Constructing subsurface structures of the Chelungpu fault to investigate mechanisms leading to abnormally large ruptures during the 1999 Chi-Chi earthquake, Taiwan

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[1] The Chelungpu fault, a NS oriented thrust fault, was activated by the 1999 Chi-Chi earthquake (Mw = 7.6), Taiwan. At its northern end, the fault turned east causing an extra 15 km EW branch, which experienced abnormal 9 m surface rupturing. In this paper, we used shallow reflection seismics to investigate the subsurface structure, attempting to find the relationship between the structure and large ruptures. Over 90 short seismic lines were distributed throughout a 10 km × 20 km area. Approximate 3D subsurface structures can be constructed by carefully compiling all seismic profiles with well data. The revealed structural pattern shows that the Chinshui shale, the key-bed layer on which the Chelungpu fault slips, arises toward the north and becomes quite shallow under the EW branch. This structural variation is believed to be the main factor causing the abnormal rupturing of the Chelungpu fault. *INDEX TERMS:* 0935 Exploration Geophysics: Seismic methods (3025); 3025 Marine Geology and Geophysics: Marine seismics (0935); 8107 Tectonophysics: Continental neotectonics; 8110 Tectonophysics: Continental tectonics—general (0905); 8123 Tectonophysics: Dynamics, seismotectonics. **Citation:** Wang, C.-Y., C.-L. Li, and H.-C. Lee (2004), Constructing subsurface structures of the Chelungpu fault to investigate mechanisms leading to abnormally large ruptures during the 1999 Chi-Chi earthquake, Taiwan, *Geophys. Res. Lett.*, *31*, L02608, doi:10.1029/2003GL018323.

1. Introduction

[2] The Chelungpu fault is a NS oriented fault, about 90 km long, that separates central Taiwan's foothills and coastal plains [*Lee et al.*, 2002]. It was reactivated during the Chi-Chi earthquake (Mw = 7.6) on 21 Sep. 1999, which caused much damage throughout the island [*Shin and Teng*, 2001]. The fault is considered to be a bedding-parallel thrust that follows the Chinshui shale layer, probably a decollement in the thin-skinned thrust model [*Wang et al.*, 2000]. It is quite peculiar that the fault trace turned east at its northern end (50 km north of the epicenter), cutting through the bedding formations and causing a series of en echelon ruptures over 1 $\sim$ 2 km in width (Figure 1). Abnormally large displacements (9.8 m vertically and 12 m horizontally), both on the surface and underground, were observed here [*Ma et al.*, 1999].

[3] Figure 1 shows the map of the study area, which is traversed by two rivers, the Tachiahsi river and the Ta-Anhsi river, hence, it is called the 'two-river' area. The area can be divided into two parts: the Hsinhse terraces south of the Tachiahsi river (area M in Figure 1a) and the part north of the Tachiahsi river. The terraces are covered by lateritic deposits with no visible outcrops. According to GPS data measured after the Chi-Chi earthquake, the Hsinhse terraces were displaced 3 m vertically and 7 m horizontally [*Yu et al.*, 2001] toward the NW, a really large movement from a single earthquake. The northern part is relatively low, surrounded by terraces or mountains.

[4] The purpose of this paper is to use the shallow seismic reflection method to delineate the 3D structure of the area, which may help to find the factors leading to the abnormal rupturing. The obtained seismic sections may be only 1 sec long, but this is enough to detect the target layer, which is shallower than 1 km in most places of the study area.

2. Regional Geology

[5] According to the geological and geophysical evidence [high pore pressure, weak shale, etc.; *Suppe and Wittke*, 1977], the Chinshui shale is thought to act as a shallow decollement in the thin-skinned thrust model. The Chelungpu fault is a bedding thrust fault that slips along this 150–300 m thick Chinshui shale. The major structure on the hanging wall side (Figure 1) is a syncline (the Shihweichiang syncline) of which the west limb is steeper than the east limb, which forms a monocline structure overlaid by younger formations. There may be two small folds (the Tungshih anticline and the Neiwan syncline, Figure 1) above this major syncline. The related stratigraphic units from top to bottom are: the Pleistocene Toukoshan Formation (1–2 km thick; gravel dominant), the late Pliocene Cholan Formation (2 km thick; sandstone and shale) and the early Pliocene Chinshui shale (300 m thick; shale and mudstone).

