The 1999 Taiwan Earthquake:
A Proposed Stress-Focusing, Heel-Shaped Model

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Abstract  Stress focusing in a proposed heel-shaped model reasonably explains the occurrence of the largest onland earthquake ($M_w 7.6$) in Taiwan’s history. The epicenter of the mainshock was located in a low-seismicity block, where, historically, large earthquakes have not been documented for the past century. Spatial variations in crustal deformation reported in Global Positioning System surveys suggest that the crustal strength in the low-seismicity block was stronger than in the surrounding area. Since the low-seismicity block, which roughly coincides with the northern part of the Peikang High, is defined by a convex curve, stress partitioning or reorientation might well have taken place along the convex boundary; it then likely stored a lot of strain energy before eventually failing. The low-seismicity block with strong crust characteristics was finally overcome by stress focusing, resulting in the generation of the 921 Chi-Chi earthquake near the focus of the low-seismicity block, where a cluster of earthquakes had occasionally occurred during the past decade. Significant surface ruptures with vertical offset ranging from 2 to 8 m, primarily along the Chelungpu fault, were restricted to within the low-seismicity block. In short, when a low-seismicity block with small velocity fields of crustal deformation is identified in an active foreland belt, there should be a greater risk of a larger earthquake to release energy that accumulates in the strong crust. This finding provides some useful insight with which to evaluate potential earthquakes in Taiwan and other convergent zones.

Introduction

On 21 September 1999, a major earthquake (referred to here as the 921 Chi-Chi earthquake) occurred at 1:47 a.m. local time near the town of Chi-Chi in the central part of Taiwan (Fig. 1). The epicenter, located by a regional seismic network of the Central Weather Bureau Seismic Network (CWBSN), was at 23.87° N, 120.75° E, or approximately 150 km south of Taipei. Its magnitude, $M_L 7.3$ as obtained by the regional seismic network (Shin et al., 2000) and $M_W 7.6$ as reported by the global seismic network (U.S. Geological Survey [USGS]), made it the largest event in the historical record of Taiwan. Apart from a death toll exceeding 2400, thousands of houses collapsed, which left more than 150,000 people homeless. The event is considered the most serious disaster since World War II in Taiwan and one which seriously disrupted the local economy. The 21 September Chi-Chi earthquake occurred near densely populated Western Plain. With a very shallow focal depth of 5 km, as determined by the worldwide seismic network (USGS), or 10 km, by the regional seismic network (Shin et al., 2000), the Chi-Chi earthquake directly produced large surface ruptures along the fault as well as serious damage near the epicenter. Many structures that had already been damaged by the main-shock were totally destroyed by a large number of strong aftershocks, particularly by one with a magnitude of $M_L 6.8$ the day after the mainshock.

In addition to serious damage, the 21 September Chi-Chi earthquake left behind unusual, yet serious, concerns for earth scientists. For one, although a larger earthquake in the foreland belt of Taiwan had been expected during the past decade, it surprisingly did not occur in more active seismic zones, such as in the Sanyi-Puli and Chaiyi-Tainan areas. Instead, it erupted in a low-seismicity (or aseismic) block where large earthquakes had been absent throughout previously recorded history (Cheng et al., 1999), and background seismicity is rare (Fig. 1). This made the 1999 Taiwan earthquake distinct and not unlike a few other major earthquakes, such as the 1857 Fort Tejon and the 1906 San Francisco earthquakes (Healy et al., 1972) as well as the 1923 Kanto earthquake (Shimazaki, 1971). Obviously, the occurrence of these earthquakes did not conform with the popular notion that the more microearthquakes there are, the greater is the risk of a strong earthquake. Another distinct feature was that there was significant anomalous seismic clustering for two decades before the Chi-Chi earthquake near the epicenter of 1053
At first, I briefly review the tectonic and geological backgrounds. Then, I estimate the characteristics of crustal deformation from the surface geology, background seismicity, Global Positioning System (GPS) surveys, surface ruptures, and aftershocks. Finally, I introduce the effects of both stress partitioning and focusing in a heel-shaped model to explain the plausible cause of the 21 September Chi-Chi earthquake in the low-seismicity block.

