Seismological evidence of simultaneous mountain-building and crust-thickening from the 1999 Taiwan Chi-Chi earthquake (Mw=7.6)

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High-quality seismic data recorded during the 1999 Taiwan Chi-Chi earthquake (Mw=7.6) show that a small-scale orogenic process of both mountain-building and crust-thickening was simultaneously accomplished along one set of crustal-scale conjugated faults. Mountain-building near the surface was primarily produced by the main shock along an eastward low-angle thrust fault in the upper crust. In the meanwhile, a sequence of aftershocks along a westward high-angle reverse fault in the lower crust could increase crustal thickness even though major crustal deformation in generally taken place under ductile deformation. Also, velocity structures inverted from seismic tomography suggest that the crustal deformation in the form of both mountain-building and crust-thickening has been repeatedly generated by a similar orogenic process during the past million years. The dynamic dual process observed here contributes to the growth of the orogenic zone in the near the surface and deep crust in Taiwan.

Key words: Chi-Chi earthquake, crust-thickening, mountain-building.

1. Introduction

Although crustal deformation in orogenic belts is often characterized by mountain-building near the surface, the greatest amount of crustal deformation in the crust is not mountain-building, but rather crust-thickening. Based on the isostasy theory (Airy compensation), the anomaly of crust thickness (crustal root) is not only proportional to, but also significantly larger than that of the topographic relief on the surface (Turcotte and Schubert, 1982). In the cases of such great mountains as the Himalayas, the Alps and the Rockies, it is widely accepted that mountain-building near the surface was primarily caused by a large amount of horizontal shortening taking place along one and/or several major thrusting faults in the upper crust (Molnar, 1988; Schelling and Arita, 1991; Srivastava and Mitra, 1994). However, the dynamic process of involved in crustal deformation in the lower crust of collision zones has still not yet been well understood in that reliable observations in high mountainous areas are generally hard to obtain.

Although a thick crust in the Taiwan orogeny has been consistently reported by seismic tomography (Roecker *et al.*, 1987; Rau and Wu, 1995) and wide-angle seismic profiles (Lin *et al.*, 1997; Yeh *et al.*, 1998), the possibly dynamic processes of crustal thickening are still not fully understood yet. The occurrence of the 1999 Taiwan Chi-Chi earthquake (Mw=7.6) provides an ideal opportunity to enhance our general understanding of the dynamic processes of crustal deformation in orogenic zones. Since the earthquake was an inland event located in central Taiwan, a large number of high-quality seismic data were well recorded by densely seismic stations (Shin *et al.*, 2000), and thus enabling detailed information concerning the crustal deformation generated by the earthquake to be extracted from seismic observations in the crust. Although crustal structures had been obtained from a few of previous studies (Cheng, 2000; Chen *et al.*, 2001a), interpretations of crustal deformation were concentrated at the velocity structures on the upper crust, not the whole crust.

In the first stage of this study, crustal deformation in both of the upper and lower crust generated in the past geological time was interpreted from seismic tomography using a large number of aftershocks generated by the Chi-Chi earthquake. The characteristics of the major faults were then determined from both the relocated seismicity and the focal mechanisms of the main shock and some larger aftershocks. Finally, a model of concurrent mountain-building and crust-thickening was devised to reasonably explain parts of dynamic process of crustal deformation in Taiwan's orogen.

