Sea plate (deeper than 25km). A benefit of using earthquakes with various source depths is that we can estimate the depth where a change in the anisotropy occurs. We analyze waveform data that satisfy the following list of conditions. The incident angles are less than 35° to minimize the effect of phase conversion from S to P or the distortion of particle motions at the free surface (Booth and Crampin, 1985). The magnitudes are larger than 1.5 to certify high signal to noise ratios and clear S waveforms. The sampling frequency of all waveform data is 100 Hz. We estimate the splitting parameters, ϕ and δt, using the method of Silver and Chan (1991) from the two horizontal components of S waves. We obtain a total of 330 shear wave splitting measurements, 129 at STN and 201 at INU.

Temporal and spatial variation in the splitting parameter

The fast directions, ϕ, are found to be E-W or ENE-WSW at STN (Figure 2) and ESE-WNW at INU. These directions are parallel to the axes of the horizontal maximum compression in the crust around the stations estimated by in-situ stress measurements and focal mechanisms (Tsukahara and Ikeda, 1991). We observe no apparent temporal variations in ϕ at both the stations. This means that the average crack orientation has remained the same for 17 years. However, the delay time δt shows a distinctive change associated with the 1997 Aichi-ken Tobu earthquake at STN. The delay time δt abruptly increased after the earthquake and decreased gradually to the value before the earthquake by the middle of 1999 (Figure 2 and Figure 3). On the other hand, at INU, the temporal variation in δt has been constant through the whole analysis period, exhibiting no effect from the earthquake. In Figure 3, and hereafter, we refer δt as the delay time normalized by path length. As argued by Saiga et al. (2003), we confirm that the spatial variation in the events used in this study never affects the observed temporal variation in splitting parameters (Figure 1).

A change in the Coulomb failure stress ΔCFS (Reasenberg and Simpson, 1992) due to the earthquake is employed to represent the enhancement of both crack density and the pore fluid pressures in the region (Saiga et al., 2003). ΔCFS is defined as $\Delta CFS=\Delta\tau-\mu\Delta\sigma_n$, where $\Delta\tau$, μ and $\Delta\sigma_n$ are the shear stress change, an effective friction coefficient and the normal stress change, respectively (King et al., 1994). Figure 4 shows ΔCFS at a depth of 5 km caused by the coseismic and the post-seismic fault slips of the earthquake (Takai et al., 1999) using the expression by Okada (1992). The fact that δt increased at STN but remained constant at INU after the earthquake is consistent with the spatial variation in ΔCFS, indicating the increase in both the crack density and the pore fluid pressure in the shallower crust around STN. Based on a variation of δt as a function of the source depth, the region where the anisotropy was enhanced by the earthquake is constrained in the crust shallower than 10 km (Saiga et al., 2003); however, the anisotropic layer extends to 30 km depths.

As shown in Figure 3, the subsequent period after the earthquake clearly shows a rapid decay in the strength of anisotropy and recovery back toward the pre-event values by the end of 1999 at STN. We observe the recovery of δt at STN for both the earthquake groups in the crust (Figure 3a) and on the upper plane of the subducting Philippine Sea plate (Figure 3b). The spatial pattern of the subsequent decrease in anisotropy is the same as that of the increase after the earthquake, indicating that both the changes occur in the same region. The decrease in δt corresponds to a decrease in the crack density and/or a pore fluid pressure in the shallower crust. We, therefore, attribute the gradual decrease in δt at STN to healing of the cracks in the shallow crust that were opened by the earthquake. From the observed variation in δt, we can estimate a characteristic healing time of approximately two years

Characteristic time of crack healing

We approximate the decay function of δt with time by a logarithmic function of time, log*t* (Figure 3a and 3b). The logarithmic time decay is consistent with temporal features of healing reported from various laboratory experiments of rocks and field observations (Dieterich, 1972; Marone, 1998, Schaff and Beroza, 2004). Laboratory experiments showed that the frictional coefficient between two rocks under the normal stress increases logarithmically with time. A logarithmic variation in the stress drops of earthquakes of multiplets (repeating earthquakes) is also observed (Marone et al., 1995). We consider that similar mechanisms work for healing of cracks in the crust, causing possibly the decay of δt represented by the logarithmic function of time.

The characteristic duration for cracks to heal we measured here is about two years. It is interesting to note that a time constant of the decay, about two years in this study, that is a time constant of healing, seems to be a universal constant in the crust. Similar durations are estimated by various seismic observations near damaged fault zones by large earthquakes in California and Japan; two to four years from a change in seismic wave velocity change using repeated explosions (Li et al., 1998), three years from a change in ϕ of the shear wave splitting (Tadokoro and Ando, 2002), and a few years from a change in coherencies among waveforms of multiplets (Baisch and Bokelmann, 2001). It is to be noted that the healing of cracks in the shallow crust can explain all these observations. The results obtained here and previous studies stress that the characteristic duration of the crack healing in the shallow crust is about two years. We emphasize that the duration is much shorter than earthquake recurrence intervals of large faults. It is, therefore, unlikely that the damages in rocks caused by a fault motion affect the stress accumulation for the next event. The obtained short duration may provide a clue to understand the physical process of the crack healing in the crust, in particular, a possible role of water in it.