Tectonic and Geological Background

Taiwan is located in a strongly oblique convergent zone between the Eurasian plate (EUP) and the Philippine Sea plate (PSP). The convergent direction, as shown in Figure 1 and in the inset map of Figure 2a, is along N310° E with a convergent rate of about 7–8 cm/yr (Seno, 1977; Yu et al., 1996). East of Taiwan, the PSP subducts northward beneath the EUP, while to the south of the island, the EUP underthrusts eastward beneath the PSP (Tsai et al., 1977; Lin and Roecker, 1993). The suture zone between the two plates is along the Longitudinal Valley (Fig. 1). East of the suture, the Coastal Range is part of the PSP. West of the suture, the geological provinces are the Coastal Plain, Western Foothills, Western Central Range, and Eastern Central Range, which belong to the EUP (Ho, 1988). The Coastal Plain is underlain by Pleistocene rocks and sediments, while the Western Foothills are an unmetamorphosed to slightly metamorphosed (zeolite facies) fold-and-thrust belt of Oligocene to Neogene rocks and sediments. The Coastal Plain and the Western Foothills are clearly divided by one of the major foreland-belt-thrusting faults, the Chelungpu fault (Figs. 1, 2a), which was, in fact, previously recognized as an active fault (Chang et al., 1998). The Western Foothills are bounded by the Chu-chih fault, east of which is the Western Central Range, a slate belt deformed in the Pliocene–Pleistocene. The Eastern Central Range is a pre-Tertiary metamorphic complex largely composed of the Tananao Schist formation, which is an assortment of metasediments and metavolcanics with minor amounts of metagneous rocks.

The subsurface structures in the western part of central Taiwan are more complicated than the surface structures. In addition to a sequence of thrust faults (Suppe, 1981; Davis et al., 1983), a major pre-Miocene basement high, the Peikang High, was previously found beneath the Coastal Plain (Tang, 1977). The highest part of the basement high has been confirmed by a well (PK-2) at a depth of 1500 m in the vicinity of Peikang (Fig. 2). The detailed subsurface structures of the Peikang High can be divided into two by the east–west–trending normal fault B, a hinge-fault, with a rapid transition from a shelf to a deep basin south of the fault (Stach, 1957). The strata of the northern part of the Peikang High dip gently to the northeast, while those of the southern part dip to the south-southeast. In short, the Peikang High served as the part of a tectonic dam or barrier (Meng, 1971) in that it divided the western basin of Taiwan into two parts during the Miocene.
Figure 2. (a) Epicenter (the large star) of the 21 September Chi-Chi earthquake and background seismicity (small crosses) with magnitudes greater than 2.0 recorded from 1973 to 1998 in Taiwan. The thick, dashed convex line shows the western boundary of the low-seismicity block in the western part of Taiwan, while the gray background represents high-seismicity zones. The main structures (solid lines) and the Chelungpu fault (CLPF, thick dashed line) are also plotted. The index map in the left-hand corner shows the general tectonic setting of Taiwan. The large arrow shows the convergent direction between the Eurasian plate (EUP) and the Philippine Sea plate (PSP). (b) Hypocenter projection along the A–B profile.
Detailed subsurface structures in western Taiwan also show that the characteristics of rock deformation in the Peikang High are significantly different from those in the surrounding areas (Ho, 1988). Subsurface structures cutting through the Peikang High (profile B in Fig. 3) are largely dominated by thrust faulting with a significant slip of about a few kilometers. Such a large-slip-thrusting dominant profile B indicates that the strata are more brittle than ductile. Conversely, subsurface structures to the north and south of the Peikang High (profiles A and C in Fig. 3, respectively) are generally represented by significant folding and small faulting. Significant folding as shown by several anticlines such as the Chihshui, Chuhuangkang, and Pakuali anticlines in profile A as well as the Hsiaomei and Fenchihu anticlines in profile C implies that the strata in profiles A and C are more ductile than brittle, just the opposite of those in profile B. Furthermore, the physical modeling of sandbox experiments (Lu et al., 1998) shows that the Peikang High acts as a strong backstop in the progress of foreland fold-and-thrust structures.