3. Methods

[6] The field work used small-scale shallow reflection seismics, which is a high-resolution method designed to detect shallow structures. The method requires only a small budget, limited man power, and is easy to move around to detect regional structures. The used equipments were: (1) source, an EWG-III weight drop impact pulse generator; (2) receiver, OYO 40 Hz geophone; (3) recorder, DAS-1 96 channel seismograph. The acquisition geometry used the end-on shooting with the survey parameters as: (1) 6 m source interval; (2) 2 m receiver interval; (3) 100 m near-offset; (4) fold of 16; (5) 0.25 ms sampling rate; (6) 40 Hz

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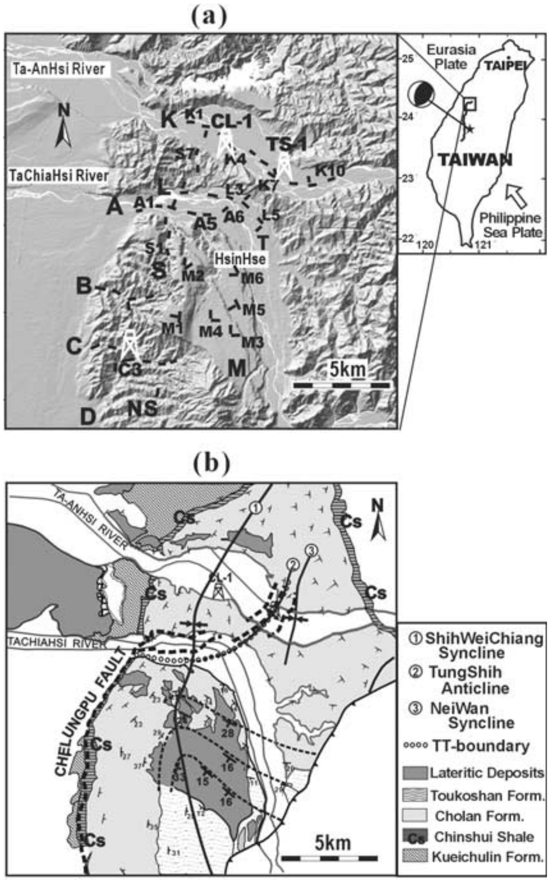

Figure 1. (a) is the digital shaded-relief map of the study area, on which seismic lines are denoted. The inlet Taiwan map explains the tectonic setting around the island, i.e., a northwestward arc-continent collision, which causes the reverse Chelungpu faulting in the 1999 Chi-Chi earthquake. (b) is a simplified geologic map. Note the TT-boundary (a chain of circles in (b)) which will be described in the text. Five different formations are exposed. Among them, the Chinshui shale (Cs) is the most important one.

low-cut filter. Most of the field work was carried out at night to avoid traffic noise. The data processing follows standard procedures for CDP data, except for additional emphasis on some dip filters to suppress strong groundrolls. The obtained seismic signals are of the frequency content: 50 ~ 150 Hz. All the seismic section plots (Figures 2 to 5) have been converted to the depth scale, and a 1:1 horizontal to vertical scale is kept. The depth conversion uses velocity values (reform to layer velocities by Dix's equation) found from walk-away noise tests (for longer range to detect more reliable velocities), adjusted by the data from nearby wells. Some of sections have also been migrated (Figure 2) to reveal more accurate layer dip angles. No multiples are observed, which can be judged by their velocities in shot records.

4. Seismic Survey Results

[7] A total of 92 seismic lines were obtained, composed of 6 EW profiles, 3 NS profile and 6 pairs of perpendicular sections on the Hsinhse terraces (Figure 1a). Figures 2 to 5 show most of the seismic sections. The data are of relatively high quality, with plenty of reflection events down to a depth of 1400 m. Most of the structural layers in these seismic sections belong to the Cholan formation with uniformly inclined sandstone-and-shale. There are two sets of well data from the Chinese Petroleum Corporation (CPC; CL-1 and TS-1; Figure 1a, positions K4 and K7), which provide information needed for layer identification and depth control. The key bed can thus be fixed and extended to establish the general structural pattern of the area.

