Observations of changes in waveform character induced by the 1999 M_w7.6 Chi-Chi earthquake

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[1] We observe changes in the waveforms of repeating earthquakes in eastern Taiwan following the 1999 M_w7.6 Chi-Chi earthquake, while their recurrence intervals appear to be unaffected. There is a clear reduction in waveform similarity and velocity changes indicated by delayed phases at the time of the Chi-Chi event. These changes are limited to stations in and paths that cross the 70 × 100 km region surrounding the Chi-Chi source area, the area where seismic intensity and co-seismic surface displacements were largest. This suggests that damage at the near-surface is responsible for the observed waveform changes. Delays are largest in the late S-wave coda, reaching approximately 120 ms. This corresponds to a path averaged *S* wave velocity reduction of approximately 1%. There is also evidence that damage in the fault-zone caused changes in waveform character at sites in the footwall, where source-receiver paths propagate either along or across the rupture. The reduction in waveform similarity persists through the most recent repeating event in our study (November 15, 2007), indicating that the subsurface damage induced by the Chi-Chi earthquake did not fully heal within the first 8 years following the Chi-Chi earthquake. **Citation:** Chen, K. H., T. Furumura, J. Rubinstein, and R.-J. Rau (2011), Observations of changes in waveform character induced by the 1999 M_w7.6 Chi-Chi earthquake, *Geophys. Res. Lett.*, *38*, L23302, doi:10.1029/2011GL049841.

1. Introduction

[2] Repeating earthquake sequences (hereafter referred to as RES) are groups of events with nearly identical waveforms, locations, and magnitudes, thus representing a repeated rupture of the same patch of fault. They have a common source and path such that changes in their waveforms can be attributed to variation in material properties along the travel path. Studies of RES following large earthquakes have often revealed co-seismic and post-seismic velocity changes in the aftershock zone, which provide *in-situ* measures of fault healing processes [e.g., *Peng and Ben-Zion*, 2006; *Li et al.*, 2006; *Rubinstein et al.*, 2007]. The recurrence behavior of repeating earthquakes can also change following a large earthquake where their behavior is similar to that of aftershocks; recurrence intervals (*Tr*) are short immediately following the mainshock and increase with time back to their pre-mainshock rate [*Schaff et al.*, 1998]. The dependence of *Tr* on time elapsed since the mainshock has been used to determine the healing rate on natural faults [*Vidale et al.*, 1994; *Marone et al.*, 1995; *Peng et al.*, 2005]. Combining *Tr* and waveform similarity, their time dependence indicates the changes in medium characteristics [e.g., *Poupinet et al.*, 1984].

[3] The 21 September, 1999, M_w 7.6 Chi-Chi earthquake is the most damaging earthquake to occur in an urban area of Taiwan during the past 100 years. Understanding how faults heal between earthquakes is of fundamental importance to explaining the earthquake cycle. The Chi-Chi event induced surface rupture extended over 100 km [*Kao and Chen*, 2000] with lateral and vertical surface displacements on the hanging wall of up to 9.1 m and 4.4 m, respectively [*Yu et al.*, 2001]. Subsurface structure and fault zone characteristics were measured directly in the Chelungpu Fault Drilling Project [*Ma et al.*, 2006], but there are only a few of these measurements. The spatial extent, the strength, and the recovery of subsurface damage over Taiwan therefore remain unexplored. Repeating earthquakes recently found in eastern Taiwan [*Chen et al.*, 2008, 2009] provide a good opportunity to investigate fault healing processes. The time-varying rock properties monitored by repeating earthquakes are usually found to be localized near the mainshock rupture zones [e.g., *Baisch and Bokelmann*, 2001; *Schaff and Beroza*, 2004; *Rubinstein and Beroza*, 2004, 2005], with evidence for damage in the fault zone [*Zhao and Peng*, 2009; *Rubinstein et al.*, 2007] and/or at the near surface [e.g., *Rubinstein and Beroza*, 2004, 2005; *Peng and Ben-Zion*, 2006]. Here we report a significant change in the seismic wave characters of RES that occurred ~70 km away from the 1999 M_w 7.6 Chi-Chi mainshock, while the *Tr* of these events remains unaffected. This observation allows us to document the spatial and temporal extent of subsurface damage associated with the Chi-Chi earthquake.