Seismicity and GPS Surveys

Earthquake activities in Taiwan largely result from plate convergence between the EUP and PSP (Fig. 1). Seismic activities in the northeastern and southern Taiwan regions are clearly associated with the two subduction zones (Tsai et al., 1977). Seismicity in the remaining larger part of Taiwan, however, is more complicated and unpredictable (Lin, 2000). In addition to strong earthquake activities in the eastern Taiwan area along the convergent boundary, clear clustering has been evident in some seismic zones, such as in the Sanyi-Puli seismic zone and the Chiayi-Tainan area. In contrast, earthquakes have been relatively absent in other areas such as in parts of the Central Range (Lin and Roecker, 1993; Lin, 2000) and in the Peikang High.

As mentioned, the Chi-Chi earthquake was located within an area where seismicity has been considerably lower than in the surrounding areas during the past decade (Fig. 2). The low-seismicity block, roughly coinciding with the northern part of the Peikang High, is limited by an eastward convex curve, passing through the towns of Tungshih.

Figure 3. Subsurface structures of three geological profiles across the western Taiwan area (Modified from Ho, 1988): (a) north of the Peikang High, (b) cross-section of the Peikang High, and (c) south of the Peikang High.
(24.25° N, 120.8° E), Puli (23.9° N and 121.0° E), and Meishan (23.6° N, 120.55° E). Only been a few earthquakes have occurred west of the convex curve, while seismic activities have been high both along and to the east of that boundary. The top of the convex curve passes roughly around the town of Puli, an isolated basin in the Central Range. The western endings of the convex curve intersect the deformation front, resulting in a clear topographic boundary between the Coastal Plain and the Western Foothills at Tungshi and Meishan, respectively.

Although there had only been a few earthquakes west of the convex curve, it is worth noting that some earthquakes had been clustering around the focus of the convex curve (Fig. 2). Those anomalous earthquakes in that area contrast sharply with the surrounding area inside the convex curve where earthquakes had generally been absent. Of significance is that the epicenter of the Chi-Chi earthquake was near the anomalous clustering at the focus of the convex curve, and the hypocenter of the mainshock was also close to the focal depths of the clustered earthquakes.

In addition to surface geology and seismic activities, crustal deformation in the study area can be more accurately obtained from GPS surveys, which have been continuous since 1991 (Yu et al., 1996). In the central Taiwan area, some interesting spatial variations in crustal deformation should be pointed out (Fig. 4). In general, the velocity field of crustal deformation decreases westward. Small crustal deformation (less than a few millimeters per year) was measured in the Coastal Plain (or the Peikang High), whereas significant deformation with velocity of tens of millimeters was observed in the Western Foothills and Central Range. More specifically, the velocity field of the crustal deformation in the northern part of the Western Foothills is significantly less than that in the southern part. In addition, the velocity vectors systematically change from the east to the west. In the Coastal and Eastern Central Ranges, crustal deformation consistently points to the NW (305–320°), which agrees with the convergence direction between the EUP and PSP (Seno, 1977; Yu et al., 1996). The velocity vectors slightly change direction as they approach the Peikang High. The vectors rotate clockwise in the NNW direction in the northern part of the Western Central Range, while they rotate anticlockwise in an almost westward direction in the southern part of the Western Central Range and the Western Foothills. Within the low-seismicity block (i.e., the northern part of the Peikang High), the vectors roughly point to the geometrical center with smaller velocity and larger uncertainty.

Surface Ruptures and Aftershocks

Significant surface ruptures (Chang et al., 2000) ranging from 2 to 8 m (or more) were observed between 23.65° N and 24.25° N primarily along the Chelungpu fault, which is one of the major active thrustings in the foreland belt of Taiwan. The major surface ruptures began north of Meishan with a small vertical offset of less than 2 m and gradually increased northward to Tungshi with a large vertical offset of greater than 8 m (Fig. 2). Although some complicated minor ruptures could also be found east of Tungshi, the major surface ruptures were limited to within the low-seismicity block of the northern part of the Peikang High. Compared with earthquake ruptures that usually end with a small offset, the major rupture generated by the 1999 Taiwan earthquake was peculiar since it abruptly stopped north of Tungshi.