2. Chi-Chi Earthquake

The 1999 Chi-Chi earthquake (Mw=7.6) occurred beneath the Western Foothills (WF) in the central part of Taiwan (Fig. 1). Significant surface ruptures totaling about 80 km in length with a vertical offset ranging from 2 to 8 meters (Chang, 2000) were produced by the earthquake along the Chelungpu fault, which is a geological boundary between the Coastal Plain (CP) and the Western Foothills (WF). From the tectonic point of view, obviously, this was a typical small-scale orogenic process under strong convergence between the Eurasian plate (EUP) and Philippine Sea plate (PSP) at a short-period geological time. In addition to the significant surface ruptures, the Chi-Chi earthquake triggered more than 20,000 aftershocks throughout greater Taiwan in the following year. Those aftershocks were well recorded by a dense regional seismic array, the Central Weather Bureau Seismic
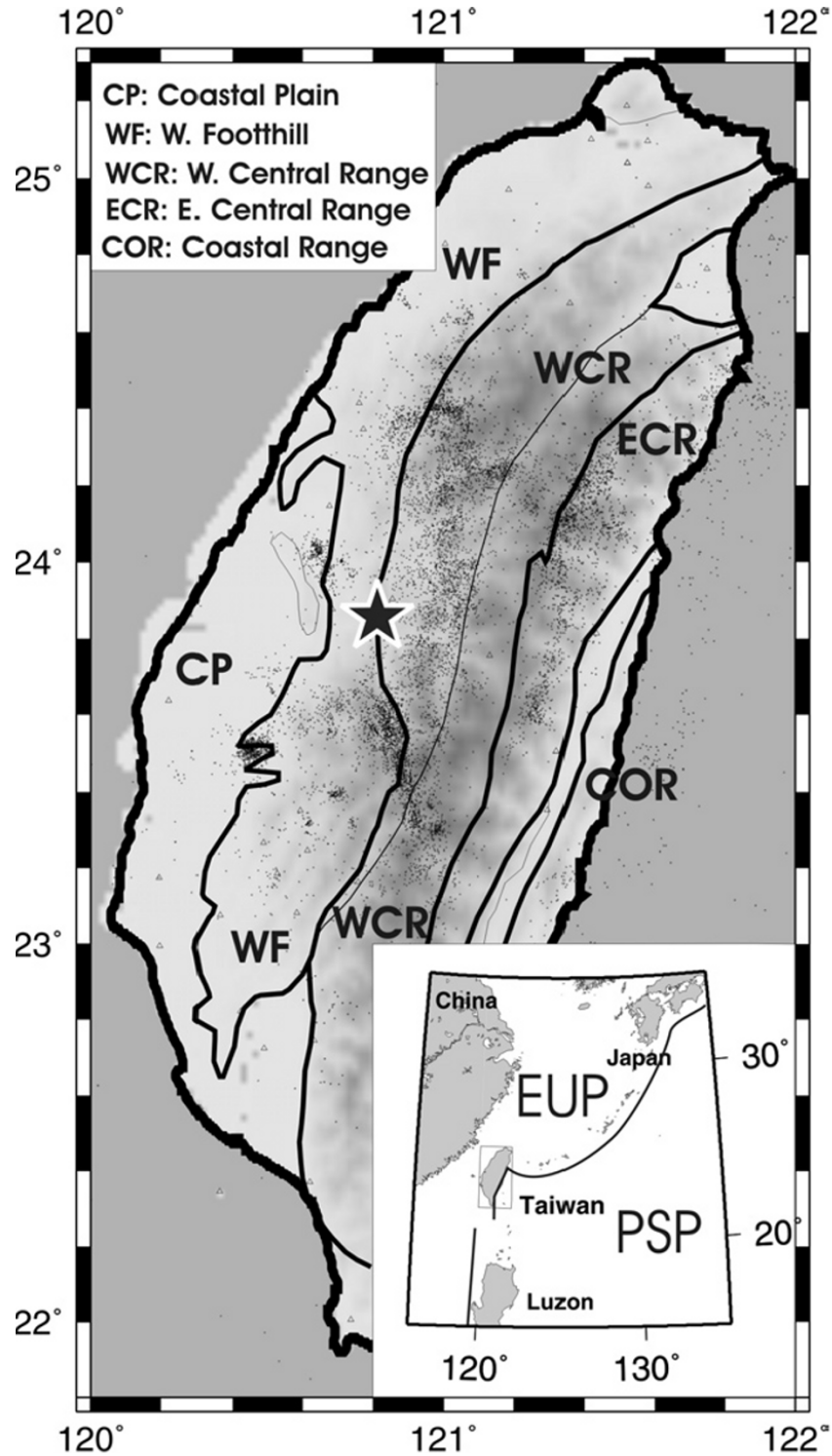
Fig. 1.   Locations of the 1999 Taiwan Chi-Chi earthquake (a big star), aftershocks (small dots) and regional seismic stations (triangles). The major geological boundaries and topographic relief (gray-scale) are also plotted. The inset maps show the index of the geological provinces (upper left-hand corner) and the location of Taiwan (lower right-hand corner).

Network (CWBSN), which is composed of 79 permanent seismic stations.

