Active fault creep variations at Chihshang, Taiwan, revealed by creep meter monitoring, 1998–2001

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[1] The daily creep meter data recorded at Chihshang in 1998–2001 are presented. The Chihshang creep meter experiment was set up across the Chihshang thrust fault, the most active segment of the Longitudinal Valley Fault, which is the present-day plate suture between the Eurasian and the Philippine Sea plates in eastern Taiwan. Near-continuous data recording at two sites revealed different surface fault motions yet similar annual shortening rates: 16.2 mm at the Tapo site (comprising two connected creep meters) and 15.0 mm at the Chinyuan site (three creep meters straddling parallel fault branches). Four of the five creep meters showed a seasonal variation, with the fault moving steadily during the rainy season from April to October, and remaining quiescent during the rest of the year. The only exception was recorded by the creep meter located on a mélange-composed hillslope, where local gravitational landsliding played an additional role other than tectonic faulting. Through comparison with daily precipitation data, we inferred that moderate rainfall suffices to trigger or facilitate slippage on the surface fault, during the transition period of the dry/wet season. During the observation period from 1998 to 2001, the subsurface seismicity exhibited clusters of microearthquakes on the Chihshang Fault at depths of 10–25 km. Recurrent earthquakes occurred regardless of whether the season was wet or dry, indicating that the stress relaxation associated with seismicity in the seismogenic zone did not transfer immediately up to the surface. The accumulated strain on the Chihshang Fault at shallow surface levels was released through creep during the wet season. In addition to these short-term seasonal variations, an apparent decrease in the annual slipping rate on the Chihshang Fault during the last few years deserves further investigation in order to mitigate against seismic hazard.   *INDEX TERMS:* 1206 Geodesy and Gravity: Crustal movements—interplate (8155); 7223 Seismology: Seismic hazard assessment and prediction; 8102 Tectonophysics: Continental contractional orogenic belts; 8107 Tectonophysics: Continental neotectonics; 8150 Tectonophysics: Plate boundary—general (3040); *KEYWORDS:* active fault, creep meter, creep, seasonal variation, Taiwan

1. Introduction

[2] The Chihshang Fault, located in eastern Taiwan, is a 20-km-long segment of the Longitudinal Valley Fault (LVF) (Figure 1), a plate-suture boundary fault between the Eurasian continental margin and the Philippine Sea Plate. It has been undergoing rapid creep motion with a rate of about 20–30 mm/yr at least for the last 16 years (1985–2001) in the absence of major earthquakes. The creep motion across the Chihshang Fault has been measured by techniques on different scales of time and space. These techniques included geodetic distance measurements (EDM) within trilateration networks [*Yu and Liu*, 1989; *Yu et al.*, 1990], displacement kinematic analysis in outcrops and cultural features [*Chu et al.*, 1994; *Lee*, 1994; *Angelier et al.*, 1997, 2000], records of creep meters straddling the fault [*Lee et al.*, 2000, 2001], and global positioning system (GPS) measurements [*Yu et al.*, 1997b; *Yu and Kuo*, 2001]. In the early stage, based on annual surveys, a rather steady creeping rate was identified along the Chihshang Fault. More recently, the accumulated data from more frequent surveys, together with biannual in-site measurements and especially the daily creep meter measurements discussed herein, revealed a seasonal variation in the creep activity of the Chihshang Fault. We present and discuss the new creep

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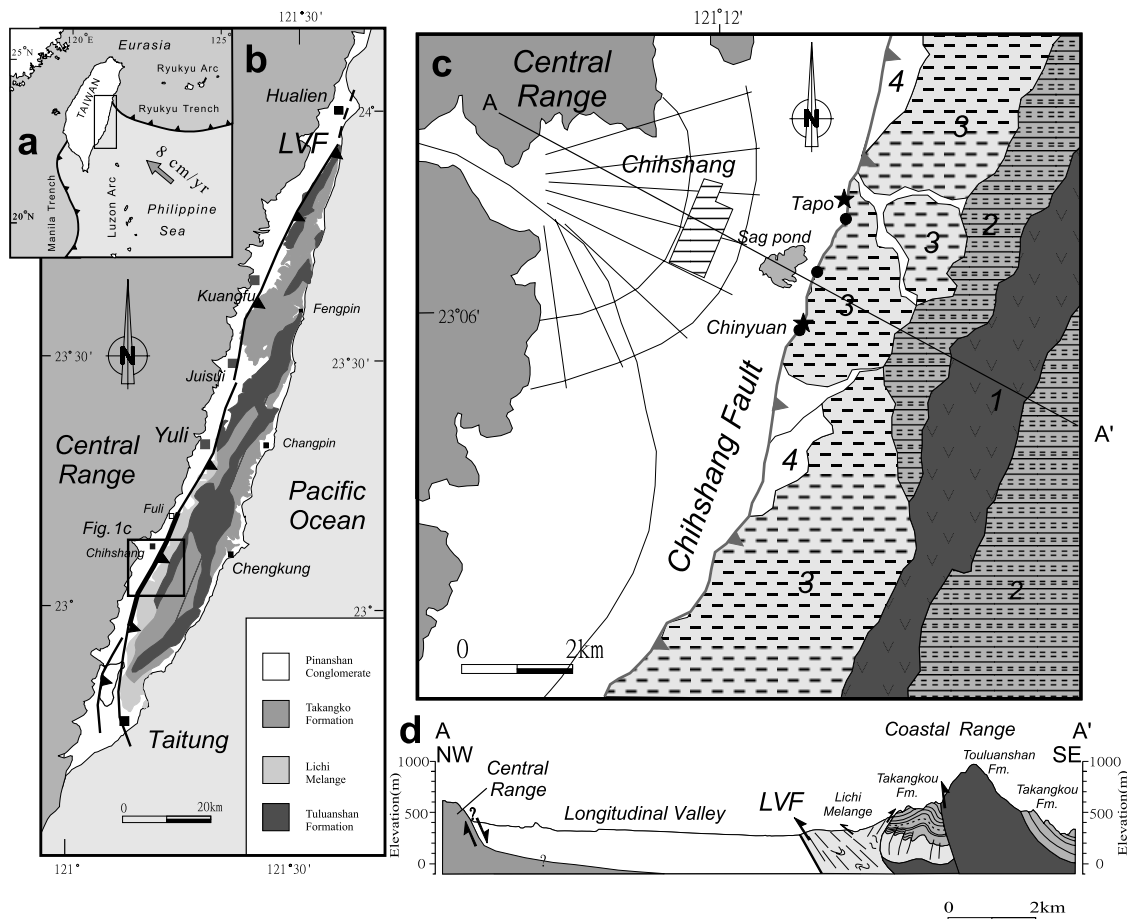
Figure 1. (a) Tectonic setting of Taiwan. (b) General geology of the Coastal Range. The Coastal Range is thrust over the Longitudinal Valley and the Central Range along the active Longitudinal Valley Fault (LVF, thick line with triangles). (c) General geology in the Chihshang area. Geological units of the Coastal Range: 1, Touluanshan Formation; 2, Takangkou Formation; 3, Lichi Mélange; and 4, Quaternary terrace. The Chihshang Fault is situated on the western margin of the Coastal Range. The two stars indicate the sites of creep meters. Three dots indicate the site of cultural feature measurements. (d) General cross section of the Longitudinal Valley at Chihshang.