Conclusions

We investigate the temporal variation in seismic anisotropy for 17 years in the crust beneath the Tokai region, Japan, from the observation of shear wave splitting.

Following a M_W5.7 earthquake, we observe a coseismic increase and subsequent relaxation of the strength of seismic anisotropy in the shallower crust. The delay time between the two split shear waves decreased to pre-event values after two years. The decrease in the delay time is approximated as a function of logarithm of time. This temporal behavior is similar to the temporal evolution of the healing of cracks reported by laboratory experiments. We, together with previous studies, conclude that the healing of crustal rocks is complete in approximately two years.

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Figure captions

Figure 1. (a) Distribution of epicenters of analyzed events at STN (circles are before the M_W5.7 event and diamonds after the M_W5.7 event) and those at INU (squares are before the M_W5.7 event and pluses after the M_W5.7 event) used in this study. Seismic stations are indicated by triangles. A star is the epicenter of the Aichi-ken Tobu earthquake (M_W5.7) that is the largest event during the analysis period. (b) Cross-sections of hypocenter distribution beneath the rectangle area along AA' in (a). (c) Cross-sections of hypocenter distribution beneath the rectangle area along BB' in (a).

Figure 2. Examples of shear wave splitting at different periods observed at STN. Inc and baz represent the incident angle to the station and the back azimuth of the event, respectively. Dep is the depth of the event. Note that the delay time that increased after the Aichi-ken Tobu earthquake (1997/03/16) is back to the pre-event values.

Figure 3. The temporal variations in the delay time normalized by path length for (a) crustal earthquakes (shallower than 25km) at STN, (b) slab earthquakes (deeper than 25 km) at STN, and (c) slab earthquakes at INU. Thick line of each panel shows a schematic temporal variation in strength of anisotropy. Dashed line indicates the time when the Aichi-ken Tobu earthquake occurred. An error of each normalized time delay is shown by solid bar. Gray hatch represents a relaxation period of two years estimated from the temporal variation in time delay at STN.

Figure 4. The contour map of a change in the Coulomb failure stress (ΔCFS) at a depth of 5 km for right lateral slip on an NE-SW trending vertical fault due to both coseismic and post-seismic slip of the Aichi-ken Tobu earthquake (after Saiga et al. (2003)). The effective friction coefficient is 0.4, Poisson ratio is 0.25, and the rigidity is 40GPa. Crosses are the stations and the star is the epicenter of the earthquake. The unit of ΔCFS is kPa.

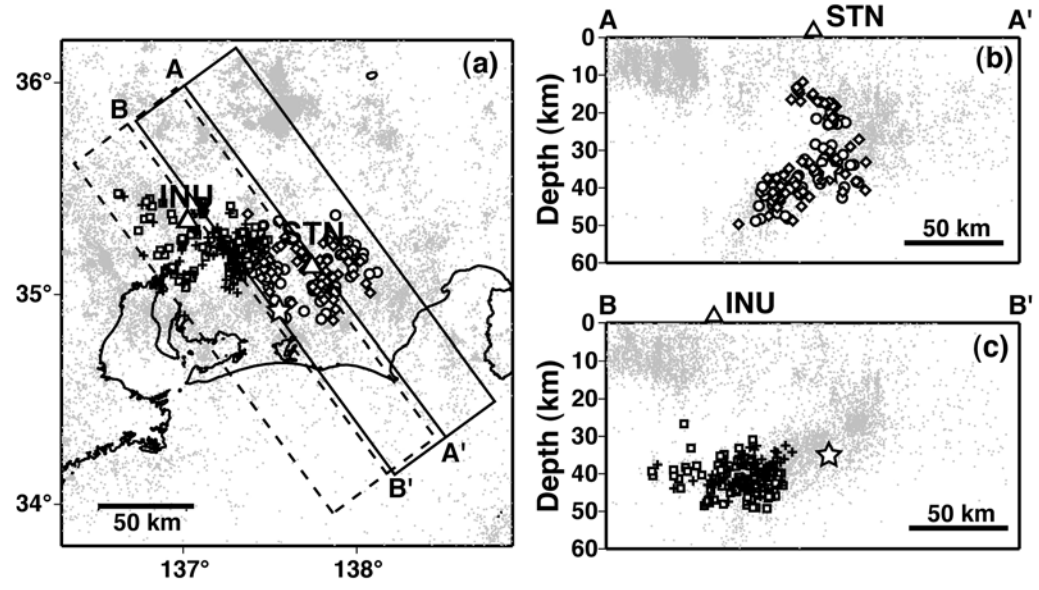
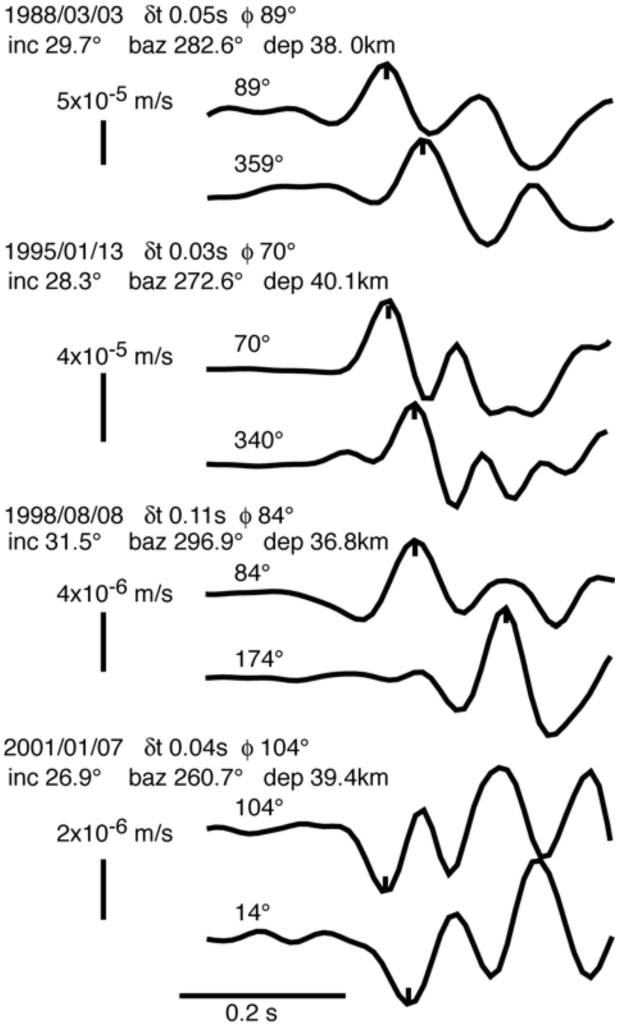


