Reply to “Comment on ‘Systematic Analysis of Shear-Wave Splitting in the Aftershock Zone of the 1999 Chi-Chi, Taiwan, Earthquake: Shallow Crustal Anisotropy and Lack of Precursory Changes,’ by Yunfeng Liu, Ta-Liang Teng, and Yehuda Ben-Zion,” by Stuart Crampin and Yuan Gao

by Yunfeng Liu, Yehuda Ben-Zion, and Ta-Liang Teng

Introduction

We thank Crampin and Gao (2005, hereinafter referred to as CG) for their interest in the analysis and results of Liu et al. (2004, hereinafter referred to as LTBZ). We disagree that the lines they draw through some of the data points of figure 14a of LTBZ (reproduced here as Fig. 1) carry quantitative scientific information, and we maintain our assessment that the results of LTBZ do not show systematic temporal evolution of anisotropy parameters that could be used to forecast impending large earthquakes in our study area. Our response to CG focuses on features involving directly the results of LTBZ. We do not discuss the broader claims of CG on general scaling relations, associated with their figures 2 and 3, other than to note that they have been controversial (e.g., Aster et al., 1990, 1991; Seher and Main, 2004). Prompted by the comment of CG, we perform a more detailed analysis of spatio-temporal variations of the time delays between fast and slow shear waves in our data. The detailed examination indicates clearly that the apparent precursory pattern identified by CG is dominated by spatial rather than temporal variations of properties.

Results

Figure 1 is an enlarged version of figure 14a of LTBZ, with sequential numbering of the data points before the 1999 Chi-Chi mainshock and several later points. The “subtle temporal changes” referred to by CG are associated with a selection of a small number of points from the available data that follow the pattern they seek to identify. A glance at Figure 1 shows changes of time delay (TD) over short time intervals on the order of days to weeks, both before and after the Chi-Chi mainshock (e.g., around data points 14, 154, 224, and 319), with magnitude similar to or larger than the apparent precursory increase over ~600 days associated with the line fit of CG. The apparent “immediate” precursory decrease discussed by CG is based on 1–3 data points and TD variation that is within the standard deviation of the results. These statements already indicate that the changes associated with the line fits of CG are not statistically significant. However, it is useful to examine the results more closely to clarify further the possible existence and origins of changes that are present in the TD values of Figure 1.

In general, the measured shear-wave splitting parameters are functions of both space (ray paths of the seismic waves) and time. An effort to detect temporal variations of properties should employ sources that produce identical (or highly similar) ray paths to a given receiver at different times. The data of Figure 1 are based on evolving seismicity with variable event locations and thus contain, as pointed out by LTBZ, a mixture of temporal and spatial changes. The shear-wave splitting parameters measured by LTBZ for the top 0.2 km of the crust are relatively free from spatial changes since the ray paths of the employed waveforms, propagating from the borehole station to the free surface, are nearly identical. As shown in figure 14c of LTBZ, the TD values for the top 0.2 km have far smaller variations than (and a different pattern from) the corresponding values in Figure 1 for the deeper section. In contrast, the measured TD values of Figure 1 are associated with considerable variations of ray paths. As shown below, changes in those values, and the pattern depicted by the line fits of CG, are dominated by spatial rather than temporal variations of properties.

The apparent precursory increase argued for by CG hinges on the three data points 14, 15, and 17 of Figure 1 with TD values less than 0.1 sec. (If these points are ignored, a least-squares fit to the data before the Chi-Chi mainshock is essentially horizontal.) As indicated by figure 8a of LTBZ, all measured TD values smaller than 0.1 sec, both before and after the Chi-Chi mainshock, are associated with relatively shallow ray paths (near the boundary of the shear-wave window) produced by events with a ratio of epicentral distance over depth larger than 0.4. Figure 2a gives the locations of all the events used in the study of LTBZ, with occurrence times before and after the Chi-Chi mainshock marked by cubes and spheres, respectively, and measured TD values indicated by the color scale. Figures 2b and 2c show projections of the data on horizontal and vertical surfaces, along with contours of the measured delay times. Several observations can be made from Figures 2a, 2b, 2c. First, we note the existence of spatial domains that produce relatively high (e.g., the central region) or relatively low (e.g., the boundary...
Figure 1. Observed time-delay values for the section deeper than 0.2 km versus time. Each data point is a time-delay measurement with an error given by the vertical line. The mean values and standard deviations of the measurements before and after the Chi-Chi mainshock are indicated by solid and dashed lines, respectively. The numbers near the points mark the sequential ordering of the measurements.

regions) TD values both before and after the Chi-Chi mainshock. A similar point can be made from figure 15 and related discussion of LTBZ. Second, we note in agreement with figure 8a of LTBZ that most events with small TD values, including those generating points 14, 15, and 17 of Figure 1, are located near the boundary of the shear-wave window and are associated with relatively shallow ray paths. In contrast, the events generating points 13 and 19 are located near the center of the plot in a region that produces consistently relatively high TD values. We note further that the event pairs 13–14 and 17–19 show considerable variations of TD values over very short time intervals (Figure 1), but each of these events resides in a region that produces similar TD values over much longer time intervals spanning the occurrence of the Chi-Chi mainshock. This indicates that the changes in Figure 1 from point 13 down to points 14, 15, and 17, and back up to point 19 are dominated by spatial variations of properties.