data, in order to better understand the slip behavior in this active segment of the Longitudinal Valley Fault.

[3] The Longitudinal Valley Fault is a plate-boundary fault created by the oblique convergence between the Eurasian and Philippine Sea plates. Around the Taiwan area, this oblique plate convergence began about 5–7 Myr ago and is still ongoing at the present time [*Ho*, 1975, 1986; *Suppe*, 1981; *Tsai*, 1986; *Kao et al.*, 2000]. The present plate convergence occurs in Taiwan in the NW-SE direction at a shortening rate of 85 mm/yr as revealed by the recent GPS measurements across the 200-km-wide island [*Yu et al.*, 1997b]. Although this shortening is widespread across the Taiwan collision zone, most of it is accommodated in several well-identified major deformation zones within the island. For instance, about one fourth to one third of the total convergence rate, amounting to 20–30 mm/yr, is absorbed across the plate suture of the 150-km-long Longitudinal Valley. At present, earthquake activity is quite high to the north of the Longitudinal Valley (the northern tip of the Philippine Sea Plate), where the regional structure is complex. In contrast, earthquake activity is relatively mod-

erate in the middle and southern portions of the Longitudinal Valley, including the Chihshang area (i.e., the study area in this paper). During the last century, two historic major earthquakes struck the Longitudinal Valley area. The largest earthquakes of the 1951 sequence had magnitudes 7.1, 6.2, 6.9, and 5.4 and occurred from north to south along the valley in a time span of 1 month [*Taiwan Weather Bureau*, 1952]; and the 1972 Juisui earthquake of magnitude 6.8 occurred in the middle of the valley. Significant surface ruptures occurred along the Longitudinal Valley Fault at several places during the events. There is therefore a great concern for seismic hazard along the Longitudinal Valley, considering its historic record and the present high shortening rate.

[4] The Longitudinal Valley Fault also provides a good opportunity for studying on-land plate-suture thrusts with a rapid shortening rate. Along the well-studied San Andreas Fault system in California, rapid displacement rates are mostly accommodated on several strike-slip faults, for instance, 14–17 mm/yr of dextral-lateral movement on the Calaveras Fault [*Galehouse*, 1995], 4–5 mm/yr dextral

creep on the Hayward Fault [*Lienkaemper et al.*, 2001], and 21.3 mm/yr of right-lateral slip on the San Andreas Fault at Parkfield [*Langbein et al.*, 1990; *Roeloffs*, 2001]. However, there is little documentation of high creep rate thrust faults in the literature. As one of the most active segments of the Longitudinal Valley Fault, the Chihshang Fault provides a key to understand the slip behavior of thrust faults (although with some strike-slip components) in a plate suture, especially in terms of creep activity and its relationship with seismicity.

[5] The seasonal variations in creep rate deserve particular attention, as they may introduce bias in estimates obtained for periods lasting from days to months. Through comparisons between meteorological data and creep measurements, we will show that the effect of seasonal precipitation is a first-order factor in explaining the near-surface slip seasonal variations. The influence of lithology at shallow crustal levels also deserves consideration. In the following sections, we begin by summarizing the geological and structural setting of the Chihshang Fault and its general features of surface rupturing and creeping. We then present and describe our measurements and analysis of the 1998–2001 data obtained from the creep meters across the Chihshang Fault, which requires a brief presentation of the instruments and their deployment. On the basis of these data, we characterize and quantify the creep variations, including the seasonal rainfall effect, and discuss the possible causes. Then we touch upon the local effect of the gravitational landslide at one site. We will also discuss the relationship between the shallow crust level near-surface creep and the deeper subsurface seismic activity, which exhibits a decoupled behavior on the Chihshang Fault at the different crustal levels.