2. Repeating Earthquake Sequences in Eastern Taiwan

[4] Previously, *Chen et al.* [2009] identified 55 *M* 2.1 to 4.6 repeating earthquake sequences along the Longitudinal Valley Fault in Eastern Taiwan in the time period between 1991 and 2008 (Figure 1b). We study the three largest repeating earthquake sequences to maximize the number of stations available for analysis. Each event has magnitude greater than *M* 3.5 and is denoted by a black star in Figure 1a. We use short-period seismic data from the Central Weather Bureau Seismic Network (CWBSN) and broadband seismic data from the Broadband Array in Taiwan for Seismology (BATS). The selected *M* 3.8, *M* 3.9, and *M* 4.6 RES are composed of events from 1991 to 2007 and have average

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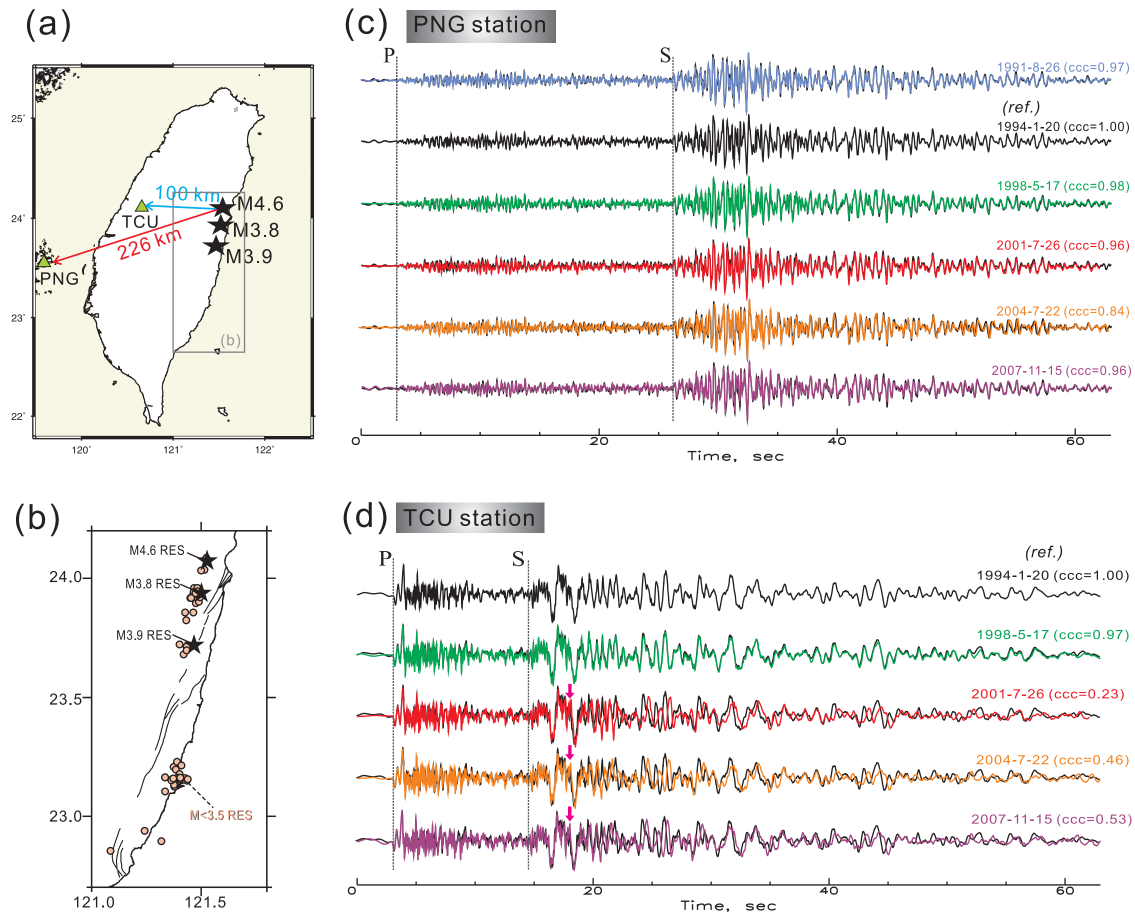

Figure 1. (a) Map of the *M*3.8~4.6 RES in eastern Taiwan. (b) A close-up view of eastern Taiwan. The 55 repeating earthquake sequences identified by *Chen et al.* [2009] are shown as pink circles, and the three M > 3.5 RES are denoted as stars. Active faults in eastern Taiwan are shown by solid lines. (c, d) Unfiltered seismograms of the *M*4.6 RES recorded at stations PNG and TCU. Waveform cross-correlation coefficient with a reference event (1994 event, black curve) determined over the 60-s-long unfiltered seismogram is denoted by ccc. Arrow indicates the onset of the delayed arrivals.