3.   Seismic Tomography

Three-dimensional P- and S-wave velocity structures in the central Taiwan area were inverted by using a tomographic method with a circular ray tracing (Lin and Roecker, 1997; Lin *et al*., 1998). On account of the very good ray cover-age based on plenty of earthquakes and dense seismic sta-tions (Fig. 2(a)), the velocity structures in the major part of the study area were well resolved by using 2,391 after-shocks with high-quality P- and S-wave arrivals provided by the Central Weather Bureau in Taipei. A typical seismic velocity structure across the major part of the study area is presented here for the discussion of the crustal deformation (Fig. 2(b)), and the detailed data analyses and results have
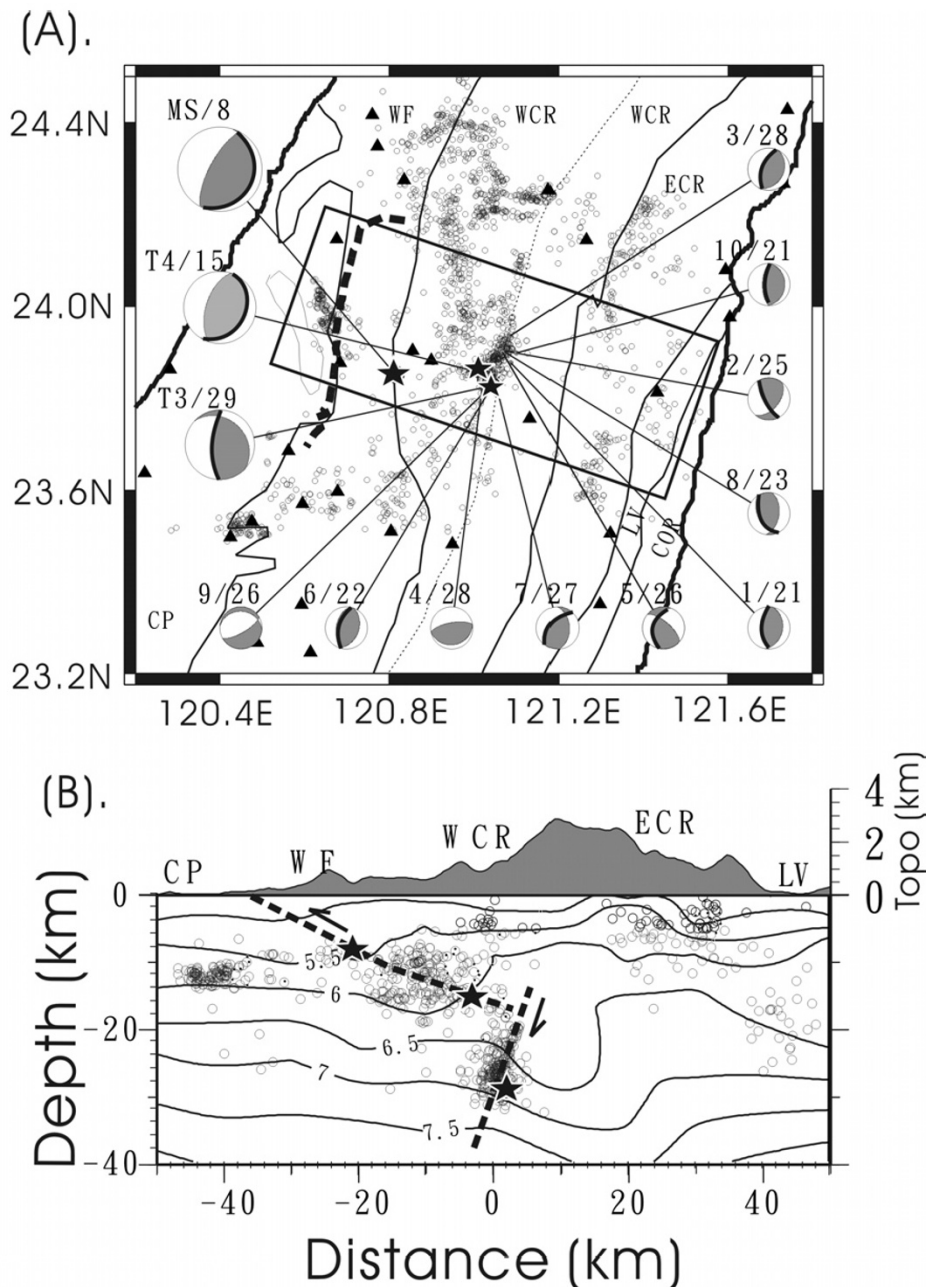
Fig. 2. (a) Relocated seismicity (small circles) and focal mechanisms of the main shock and 12 larger aftershocks of the 1999 Taiwan Chi-Chi earthquake. The locations of the main shock (MS) and the two largest aftershocks (T3 and T4) with magnitudes greater than 6 are plotted with stars. The numbers above each fault plane solution are the event index (left) and the focal depth (right). A possible fault plane in each focal mechanism is marked by a thick line. Regional seismic stations are marked with triangles. The major surface rupture largely along the Chelungpu fault is indicated by the thick dashed line. (b) *P*-wave velocity structures, topographic relief and the relocated hypocenters projected onto the box in Fig. 2(a). The numbers along the contours indicate the *P*-wave velocity. The two dotted lines with vectors show one set of conjugated faults constructed from the main shock and aftershocks.