2. Geological and Structural Setting of the Active Chihshang Fault

[6] The NNE-trending Chihshang Fault is located in the middle southern portion of the Longitudinal Valley (Figure 1b). The pre-Tertiary metamorphic basement of the Chinese continental margin and the overlying Miocene slate (the Central Range) crop out to the west of the valley, and the Miocene volcanic arc and the overlying Plio-Pleistocene forearc turbidities and mélange (the Coastal Range) are exposed to the east [*Hsu*, 1976; *Teng and Wang*, 1981]. The Longitudinal Valley, situated between these two ranges with a remarkable physiographic linear expression, is covered by Holocene recent alluvium deposits.

[7] Geologically, the Chihshang Fault represents a major boundary, along which the Coastal Range is thrust westward over the Longitudinal Valley and the Central Range (Figure 1d). At one outcrop near Fuli, a vertical exposure clearly reveals this structural pattern: the Lichi Mélange of the Coastal Range is thrust with a left-lateral strike-slip component at a high dip angle, about 60°, onto the recent fluvial deposits of the Longitudinal Valley [*Angelier et al.*, 2000]. In the present paper we paid particular attention to the central segment of the Chihshang Fault (Figure 1c), where studies of the fault displacement have been done during the last 10 years on a yearly or twice-a-year basis [*Chu et al.*, 1994; *Lee*, 1994; *Angelier et al.*, 1997, 2000]. The surface trace of the Chihshang Fault closely follows

the geomorphic escarpment that bounds the Coastal Range to the east. Furthermore, a large sag pond situated in the valley near the Chihshang town, immediately west of the Chihshang Fault (Figure 1c), also illustrates a typical geomorphic feature in the footwall of an active reverse fault, with a marked footwall subsidence close to the fault line.

3. Active Movement of the Chihshang Fault

[8] The Chihshang Fault ruptured during the 1951 *M*6.2 (or more likely minutes later *M*6.8) earthquake and produced surface breaks with scarps tens of centimeters high extending for tens of kilometers [*Hsu*, 1955; *Bonilla*, 1975; *Cheng et al.*, 1996; *Yu et al.*, 1997a; *Chung et al.*, 2002]. Later, this fault showed clear evidence of active creep at the surface, at least during the last 20 years, when scientific observations were made. The surface creep on the Chihshang Fault may have occurred earlier but was not recognized until the observations by *Barrier and Chu* [1984] on the retaining wall near the Tapo village. It generated numerous ruptures and surface breaks, mainly along the 1951 historical earthquake surface fault trace. Different kinds of deformation structures have been observed in culture features, such as fractures and offsets in concrete walls, pressure ridges on top of concrete surfaces, tilted water wells, and so on. In particular, not only did the thrust-type fractures in the concrete retaining walls of large water channels reveal compressive deformation structures but they also allowed quantification of the fault movement [*Chu et al.*, 1994; *Lee*, 1994; *Angelier et al.*, 1997]. Annual surveys including fault slip quantification were performed since the early 1990s and showed displacements with a rather steady annual slip rate on the surface ruptures of the Chihshang Fault. The shortening concentrated inside a 30–120 m wide fault zone (deformation zone) at an estimated rate of 2–3 cm/yr and was accommodated by one or up to three branches of oblique reverse faults depending on the locality [*Angelier et al.*, 1997, 2000].

[9] Different regional-scale instrumental measurements across the Chihshang Fault have been performed during the past 15 years, including trilateration networks, leveling, and GPS measurements. The first systematic geodetic measurement across the Longitudinal Valley was done in the "Chihshang trilateration network," which included 11 stations deployed during the period 1985–1988 [*Yu and Liu*, 1989] (Figure 2a). Surveys were carried out annually within this network and similar ones to the north and to the south (Figure 2a). At the same time, a leveling survey line across the valley was also carried out. Significant horizontal shortening and vertical movement were thus documented across the Chihshang Fault [*Yu and Liu*, 1989; *Yu et al.*, 1990]. Later on, *Lee and Angelier* [1993] showed that these geodetic data were consistent with a rigid block model of reverse faulting with minor left-lateral component on the Chihshang Fault. According to this reconstruction, the Coastal Range was moving at a rate of 20 mm/yr in the N321°E direction with respect to the Longitudinal Valley in the Chihshang area (Figure 3). The annually surveyed GPS measurements during the last 10 years (1992–1999) indicated a higher rate of convergence [*Yu and Kuo*, 2001], with 31 mm/yr shortening across the Longitudinal Valley based on
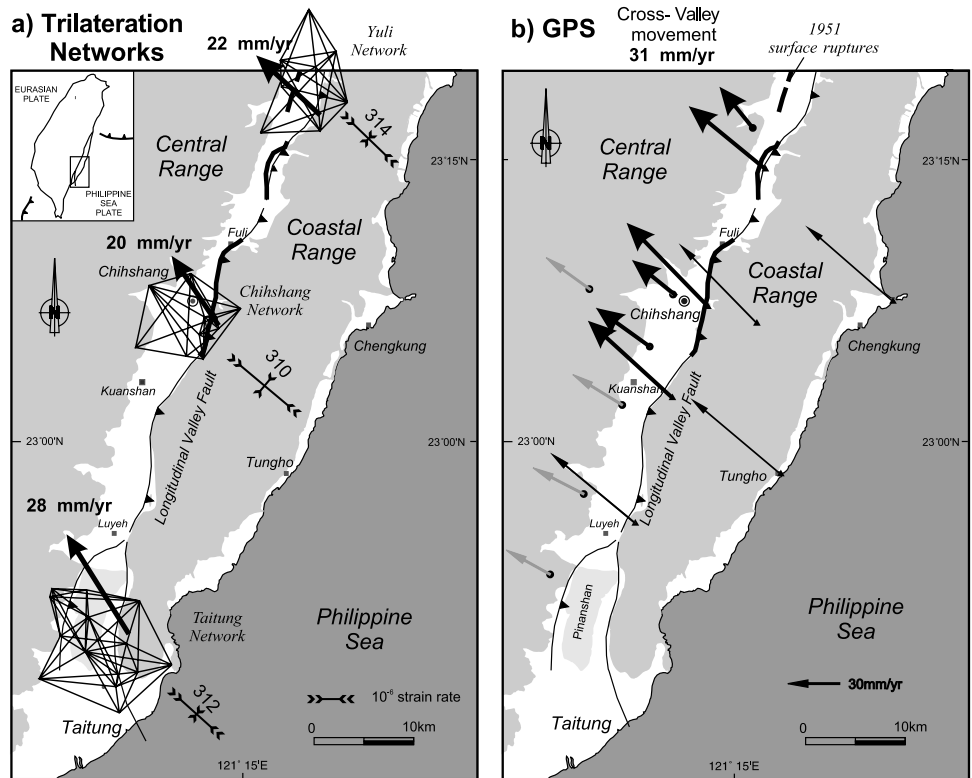
Figure 2. Relative displacement across the Longitudinal Valley Fault derived from geodetic measurements. The Longitudinal Valley Fault and the 1951 surface ruptures have been drawn as the bold lines in the maps. (a) Trilateration networks measured in 1983–1988 across the central and southern Longitudinal Valley. Axes of maximum and minimum shortening are shown by pairs of convergent arrows with double and single arrowheads, respectively, with lengths proportional to principal strain values [data from *Lee and Angelier*, 1993]. (b) Displacement vectors deduced from GPS measurements across the central and southern Longitudinal Valley (GPS data after *Yu and Kuo* [2001]). Seven stations near the valley in the Coastal Range (triangles) and seven stations near the valley in the Central Range (circles) have been plotted. Each vector represents the annual displacement vectors (1992–1999) for each station relative to the Paisha station situated in the Taiwan Strait (west of Taiwan). Among them, three pairs of GPS stations near Chihshang (bold arrows) have been selected for determination of the displacement across the valley in the Chihshang area.