In addition to the significant surface ruptures, the 21 September Chi-Chi earthquake generated some interesting patterns of aftershocks and focal mechanisms. Since the Chi-Chi earthquake, more than 10,000 aftershocks have been recorded (Fig. 5) over a large area of central Taiwan, but the low-seismicity block, as determined by the background seismicity in the Western Foothills, has become relatively aseismic again. Most of the aftershocks were distributed along the convex curve of the low-seismicity block and not near the mainshock. Furthermore, different stress patterns were obtained from the focal mechanisms of the larger aftershocks in and around the low-seismicity block (Kao and Chen, 2000). A pure thrusting, similar to the focal mechanism of the mainshock, was usually observed in the middle of the convex curve. In contrast, a typical strike-slip was often observed in the northern and southern parts of the low-seismicity block even though the two parts probably had different tectonic indications. The largest aftershocks in
these parts of the convex curve showed left- and right-lateral mechanisms, respectively (Fig. 5). Regardless of the type of focal mechanism, the aftershocks all suggest that the principal stress was along the NW–SE direction, which is a result of the convergence between the EUP and PSP.

Discussion

In general, the Western Foothills, which represent an active foreland fold-and-thrusting belt in the Taiwan orogeny, have significant crustal deformation. In addition to the topographic relief and a sequence of active faulting (Suppe, 1981; Ho, 1988; Lee et al., 1996), the crustal deformation in the Western Foothills has a larger velocity field of crustal deformation as observed from GPS surveys (Yu et al., 1997) and strong seismic activities in the crust (Lin, 2000). As a result, the deformation front, characterized by a low-angle thrusting fault with a lot of relative movement, is more or less consistent with the western boundary of the high-seismic area in western Taiwan.

East of the Peikang High, however, it is noteworthy that neither low-level seismicity nor a small velocity field of crustal deformation in the Western Foothills and part of the Western Central Range is typical. In other words, the crustal deformation in the Western Foothills around the epicenter of the Chi-Chi earthquake is primarily represented by a sequence of thrust faults, with no strong seismic activity (Fig. 2) or significant velocity field of crustal deformation (Fig. 4). In particular, over the past 25 years, no significant energy has been released by earthquakes in and around the Peikang High, except near the epicenter of the Chi-Chi earthquake (Fig. 6). In fact, any energy that released by earthquakes was concentrated in areas east of the Peikang High, and it roughly followed the convex zone. To illustrate this, significant energy has been released in the Chaiyi area and is consistent with the strong crustal deformation observed in the GPS survey (Fig. 4).

Such an unusual low-seismicity block with a small velocity field in the Western Foothills around the Peikang High probably indicates that the strength of the block is greater than that in the surrounding area and that it can store a lot of elastic strain before failing. A few explanations to account

Figure 5. (a) Aftershocks (small circles) of the 921 Chi-Chi earthquake recorded by the CWBSN during the past year and the focal mechanisms of the mainshock (the star) and three larger aftershocks (large circles). The geological provinces shown in Figure 1 and the eastern boundary (dashed line) of the low-seismicity block in Figure 2 are also plotted. (b) Hypocenter projection of aftershocks along the W–E cross-section.

Figure 6. Energy released by earthquakes which occurred from 1973 to 1997. Earthquakes in each area 5 km by 5 km area were added together to estimate the released energy during the 25 years before the Chi-Chi earthquake. An equation, log \( E = 4.78 + 2.57m \) (where \( E \) is energy and \( m \) is magnitude), was employed to estimate the amount of released energy. The total energy released within each area was scaled to one unit, namely, \( 3.54 \times 10^6 \) erg/km². The star indicates the epicenter of the Chi-Chi earthquake.
for this low seismicity within the crust might come to mind. First, it might be said that earthquakes do not occur if there is no stress applied in the crust. Alternatively, it might be claimed that a low-seismicity zone within the crust could indicate that it is either stronger or more ductile than the surrounding area. Obviously, both of these possibilities, that is, there being no stress applied and it not being ductile, must be ruled out on account of the occurrence of the major Chi-Chi event in the low-seismicity block. Thus, that it is a stronger block is the most plausible explanation for the low-seismicity block under strong convergence.