[8] The obtained seismic sections can be grouped into 10 profiles (Figure 1a). Among them, profiles A, B, C, D, and NS have been discussed in *Wang et al.* [2002]. This has led to a 2 km well, scheduled to be drilled in 2004 (Figure 1a, position C3). In this paper, we will concentrate on other profiles. First, we check the M group of data, shown in Figure 2. It has been organized into 6 pairs (only shows 3 pairs), each pair containing two seismic lines, purposely arranged to be perpendicular. These sections are from the Hsinhse terraces (Figure 1) which are covered with lateritic deposits more than 5 meters thick. It is interesting to see that we can use these paired, perpendicular seismic lines to detect the true dip and strike angles of layers not visible on the surface. It is that such paired seismic sections can produce 'artificial outcrops'. Figure 2b shows the simple geometry of such a mapping technique. This case nicely illustrates an interesting and useful application of shallow seismics exploring the hidden layers in geological mapping.

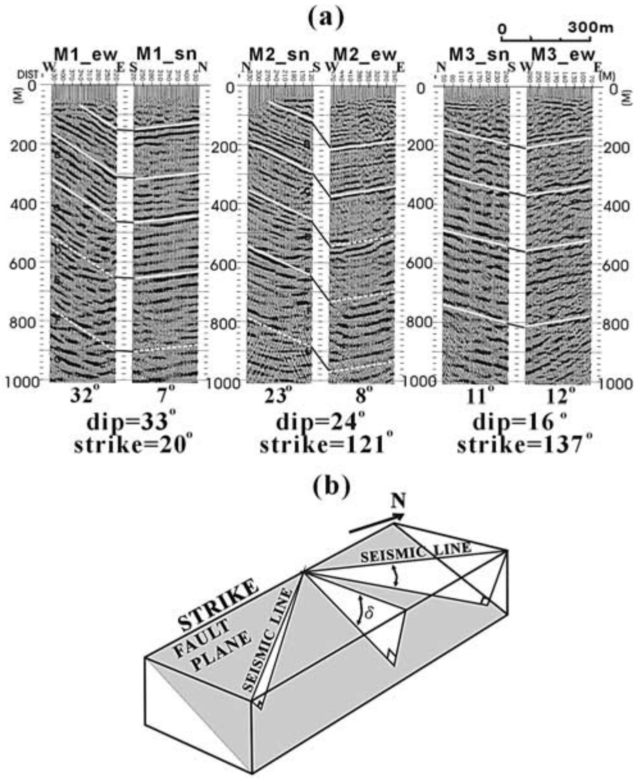

Figure 2. (a) Three pairs of reflection sections used to measure the true dip- and strike-angles of unexposed underground layers on the Hsinhse terraces. The sections have been migrated and depth converted. (b) shows simple geometry for layer mapping by two crossing seismic lines.

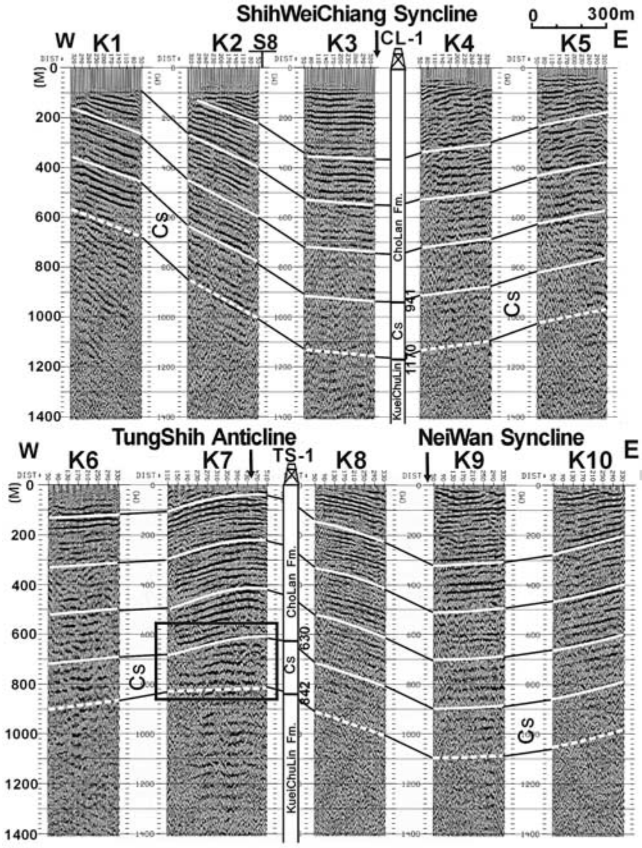

Figure 3. Seismic reflection sections along Profile K which follows the Ta-Anhsi river. Two CPC wells give proper layer controls. Three folds are visible along this profile. An interesting layer thickness bulge appears in section K7, evidence of the detachment movement. All sections are in depth scales. The 'tie' positions of different lines are also indicated.