consideration of neighboring stations on both sides of the valley near Chihshang (Figure 2b).

[10] Both the above cultural feature measurements and regional-scale geodetic measurements consistently revealed the active creeping Chihshang Fault moving at a rapid steady rate, about 2–3 cm/yr during the past 15 years. However, detailed creep data did not become available until the recent installation of creep meters. Five rod-type creep meters were installed straddling the surface traces of the Chihshang Fault in 1998 [*Lee et al.*, 2000]. The results of the first year of measurements with these five creep meters showed a 19.4- and 17.3-mm shortening at the two sites, Tapo and Chinyuan, respectively (Figure 4). The study during the first year also revealed that the preliminary results were consistent with other measurements, and the creep meters could be considered reliable and robust [*Lee et al.*, 2001]. In the present paper, we show and discuss the creep meter data obtained during the 1998–2001 period, which are more representative than those solely from the first year and thus allow further analysis of the creep
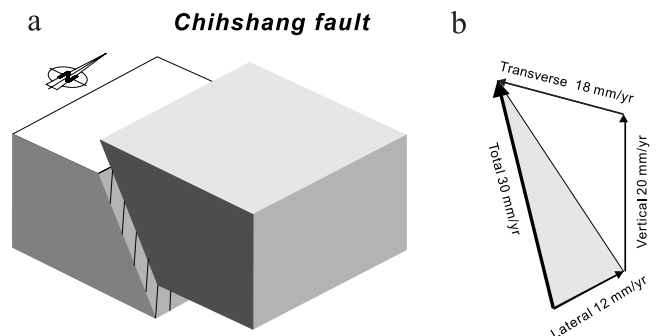