recurrence interval of 2.96, 2.64, and 3.24 years, respectively, behaving in a quasi-periodic manner (Table S1 of Text S1 in the auxiliary material).[1] Differential S minus P times confirm that the events in each sequence are co-located [*Chen et al.*, 2008]. For the *M* 4.6 RES, waveform cross-correlations methods indicate that the centroids of the events are within 200 m of each other, much smaller than the likely rupture dimension of 650 m (Figure S1 of Text S1 in the auxiliary material).

[5] As shown in Figure 1c, the consistently high waveform similarity defined by waveform cross-correlation coefficient (ccc > 0.80) is commonly found. At some stations, however, ccc falls below 0.5 at the time of the 1999 earthquake and the ccc reduction remains significant in the following years, continuing through the last event in a sequence (Figures 1d and S2b–S2d). On visual inspection, delayed arrivals can be seen with a gradual recovery from 2001 to 2007, as illustrated by arrows in Figure 1d. As illustrated in Figure S2a, a sudden reduction in waveform similarity is commonly observed for these events after the Chi-Chi earthquake, while the corresponding seismograms shown in Figure S3.

3. Spatial Extent of Seismic Waveform Similarity Reduction

[6] After an earthquake, velocity reductions have been observed to occur in a very shallow layer (tens to hundreds of meters) due to strong shaking [e.g., *Rubinstein and Beroza*, 2004, 2005; *Schaff and Beroza*, 2004; *Peng and Ben-Zion*, 2006] or deep fault zone due to structural weakening or decrease in crustal stress [e.g., *Li et al.*, 1994; *Vidale and Li*, 2003; *Peng et al.*, 2003; *Taira et al.*, 2008; *Zhao and Peng*, 2009; *Wegler et al.*, 2009]. To illustrate whether the change in waveform similarity and the delayed arrivals vary with source-receiver path and which physical model explains the data, evaluating the spatial extent of this change is needed. We determine the ccc and time lag of individual seismograms to reference events for each station, by conducting a moving-window cross-correlation analysis using a 2-sec-long window, sliding forward at 1.5-sec increments through 60 sec window. A clear variation of ccc between the pre- and across-1999 pairs is demonstrated by color presentation of ccc vs.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049841.