[9] We can thus determine the distribution of the layers and the syncline axis by combining the geological map, the field observations and the artificial outcrops. Figure 1b shows the result. The layers bend under the Hsinhse terraces. The axis of the Shihweichiang syncline mostly follows the bending axis of the layers. This bending pattern forms an asymmetric, south-plunging syncline. The west limb of the syncline is steeper than the eastern. The axis is directed toward the corner where the Chelungpu fault suffered huge ruptures (position A1 in Figure 1a). We may say that the Chinshui shale forms the sharp end of a tilted syncline which is uplifted almost to the surface at the southern bank of the Tachiahsi river.

[10] In the area around the two rivers, three EW profiles (K, L, and A; Figures 3 and 4) and two NS profiles (S and T; only show S in Figure 5) formed a network to construct the underground structure. Fortunately, two CPC wells (CL-1 and TS-1) in the area could confirm the layer's identification and depth. Figure 3 shows correlated seismic sections and well data. They merge quite smoothly. The K profile actually follows the same track as a CPC profile described in *Wang* [2002, Figure 2a] as well as *Lee et al.* [2002, Figure 4]. The most interesting feature of this profile is the 'detachment buckling' clearly seen in section K7 (bracketed in Figure 3).

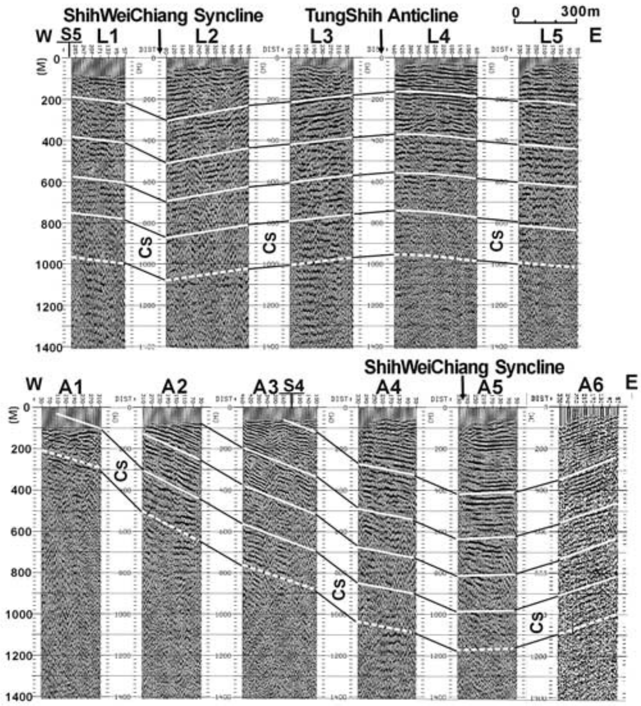

Figure 4. Seismic reflection sections along Profiles L and A, on both sides of the Tachiahsi river.

A similar phenomenon is also visible in the CPC profile. This buckling occurred within the weak Chinshui shale layer, which was easily twisted and deformed to induce thickness variations. Two synclines and one anticline are apparent along this profile. The Tungshih anticline may have sharper limbs, a response to the squeezing effect from the detachment buckling.