Figure 3. 3-D schematic reconstruction of the Longitudinal Valley Fault. (a) Illustration of oblique slip, showing the reverse and left-lateral components of motion. (b) Quantification of present-day fault slip components, based on fault geometry (strike and dip) and results of geodetic surveys near Chihshang.
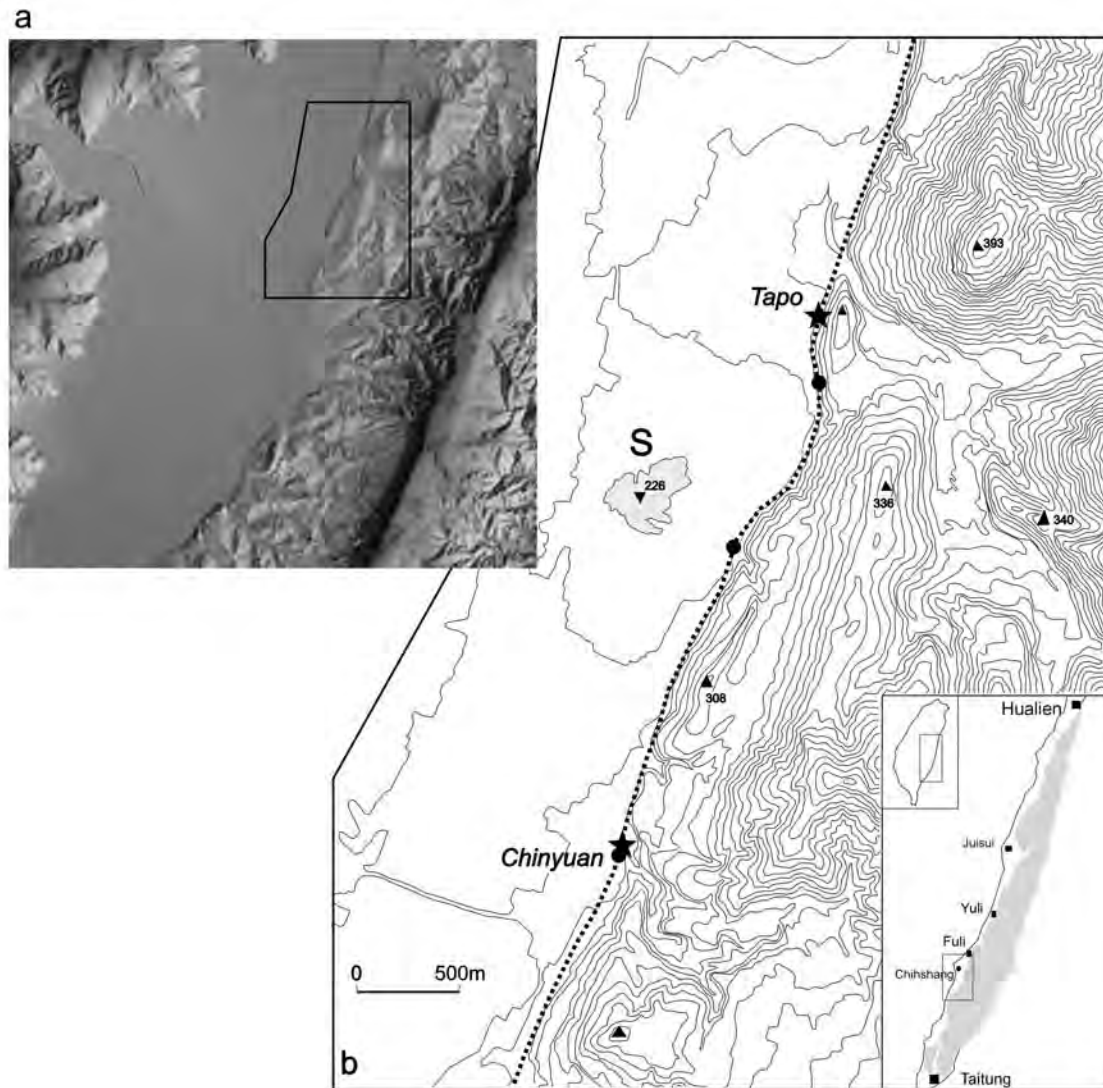
Figure 4. (a) The 40-m DEM shaded relief map of the Chihshang area. (b) Contour map showing the topographic features at the creep meter sites in the Chihshang area. The surface trace of the Chihshang Fault closely follows the edge of the hills of the Coastal Range. The two stars indicate the sites of creep meters. Three dots indicate the sites of cultural feature measurements.

behavior of the Chihshang Fault, in particular the seasonal variations.

4. Instrumentation, Data Collection, and Site Description

[11] Our rod-type creep meter is designed for measuring the relative movement across well-defined active faults on the surface (Figure 5). The creep meter measures displacements between two anchored piers on opposite sides across the active fault. The piers were mounted on 60 cm × 60 cm wide concrete bases. While located on the soil surface, an extra 0.5-m-deep cavity was dug for each pier and filled with pebbles, concrete, and iron bars, which were implanted more than 1 m deep. The instrument itself is composed of two parallel Invar rods, which are attached to each pier via a universal connector and are supported by the rollers fixed on a U-shaped steel cover-and-support system (Figure 5).

The relative movement of two Invar rods can be measured by a mechanical dial-gauge sensor. The resolution of the dial-gauge is 0.01 mm with a range of 50 mm. The data of the creep meters were manually read on the dial-gauge and recorded once a day. The technical characteristics of the instrument have been described elsewhere [*Lee et al.*, 2000], so that we will not present them here in detail.

[12] Five creep meters were installed at two sites, Tapo and Chinyuan, in 1998. These two sites are located 2 km from each other along the Chihshang Fault (Figure 4). Two connected creep meters were installed at the Tapo site, where the fault zone appears to be less than 10 m wide (Figure 6). In contrast, three creep meters were installed separately at the Chinyuan site because the present-day fault motion is distributed into three branches of surface ruptures. These three fault strands accommodate most of the deformation within a zone about 100 m wide (Figure 7).
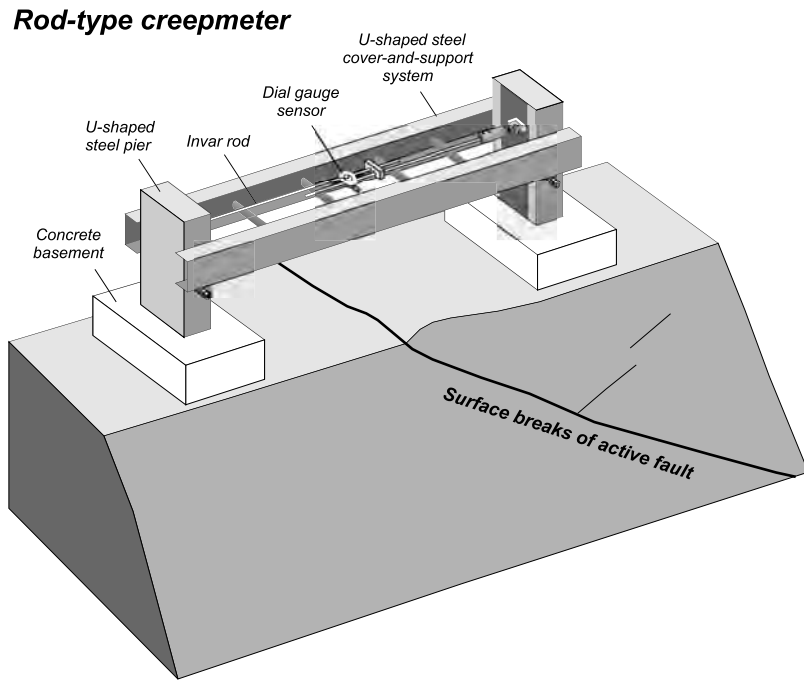
Rod-type creepmeter

Figure 5. Schematic representation of the rod-type creep meter across an active fault, rupturing the concrete wall on the surface. For a description of the instrumentation, see the text.