The presence of a stronger crust in the low-seismicity block is also clear. Crustal deformation, as observed from GPS surveys, shows that the velocities of crustal deformation systematically change direction when they collide with the low-seismicity block or with the northern part of the Peikang High. As stated earlier, in the northern part of the Western Central Range, velocity vectors rotate to the NNW direction, while in the southern part of the area they rotate almost westward. These trends are in direct contrast to the low-seismicity block, where velocity vectors point more-or-less toward the geometrical center and show lower velocity.

The phenomenon of stronger crust in the Peikang High is consistent with the variation in basement relief in the western part of central Taiwan. Since the pre-Miocene basement had experienced significant upheaval in the central part of western Taiwan, it played the role of a tectonic barrier or dam during the Miocene (Meng, 1971). At the same depth, the rock strength of the basement is clearly greater than that of the surrounding strata deposited by thick Miocene sediments. There may, nevertheless, be many other more complicated factors for this, such as an inhomogeneous distribution of rock contents, pore pressure, and heat flow (Brace and Byerlee, 1970; Byerlee, 1978). Regardless, in the upper crust, the rock strength of the Peikang High with thick basement rock and thin sediments is certainly greater than that in the surrounding areas at the same depth.

It should also be noted that the low-seismicity block coincides only with the northern part of the Peikang High and not the whole area. This phenomenon can be explained by detailed seismic profiles. The basement high is divided into two parts by an E–W–trending normal fault, fault B (Stach, 1958). Fault B serves as a hinge-line fault and shows a rapid transition from a shelf to a deep basin, which is thought to be south of the fault. Vertical offset along fault B is about 500–1000 m. In addition, north of fault B the strata dip gently to the NE, whereas south of the fault they dip to the SSE (Fig. 2). Such an abrupt turn implies that the block south of fault B has been subjected to shear stress with dextral movement and clockwise rotation (Tang, 1977). The detailed subsurface structures described here indicate that at the same depth the rock strength in the southern part of the Peikang High is probably weaker than that in the northern part.

Apart from a stronger crust, as interpreted from background seismicity and crustal deformation, the fact that the Chi-Chi earthquake struck near the focus of the low-seismicity block is another interesting feature of the event (Fig. 2). One plausible way to explain this might be to attribute it to stress focusing. Since the low-seismicity block was limited by a convex curve toward the east (Fig. 2), stress focusing might have taken place to overcome the strong crust in the low-seismicity block. It is well known that regional stress in the Taiwan area is caused by the strong convergence of the EUP and PSP (Lin et al., 1985; Yeh et al., 1991). The stress pattern east of the low-seismicity block basically follows the NW–SE convergent direction, but the stress direction could well have changed as it passed through the boundary (Fig. 7). Similar to the stress patterns observed near the major faults in California, Sumatra, and eastern Taiwan (Fitch, 1972; Zoback et al., 1987; Mount and Suppe, 1987, 1992; Lee et al., 1998), the maximum stress direction of the oblique convergence might have been reoriented (or partitioned) in a new direction perpendicular to the fault plane. It is proposed that at location A in Figure 7, stress