[11] Next, let us move southward further to the Tachiahsi area, Figure 4 showing profiles L and A on the two sides of the river. The Tungshih anticline becomes broader here (between sections L3 and L4), and its axis plunges to the southwest, as indicated in section A6 which is exactly located at its axis (Figure 1). After being combined with profile A and the north-south profile S (Figure 5), a 'saddle' shaped structure is postulated near position A5 (Figure 1a). This saddle structure includes the Tachiahsi river (between

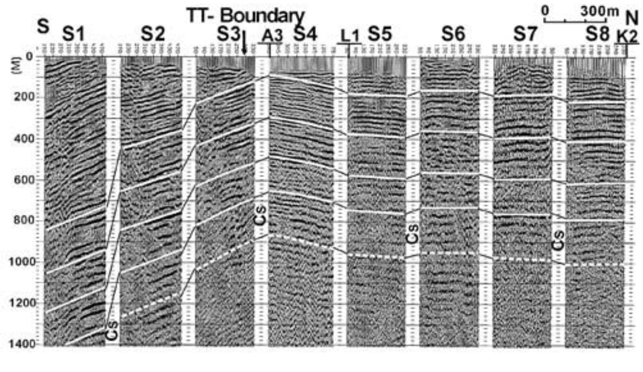

Figure 5. A NS profile S indicates the quick uplifting of the layers south of the Tachiahsi river (or TT-boundary), while to the north all the layers dip gently.

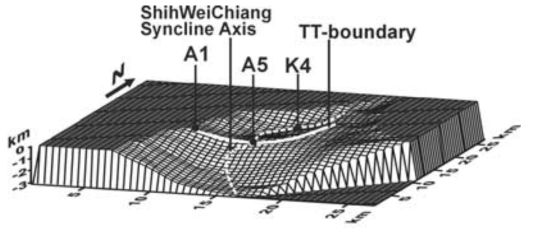

Figure 6. A conceptualization of the shape of the Chinshui shale layer (i.e., the Chelungpu fault surface) in the study area. The same area as in Figure 1 is covered. The white solid line indicates the TT-boundary.

A1 and A5) and the Tungshih anticline as a ridge developing in the west-northeast direction, called the TT-boundary (Tachiahsi-Tungshih axis; a chain of circles in Figure 1b, also Figure 6). The Shihweichiang syncline axis crosses the TT-boundary from the north at point A5 before entering the Hsinhse terrace area.

[12] Figure 5 shows a NS profile S. They indicate obvious layers south of the TT-boundary that climb sharply toward the north (at a slope of about 15 degrees); north of this boundary, the layers become flat again, even forming a shallow depression. As restricted by the surrounding higher structures, this depression may be shaped as a shallow hollow (Figure 6).

[13] When all the data sets are combined, we get a 3D picture of the Chinshui shale layer (i.e., the Chelungpu fault surface) in the two-river area. Figure 6 conceptualizes such an image. The TT-boundary forms a barrier separating the area into two halves. To the south, an asymmetric, south-plunging syncline has developed, and to the north, a shallow depression done. It is this TT-boundary which led to the behavior of the Chelungpu fault rupturing during the 1999 Chi-Chi earthquake. The 15-degree slope in the south and the flattened structure in the north form a ramp-flat geometry, which acts as a barrier extending in the EW which stops the fault rupturing from the south. Since the Chinshui shale almost reaches the surface along the TT-boundary, the rupturing was thus developed there.

5. Discussions

[14] Due to the collision between the Philippine sea plate and the Eurasia continental plate (Figure 1a), Taiwan's main structural pattern tends to be oriented in a NS direction. However, Bouguer gravity anomalies trend in the SW-NE direction across the two-river area [*Wang et al.*, 2002, Figure 1]. A respected CPC geologist, *Dr. Meng* [1964], has suggested that an EW transverse structure may exist along the two rivers. We believe that the TT-boundary could be a part of this transverse structure.

[15] The Chi-Chi earthquake was quite unusual in terms of its large rupturing (9 m) along the two-river area. 'Structural factors' are suggested to be the main reasons for such an abnormal behavior. The TT-boundary suggested in this paper plays like a barrier which interferes with rupturing propagates from the south. The fault surface climbs near the surface along the TT-boundary (about 100 $\sim$ 300 m deep), thus the ruptures may spread and produce a series of en echelon branches on the surface.

[16] Evidence of high water content (up to 45 vol.%) has been found along the slippage surface in a recent well drilled near the fault [*Tanaka et al.*, 2002]. The structural geometry found in this paper offers possibilities for water passages. It could be an interesting question whether the water may have provided enough lubrication to reduce friction on the fault's surface, thus producing large displacements. A 2 km well will soon be drilled in this area, to resolve the issue [*Mori et al.*, 2002; the project 'Taiwan Chelungpu-fault Drilling Project; TCDP' supported by the International Continental Drilling Project, ICDP].

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