[13] Here we present the data and results of the creep meter study during the first 3 years following the installation (that is, from August 1998 to the end of 2001). The presented data on amounts of shortening, which have been recorded by creep meters, are subequal to or slightly less than the actual shortening of the surface fault because the orientations of the creep meters were set up to be approximately parallel to the vectors of fault motions. As we show in a later section, it is therefore possible to calculate the actual horizontal displacement of fault creep if we introduce a geometric relationship between the orientations of the fault and that of the creep meters as well as the slip vector of the fault [*Lee et al.*, 2001]. This correction is minor because the instruments were properly oriented, and it is not required here because the main purpose of this paper is to address the creep variations through time, especially the seasonal slip variation. So we simply use and compare the apparent shortening amounts, as directly recorded by the creep meters. In this respect, it is worth noting that the motion vectors across the Chihshang Fault are still subject to some

Figure 6. Photograph of the rod-type creep meter. The creep meters CHIH001 (the lower one) and CHIH002, with a common pier in the middle, cross the active fault zone and are aligned nearly perpendicular to the fault strike at the foot of rugged hills of the Coastal Range at the Tapo School.
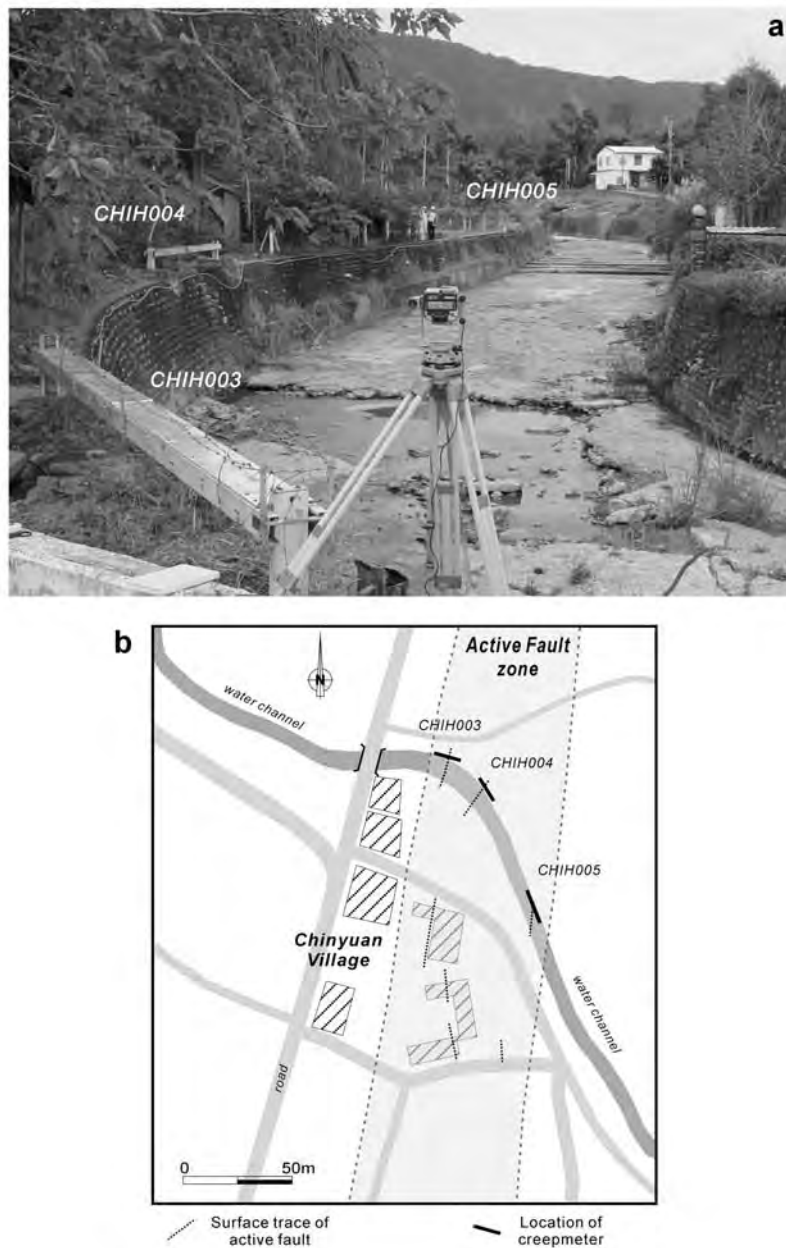
Figure 7. (a) Photograph and (b) location map of the creep meters at the Chinyuan site. Three creep meters (CHIH003, CHIH004, and CHIH005) were installed on the wall of the water channel where three surface ruptures of the active Chihshang Fault have been observed within about an 80-m-wide zone.

angular uncertainties. This provides an additional reason to ignore the minor angular corrections, which remain small with respect to these uncertainties.