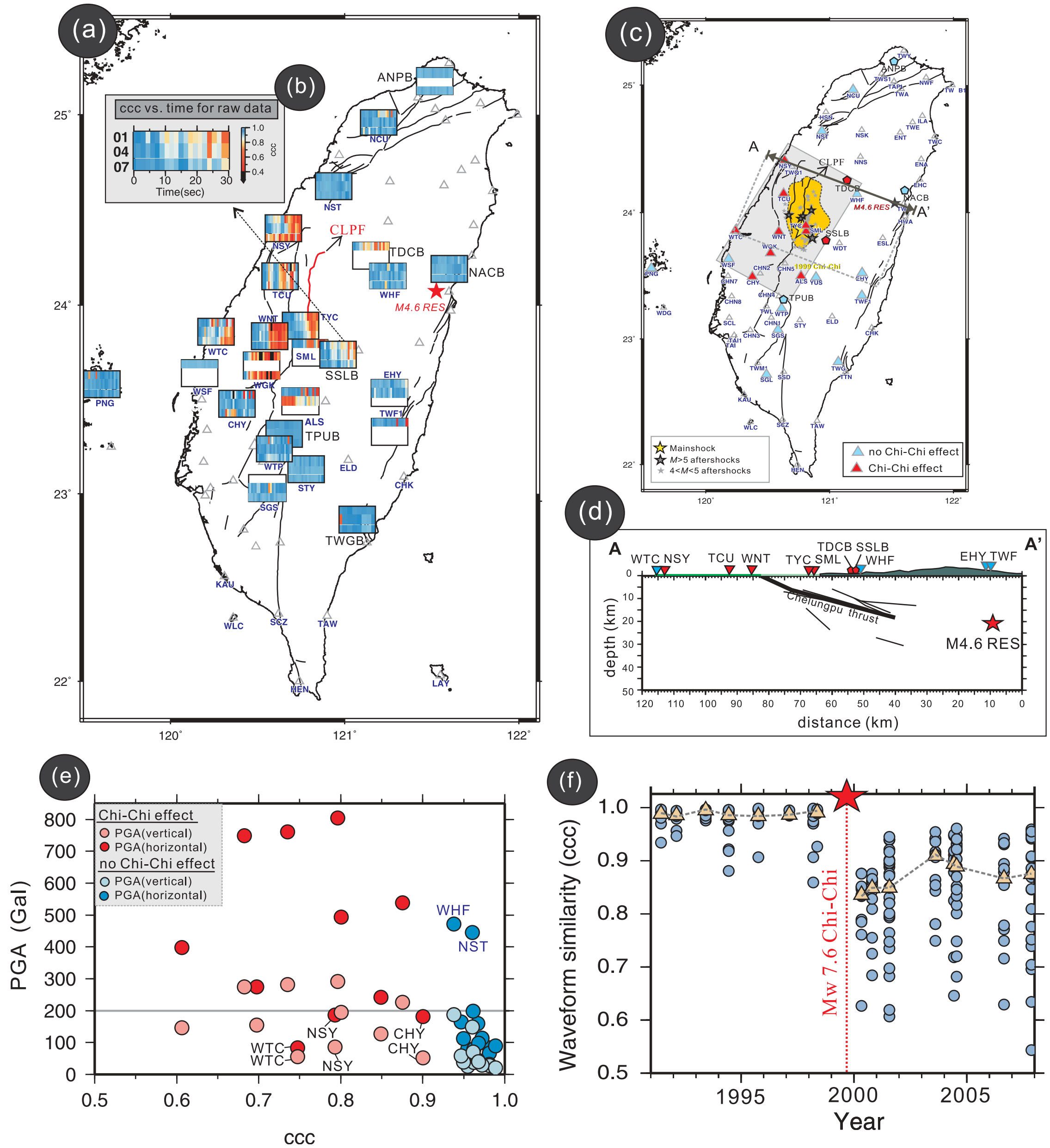

Figure 2. (a) Spatial distribution of ccc changes for the M4.6 RES. (b) Close-up of ccc vs. time plot using the 1998 event as a reference (station SSLB). Three rows in each color box correspond to the 2001, 2004, and 2007 events, respectively, and the horizontal axis is time (second). (c) Spatial distribution of stations with the Chi-Chi effect and no 1999 effect (see text for explanation). Grey area marks the area of inferred damage that is ~70 × 100 km. Open triangles indicate the stations showing clipped or noisy seismograms, or lack of pre-1999/post-1999 events. GPS derived co-seismic horizontal displacement of (>2 m) by *Yu et al.* [2001] is denoted by yellow area. Chi-Chi mainshock and aftershocks are shown by stars. The stations in the dashed box are selected for the cross section A-A′. (d) Cross section A-A′ showing the main rupture of the Chi-Chi earthquake sequence (thick line) and secondary faults (thin lines) by *Kao and Chen* [2000]. CWBSN and BATS stations are indicated by triangles and pentagons, respectively. CLPF indicates the Chelungpu fault. (e) Vertical and horizontal PGA values as a function of ccc. Median ccc value is determined using 60-s unfiltered seismograms (the 1998 and 2001 events for the M4.6 RES). For a given CWBSN and BATS station, the five closest strong motion stations are chosen to calculate the corresponding PGA values. Median ccc below 0.90 implies the Chi-Chi effect, whereas median ccc greater than 0.94 implies no Chi-Chi effect. (f) Ccc as a function of time from all three RES at red stations, with one reference event per sequence per station (open circles). Yellow triangles indicate the median value, connected by dashed line over time.

time plot in Figure 2a. The warm-colored ccc vs. time plot with the median value of ccc over 60-s seismogram below 0.90 at the 2001 event reveals strong ccc contrast between the pre- and across-1999 pairs, now is defined as Chi-Chi effect (red symbol in Figures 2c–2e). Whereas cold-colored ccc vs. time plot with median ccc greater than 0.94 is defined as no Chi-Chi effect (blue symbol in Figures 2c–2e).