been discussed in another paper (Lin, 2004). Similar to the previous studies (Cheng, 2000; Chen *et al.*, 2001a), the velocity structures in the uppermost crust generally agree with surface geology. In the upper crust (0–15 km), low velocities are usually found beneath the CP which is covered by sedimentary rock, while high velocities are located in most of the Central Range where slate or schist are exposed on surface. Although those features were created from series of complicated process during the past geological time, they are roughly similar to a crustal deformation resulting from a simply low-angle thrusting fault, much like the Chelungpu

fault. The velocity differences between the hanging wall and the footwall further suggest that there totally is about 8 km vertical offset by comparing depth difference along the velocity contour of 6.0 km/sec (Fig. 2(b)).

Although lateral variations in the velocity structures in the lower crust are less than those in the upper crust, it is significant that there are low-velocity zones at depths greater than 20 km beneath the Western Central Range (WCR) (Fig. 2(b)). The low-velocity zones are clearly distinguished by the downward buckle in the velocity contours greater than 6.5 km/sec. In contrast, the upward buckle in the velocity

Table 1. Earthquake parameters of the main shock and 12 large aftershocks beneath the Central Range.

Event	Time (y/mo/d/h/m)	Lat. (deg)	Lon. (deg)	Depth (km)	Mag. (ML)	Strike (deg)	Dip (deg)	Rake (deg)	Remark
1	9910022216	23.879	121.090	21.6	3.7	10	35	180	*
2	9910272244	23.907	121.066	25.8	3.7	40	50	150	*
3	9912070720	23.937	121.088	28.4	3.6	200	60	28	*
4	0001020833	23.851	121.026	28.3	3.8	80	20	260	*
5	0001220410	23.903	121.070	26.5	3.8	200	52	310	*
6	0002271020	23.826	121.045	22.0	3.6	20	40	190	*
7	0005201045	23.854	121.049	27.9	3.8	357	45	223	*
8	9910081549	23.903	121.075	23.9	4.1	150	47	8	*
9	9910090021	23.813	121.026	26.9	4.2	60	71	275	*
10	0001091206	23.901	121.103	21.6	4.2	181	65	1	*
T3	9909222017	23.830	120.050	29.0	6.0	314	26	43	+
T4	9909220849	23.860	121.010	15.0	6.2	32	32	102	+
MS	9909211457	23.850	120.820	8.0	7.3	18	19	80	+

* Focal mechanisms determined by the first-motion method in this paper.
+ Focal mechanisms determined by the waveform inversion method (Kao and Chen, 2000).

contours less than 6.0 km/sec is indicative of a high-velocity zone in the upper crust beneath the WCR. Both the high velocities in the upper crust and the low velocities in the deep crust beneath the WCR indicate that the crust has been significantly deformed and increased its thickness during the past geological time.

4.   Anomalous Aftershocks

In addition to the generally east-dipping seismic zone in the upper crust (0–15 km), the hypocenters relocated by the three-dimensional velocity structures indicate that one group of clustered aftershocks was unexpectedly located at depths between 20 km and 35 km beneath the WCR (Fig. 2). The projection of those relocated aftershocks on a west-east profile shows a seismic zone dipping to the west. Although a similar pattern had been found from the aftershocks located by one-dimensional models (Hirata *et al.*, 2000; Chen *et al.*, 2002), the seismic zone obtained here is more reliable by using a three-dimensional velocity model. Obviously, this feature is not associated with any of the thrusting faults dipping to the east in the western part of Taiwan. It is of particular interest that, instead, this group of anomalous aftershocks is located near the low-velocity zones in the lower crust beneath the WCR.