![Figure 7. Schematic plot of stress partitioning and focusing in and around the convex curve. The maximum stress direction of oblique convergence (gray arrows) might well have been reoriented (or partitioned) in a new direction as it passed through the convex curve. Stress partitioning might have taken place along the curve such as at points B and C. At location B, the stress direction rotated clockwise and pointed to the focus when it passed through the boundary. In the meantime, the partitioning shear stress produced a right-lateral slip along the boundary. At location C, the stress direction rotated anticlockwise when it passed through the boundary, and the partitioning shear stress produced a left-lateral slip along the boundary. As a result, stress focusing took place around the focus (the big circle with a star) of the convex curve.](image-url)
kept its original convergent direction as it passed through the boundary where the convergent vector was almost perpendicular to the low-seismicity boundary. Thus, the maximum principal stress was still in the convergent direction, and a thrust faulting was observed in the two largest aftershocks near the town of Puli (Kao and Chen, 2000). However, stress partitioning or reorientation, it is believed, took place as the stress passed through other locations, such as locations B and C, where the convergent direction was not perpendicular to the convex curve. At location B, the stress direction rotated clockwise and therefore pointed to the focus of the curve. In the meantime, the partitioning shear stress along the boundary produced right-lateral faulting, which is consistent with most of the focal mechanisms of the larger aftershocks as determined from waveform inversion (Kao and Chen, 2000). At location C, it is felt that stress partitioning took place again, which would explain why stress direction rotated counterclockwise and again pointed to the focus. The partitioning shear stress along the boundary generated left-lateral faulting, which is also in agreement with most focal mechanisms of the larger aftershocks (Kao and Chen, 2000). However, the effect of stress partitioning around location C was small because the convergence direction was almost parallel to the boundary. Briefly stated, no matter which locations are considered along the convex curve, all of the stress directions within the low-seismicity block more or less pointed to its focus. Accordingly, it is reasonable to conclude that strong stress significantly accumulated at the focus of the convex curve.

It should be stated that the quantitative modeling of stress focusing has been investigated using a numerical method of finite-element calculation. The detailed results of this study will be presented in another article (Tang and Lin, 2001).

Given the findings and implications described earlier, a 3D heel model (Fig. 8) is proposed here to explain the occurrence of the Chi-Chi earthquake in the central part of Taiwan. The low-seismicity block, delimited by an eastward convex curve in the Western Foothills, resembles the heel of a shoe in that it represents a strong block that can store a lot of elastic strain before failing. As stated, the low-seismicity strong-crust block coincides with the northern part of the Peikang High. Although deeper structures beneath the Peikang High area still remain unknown, the bulging of the basement and/or midcrust is a plausible reason for the crustal strength to be greater than in the surrounding area. The characteristics of the crust of the strong block are also supported by the small crustal deformation inside the block and the systematic change in the strain patterns outside the block. Since the strong crust of the low-seismicity block has a particular shape, stress focusing might have taken place due to stress partitioning along the convex curve. As a consequence, stress patterns at the focus and point A were different from those at points B and C. Thrust faults were observed in the former, and strike-slip faults were dominant in the latter. An anomalous seismic clustering near the focus of the low-seismicity block may represent the effect of stress focusing before the major event occurred.

The western boundary, dipping to the east in the heel model, is along the Chelungpu fault, which obviously was one of the best candidates to release the large energy generated by stress focusing in the strong block. The major surface ruptures produced by the Chi-Chi earthquake, largely along the Chelungpu fault, were limited to the low-seismicity block where the crust was strong and brittle. The southern and northern endings of the major surface ruptures were limited to around the eastern boundary of the low-seismicity block. Indeed, there was no significant rupture outside the low-seismicity strong block.

Conclusions

Some valuable insight has been obtained by proposing and applying the simple heel model to explain the occurrence of the 21 September Chi-Chi earthquake. First of all, it is important to note that the low-seismicity block with small velocity fields of crustal deformation as determined from GPS surveys in the active foreland fold-and-thrusting belt had the capacity to cause a major earthquake because

![Figure 8](image-url)
large energy could have been stored in the stronger crust. Furthermore, it seems reasonable that stress focusing could have taken place in the low-seismicity block with a particular sharp, and especially convex, curve. The effect of stress focusing may have been represented by a rare seismic clustering at the focus within the low-seismicity block before the major event occurred. The most feasible method to release the energy within the strong block was by the generation of a large earthquake along the previous fault that was a weak plane in a low-seismicity block.

All of the information gained from the Chi-Chi earthquake and through the application of the heel-shaped model, as summarized here, provides invaluable insight with which to evaluate the potential for the occurrence of major earthquakes in Taiwan. At the same time, it may prove beneficial when applied to other convergent zones, particularly those in other foreland fold-and-thrusting belts around the world.

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