[7] The Chi-Chi effect is confined in a 70 × 100 km area surrounding the Chi-Chi rupture zone while it is not necessarily observed for paths that cross this area. This area roughly corresponds to the area that experienced surface displacements of 2 m and larger in the mainshock (yellow area in Figure 2c) and the region that experienced largest peak ground motions (Figure S4), suggesting a common mechanism that strong shaking and/or large deformations are related to the waveform similarity reductions. However, the stations CHY, NSY, and WTC characterized by clear Chi-Chi effect experienced a small peak ground acceleration (PGA < 100 Gal), suggesting that near-surface damage may not be the only cause for the ccc reduction (Figure 2e).

[8] We also note that the characteristics of the ccc changes are different for stations in the hanging wall versus the footwall (Figure S5). At footwall stations, large ccc reductions are found near/before S-wave arrivals and are similar over much of the range of frequencies considered (2-6 Hz), but are smallest for the lowest frequencies (1 Hz) (Figure S5a). These travel paths cross the rupture zone, such that body waves and coda waves would be equally affected. At hanging wall stations, strong ccc changes are largest in the late S coda and are largest for the highest frequencies considered (Figure S5b). The late arrivals of ccc reduction are consistent with near-surface damage because the coda is scattered energy, such that later waves will remain in a damaged region for a long time resulting in larger changes in the waveform character. We cannot be certain that the coda is coming from the near surface, but there is evidence that coda is primarily generated very close to receivers [e.g., *Scherbaum et al.*, 1991; *Dodge and Beroza*, 1997; *Rubinstein and Beroza*, 2007]. The different frequency behavior suggests the near-surface damage is confined to a small layer, thus only affecting high frequencies, while the fault zone damage is more distributed and also affects longer period energy.

[9] The delayed arrivals, however, vary from station to station without a systematic pattern. We observe very large phase delays between pre- and post-Chi-Chi repeating events including those at the hanging wall station SSLB, which are ~120 ms at 25s after the S-wave onset. This corresponds to approximately a 1% delay of S-wave velocity reduction averaged over the propagation path. Delayed arrivals and waveform changes are found to arise from either paths that cross the fault or near surface damage.

4. Temporal Recovery of Waveform Similarity and Delayed Arrivals

[10] In Figure 2f we plot the time-evolution of waveform similarity for three RES at the stations affected by the Chi-Chi earthquake. There is a sudden decrease of waveform similarity across the year of 1999, without a clear recovery between 2000 and 2007. We also note that waveform similarity appears to decrease with increasing travel time (Figure S6). The delayed arrivals for different post-Chi-Chi events also increase with time into the seismogram, as indicated by Figure S7. However, both waveform similarity and time delays have not returned to their pre-1999 levels. We therefore conclude that the material property changes that caused the changes in seismic wave character have not completely healed in the 8 years following the Chi-Chi earthquake. Regaining strength rapidly (several months to few years) at different study areas is inferred to be associated with rapid healing in the early postseismic stage [e.g., *Li et al.*, 2003; *Schaff and Beroza*, 2004; *Rubinstein and Beroza*, 2004; *Peng and Ben-Zion*, 2006], while much longer time to fully recover the strength can be expected [e.g., *Li et al.*, 2003; *Vidale and Li*, 2003; *Schaff and Beroza*, 2004]. Here we do not have observations in the first 7 months after the Chi-Chi mainshock, therefore the information of rapid recovery behavior immediate following the mainshock is missing. The waveform similarity and velocity changes we observe are likely smaller than the ones in the early postseismic stage. We will continue the monitoring of healing process in the Chi-Chi rupture zone using the repeating events with 2–3 years recurrence interval.

5. Summary

[11] Using three quasi-periodic, *M*3.8-4.6 repeating earthquake sequences located ~70 km from the Chi-Chi earthquake, we identify systematic changes in seismic wave character and time delays following the 1999 Chi-Chi earthquake. We find that post-Chi-Chi events have reduced waveform similarity compared with the pre-Chi-Chi events. Such reduced waveform similarity is most pronounced at the stations near the Chi-Chi source area, corresponding to locations with large seismic intensities and surface displacements. We also observe delayed arrivals of ~120 ms in the S-wave coda. These observations are consistent with shallow subsurface damage induced by the Chi-Chi Earthquake. In addition to delays in the S coda, stations in the footwall also see waveform changes of the direct S-wave. This may result from fault-zone damage. The magnitude of waveform similarity reduction and time delay for the post-Chi-Chi events remains significant until 2007, the most recently observed events in the three sequences. This indicates that the healing of subsurface damage zone may not be complete within a time interval of 8 years after the Chi-Chi earthquake.

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