To better understand the possible mechanism generating those anomalous deep aftershocks beneath the WCR, the focal mechanisms of 12 larger aftershocks ($M_L > 3.5$) were examined (Fig. 2, Table 1). In addition to the two largest aftershocks with magnitudes of greater than 6.0 that had been determined from the broadband seismic data (Kao and Chen, 2000), ten other focal mechanisms of large aftershocks were obtained here by using the first-motions of short-period seismograms recorded by the CWBSN. Since those epicenters were located within the seismic network, all of the focal mechanisms were well constrained. As expected, most of the focal mechanisms are reverse faults as the island of Taiwan is under strong horizontal compression.

5.   Discussion

Based on seismicity and focal mechanisms, the major fault of the deeper aftershocks at depths between 20 km and 35 km beneath the WCR was different from that of the main shock of the Chi-Chi earthquake. The fault plane for the main shock was gently dipping to the east (Chang, 2000; Chen *et al.*, 2001b; Wang *et al.*, 2002; Johnson *et al.*, 2001; Ma *et al.*, 2001). In contrast, a clear seismic zone in the lower crust dipping to the west was shown at Fig. 2(b). Although the focal mechanism of another large aftershock (T3) is very similar to that of the main shock and the largest aftershock (T4), a different fault plane has to be selected on account of the clear seismicity. Thus, the dominant fault plane for the deep aftershocks was dipping westward with a steep angle, which is consistent with one of fault planes at most of focal mechanisms (Fig. 2(a)).

Based on these findings, a simple crustal deformation model (Fig. 2(b)) is proposed to explain the dynamic process of the Chi-Chi earthquake sequence. Under strong convergence, one set of conjugated faults roughly perpendicular to each other might have developed in the whole crust. One of them might have followed the previous fault, the Chelungpu fault. To release accumulated energy, the Chi-Chi earthquake was first induced along the Chelungpu fault in the upper crust and subsequently generated significant vertical uplifting and horizontal shortening on the surface. Then, one of the aftershock sequences must have occurred in the lower crust along the conjugated fault dipping to the west. In the meantime, crust thickness likely increased due to the high-angle, underthrusting movement.

Crustal deformation generated by such a conjugated fault system has been also recorded in the velocity structures during the past million years. The high velocity just beneath the WCR resulted from the repeated low-angle thrusting in the upper crust, while the low velocity in the lower crust was produced by a sequence of high-angle reverse faulting. The 8 km vertical offset between the CP and WCR, as estimated from the velocity structures in the upper crust (Fig. 2(b)),

indicates that there was 1,000 large earthquakes, much like the Chi-Chi earthquake, occurred during the past geological time if each of them generated a vertical offset of 8 meters. In other words, crustal thickness can be increased in both the upper and lower crusts after one thousand occurrences of large earthquakes along one set of conjugated faults during the past million years.

Although the crustal deformation generated by the 1999 Taiwan earthquake was only a small-scale orogenic process that produced only a few meters of uplifting on the surface, it is well accepted that the great mountains, like the Himalayas and the Alps in collision zones, were built by tens of thousands of large earthquakes not unlike the 1999 Taiwan Chi-Chi earthquake over a long geological time. Therefore, the dual process of simultaneous mountain-building and crust-thickening observed here contributes to the formation of the orogenic zone produced in Taiwan, but there need to be other mechanisms such as a simple thrusting on imbricate faults (Dewey *et al.*, 1988) to fully explain the height of the mountains and the thickness of the crust.

6. Conclusions

From the tectonic point of view, the crustal deformation generated by the Chi-Chi earthquake sequence shows a typical orogenic two-fold process that occurred in a very short-period geological time. Strong horizontal convergence produced both several meters of horizontal shortening and vertical uplifting in the uppermost crust along the Chelungpu fault. Meanwhile, crustal deformation in the deep part of the crust was observed from seismicity and focal mechanisms of some deep aftershocks at depths of 20–35 km. Although the deformation in the deep crust was not as clear as that in the upper crust, a clear seismic zone with a dipping angle of $\sim 70°$ to the west strongly suggests that a conjugated fault perpendicular to the major fault generated the Chi-Chi earthquake. Then, a significant orogenic process of crust-thickening occurred in the lower crust due to a sequence of aftershocks immediately after the Chi-Chi earthquake.

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