Figure 1 Hiramtsu et al.



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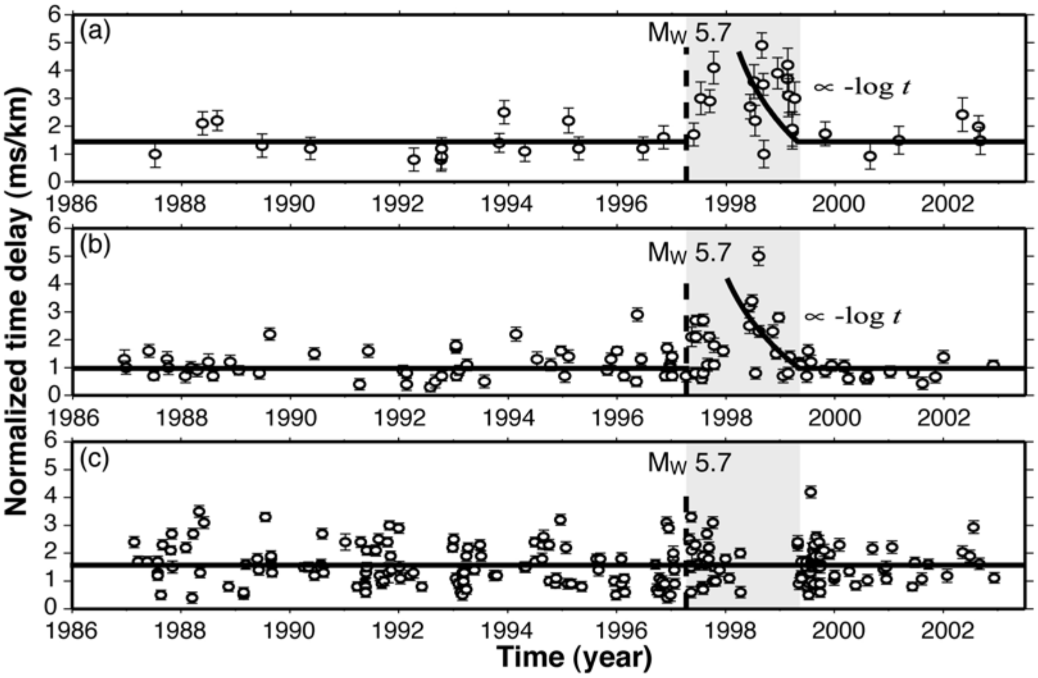

Figure 3 Hiramatsu et al.

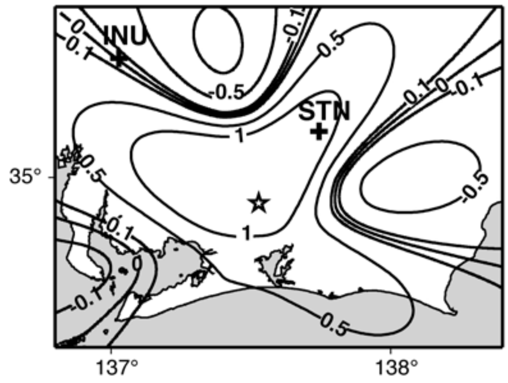

Figure 4 Hiramatsu et al.