5. Thermal-Elastic Calibration

[14] The two parallel rods of the creep meter are adopted by material with a low thermal expansion coefficient (Invar alloy), in order to minimize the effects of the variations in temperature. It was, however, necessary to determine the influence of the thermal effect on the length measurements done with the creep meters. Furthermore, the steel piers at the two ends of the creep meter appeared to show non-negligible thermal-elastic effect. Thus we carried out in-site

temperature calibrations. We considered not only the thermal expansion of the Invar rod but also the thermal effect on the whole creep meter system. The calibrations were done for each instrument, because thermal effects on the two different parts of the instrument (Invar rod and steel piers) did not necessarily exert the same comparative influence for all the creep meters.

[15] In practice, the temperature effects on the creep meters have been evaluated at two different timescales. The short-term scale involved the thermal fluctuation during a day, from day to night, and the long-term scale involved the seasonal thermal effect, from summer to winter. For the short-term effect, we carried out twice hourly measurements, each during a time span of 30 hours for the
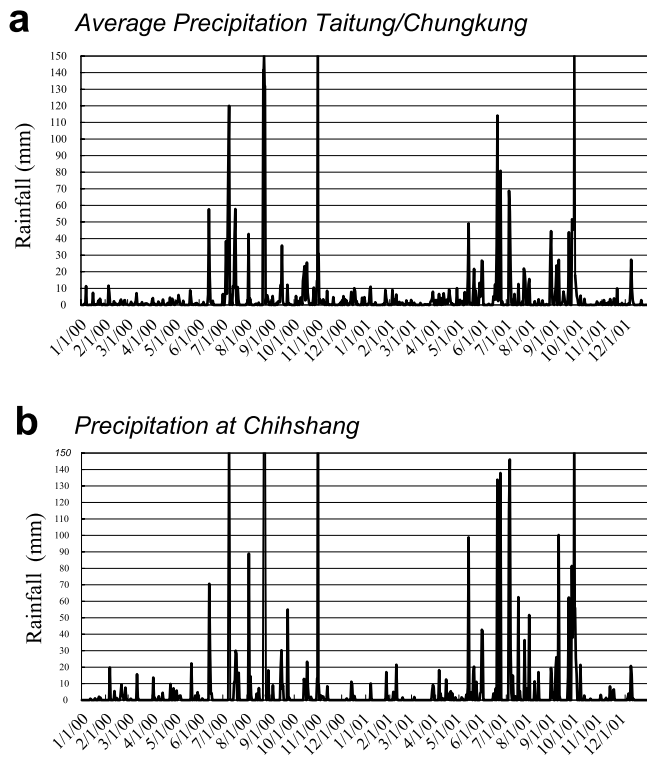
a   *Average Precipitation Taitung/Chungkung*

b   *Precipitation at Chihshang*

Figure 8. Comparison of the daily precipitation of 2000–2001 recorded at the stations of CWB in the nearby cities, (a) Chengkung and Taitung and (b) the station in Chihshang. There is a generally good agreement between these two data sets.

temperature fluctuation in the creep meter [*Lee et al.*, 2000]. The daily thermal fluctuation causes a length variation of 0.4–0.8 mm on the records of the creep meters in a local typical temperature difference of 13°–15°C between the lowest and highest temperature in a day. For the seasonal effect, we took the effect of temperature seasonal variations into account during each single year. The seasonal thermal variation shows the average lowest temperature of 15°C in winter and the highest 32°C in summer (the daily measured time is basically in the afternoon before sunset). This seasonal temperature variation yielded a length variation of 2.0–2.2 mm on the creep meters in a year. The derived thermal-elastic coefficients for each creep meter were taken as the basis of the temperature calibration. This calibration process was essential in that it allowed reliable data collection in terms of thermal-free shortening. Our daily measurements included both the length variation of the Invar rods and the temperature, which allowed for accurate correction of the data.

6. Precipitation and Groundwater Data

[16] Since we observed a time coincidence between the rapid creep periods on the creep meters and the rainy seasons, we also present the data from precipitation and groundwater level in order to better understand their relationships. The precipitation in the Chihshang area here is presented as rainfall data, which were obtained from two sources. The rainfall measurements have been carried out daily at Tapo by the Tapo elementary school since January 2000. In order to complete the rainfall record during the whole period of the creep meter measurements, we adopted data from two nearby meteorological stations of the Central Weather Bureau (CWB) at Taitung and Chengkung (for location, see Figure 1). Comparing the daily rainfall at Chihshang with the averaged rainfall at the two CWB stations during the 2 years, 2000 and 2001, we found a very good agreement between the two data sets (Figure 8). We therefore have confidence in using the average rainfall of Taitung and Chengkung from CWB as representative rainfall data for the earlier 1998–1999 period. These combined data of the monthly precipitation from 1998 to 2001 are presented in Figure 9a. Furthermore, we also calculated the daily cumulative rainfall from installation of the creep meters on 1 August 1998 (Figure 9b).

[17] In summary, the wet season in the Chihshang area is generally from May to October; however, it varies slightly each year. Not uncommonly, monthly precipitation ranges from 100 to 600 mm (normal variation between 200 and 400 mm) during the wet season. In contrast, the dry season, generally from November through April, shows monthly precipitation less than 60 mm. From the plot of daily cumulative rainfall, we are able to define the wet/dry seasons for the period of the observation (Figure 9b): (1) from August 1998 to November 1998 as wet season; (2) from December 1998 to April 1999 (5 months) as dry season; (3) from May 1999 to October 1999 (6 months) as wet season; (4) from November 1999 to June 2000 (7.5 months) as dry season; (5) from June 2000 to October 2000 (4.5 months) as wet season; (6) from November 2000 to April 2001 (6 months) as dry season; and (7) from May 2001 to September 2001 (5 months) as wet season. Note that there is usually a 1-month transition period between the wet and dry season with precipitation around 100 mm/month.