The best way to track temporal evolution in our data set is to use measurements associated with clusters of repeating earthquakes (producing highly similar waveforms). The inset in Figure 2 shows the location of earthquakes belonging to four such clusters. Point 13 is a member of one cluster (C1), which spans the time of the Chi-Chi mainshock. (The waveforms generated by the events of cluster C1 are given in figure 16 of LTBZ.) The other three clusters include only events occurring after the Chi-Chi mainshock. Figure 3 shows the TD values associated with the events of the four clusters, along with the data (diamonds) used in the pattern identified by CG. The temporal variations of the data generated by the four event clusters are considerably smaller than those associated with the other points in the figure (produced by sources with variable locations). This indicates again that the pattern identified by CG is dominated by spatial rather than temporal variations.

To measure more accurately possible small temporal
Figure 2. (a) The spatial distribution of the events used to measure the time delays of Figure 1. Cubes and spheres represent locations of events occurring before and after the Chi-Chi mainshock, respectively. The size of the time delays associated with each event is shown by the color scale. The inset gives locations of four event clusters used in Figures 3, 4, 5. The numbers near the symbols correspond to those of Figure 1. (b) Contours of delay times on a horizontal projection of the data in (a). (c) Contours of delay times on a vertical projection of the data in (a) through the line AA’ of (b). The squares and circles in (b) and (c) represent events before and after the Chi-Chi mainshock, respectively.
changes in our data we perform on the sets of similar waveforms, interpolated into 1000 samples per second, a correlation analysis with a sliding time window (e.g., Bokelmann and Harjes, 2000; Niu et al., 2003). We align both the fast and slow traces at the arrivals of the fast shear waves, and then cross-correlate sequentially each waveform with the first trace in the set of similar waveforms using a sliding window of 0.4 sec. Figure 4 illustrates the analysis for the waveforms of cluster C1. During two time windows $W_1$ and $W_2$ corresponding to the direct and surface-reflected waves, respectively, the calculated cross-correlation coefficients are close to 1 (Fig. 4a). Since the traces are aligned at the fast-shear-wave arrivals, the observed time lags over the window $W_2$ for the fast shear waves (Fig. 4b) give travel-time changes for the surface-reflected fast waves. Figures 4c and 4d show analogous calculations for the slow shear waves. Since each trace of the slow shear wave is aligned on the corresponding fast wave, the results of Figure 4d over the window $W_1$ give the temporal changes of the TD values for the section deeper than 0.2 km. The differences between the time lags associated with $W_2$ and those of $W_1$ give the travel-time changes for the surface-reflected slow waves. The temporal changes of the TD values for the section shallower than 0.2 km can be estimated from the differences between the travel-time changes for the fast and slow surface-reflected shear waves.

Similar calculations to those of Figure 4 are done using the waveforms of the events in clusters C2–C4. The obtained changes of TD values for all four clusters are shown in Figure 5. The results for cluster C1, which spans the time of the Chi-Chi mainshock, do not vary by more than a few milliseconds over the period leading to and after the Chi-Chi event. Some larger, rapid, post Chi-Chi mainshock changes of TD values are seen for the section deeper than 0.2 km in the results of the other clusters (e.g., the first five points of cluster C3). These changes are likely to be produced, at least in part, by the remaining small differences of locations and focal mechanisms of the used events.

Summary

The results of LTBZ and this note emphasize the need to perform a systematic and objective analysis of a large data set, and to distinguish carefully between spatial and temporal variations of properties. The subtle temporal changes discussed by CG are associated with mixing spatial and temporal variations, and are based on a small data set with marginal statistical significance. CG concede that details of the patterns they have in mind are not understood, but argue that point 13 occurs “before the characteristic patterns” and dismiss more accurate results (Figs. 3 and 5) not compatible with their expectations as “irrelevant.” (What exactly are the timescales of the characteristic patterns, including uncertainties, given that details of the patterns are not understood?) We note that point 13 is only several hours before point 14, which they use in their line fit and is pivotal for their approximately 600-day pattern. It is possible to identify many candidate patterns in figure 14a of LTBZ (e.g., an increase from point 14 to point 23 over $\sim$250 days followed by a decrease to point 32 over $\sim$250 days, or perhaps sinusoidal variations over $\sim$250 days), but these patterns have little statistical significance and are all associated with mixing spatial and temporal variations. We conclude that the apparent precursory pattern noted by CG does not survive a careful objective examination of the data.

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Figure 4. Cross-correlation coefficients (a) and corresponding time lags (b) between the first and following traces of the fast shear waves generated by events in cluster C1. Corresponding results for the slow shear waves are given in (c) and (d).

References


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Figure 5.  (a) Estimated changes of time delays for the section below 0.2 km from the cross-correlation analysis based on waveforms generated by the four event clusters. Changes are given with respect to the value of the first event in the cluster (e.g., event 13 in cluster C1). Note change of vertical scale from those of Figures 1 and 3. (b) Corresponding results for the section above 0.2 km. TD, time delay.