[18] The data of the groundwater level presented here were obtained from a monthly measured observation well, maintained by Water Resource Agency. This well is located near the Chinyuan creep meter site. The groundwater level during the period of 1998–2001 (Figure 9c) indicates that it rose rapidly from the lowest level of about 20 m deep up to a high level of about 12–15 m deep in the early rainy season and generally attended its highest level of about 10–12 m deep at the end of the rainy season. The groundwater dropped gradually from its highest level to the low level through the dry season and generally attained its lowest level near the end of the dry season around March/April. In summary, the level of the groundwater corresponds to the rainy/dry season at first approximation. However, a difference does exist between these two data: the groundwater rose sensitively and rapidly due to heavy rain in the early wet season, but it dropped retardatively and slowly in the dry season. As we will illustrate in the following section, the fault creep shows a good correlation with the dry/rainy season, but the slowdown in the rate of dropping of groundwater level did not show any significant effect on the creep data. Therefore we conclude that groundwater did not have a direct impact on the creep motion of the surface fault.

7. Creep Data: 1998–2001

[19] In the following sections, we present data from the creep meters and discuss the behavior of fault motions and
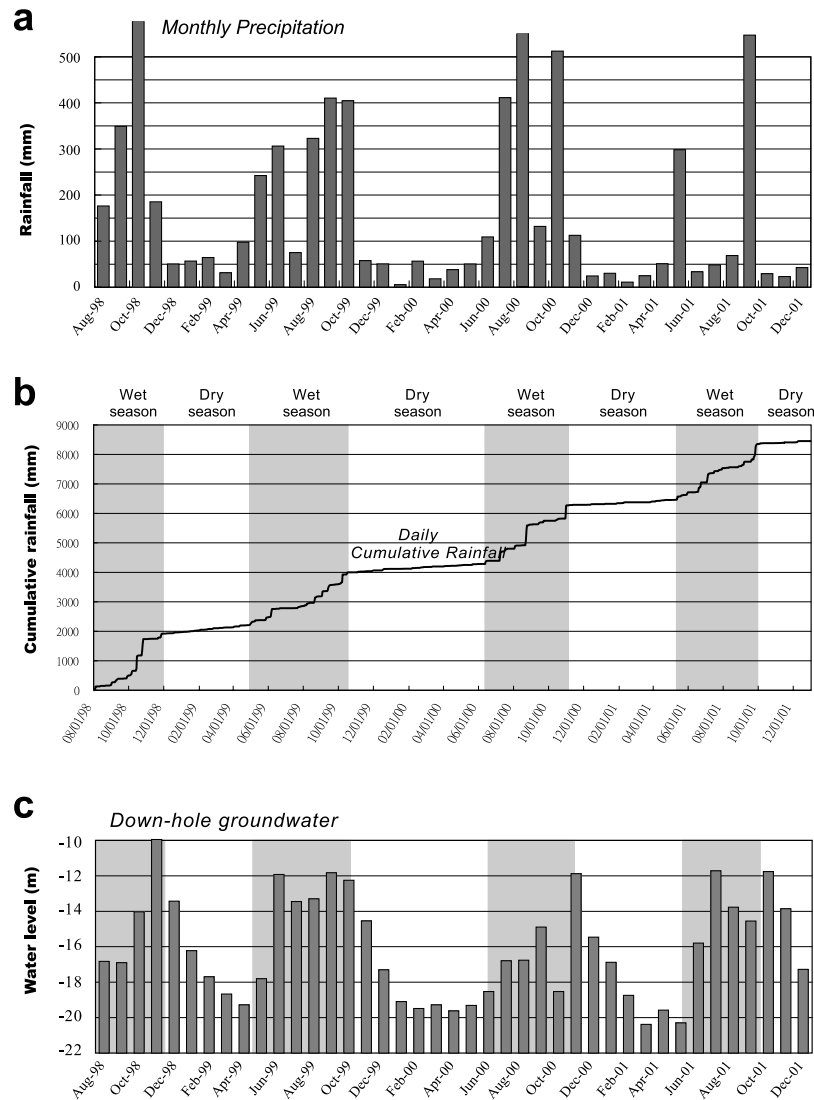
Figure 9. Precipitation and groundwater data at Chihshang. (a) Monthly rainfall. There are about 200–600 mm/month of rain during the rainy seasons, generally from April to October. Less than 50 mm/month are commonly observed during the dry season. (b) Cumulative daily rainfall. The change of the amount of rainfall can be clearly seen in this plot. We used this curve as the basis to define the dry and wet seasons. (c) Groundwater level from the nearby observational well at the Chinyuan site.

their characteristics at the Tapo and Chinyuan sites, based on simple plots of shortening on the creep meters versus time (Figures 10 and 11). The annual shortening or displacement rates are calculated by using data from January to December for each year, rather than using data from the beginning of data acquisition, that is, August 1998. The reason behind this data representation is that prior to the creep meter installation we noticed that the fault motion varied widely as a function of the survey periods. The creep meter records confirmed that the fault motion almost ceased, or remained small, during the dry season (generally from November to March or April), as compared with the wet season. The annual estimates of fault motions may be slightly affected by the variable transition periods between the dry and wet season. As a consequence, it is certainly better to present this kind of annual estimate between dry seasons, in order to minimize such undesirable effects.

7.1. Creep Meters at the Tapo Site

[20] Figure 10 illustrates the displacement with respect to time for two creep meters, CHIH001 and CHIH002, at the Tapo site. As described above, these creep meters were connected to form a single line: CHIH001 lies across the fault scarp, while CHIH002 is located on the slope just above the scarp. The cumulative daily precipitation also has been plotted in Figure 10 in order to compare the creep behavior with rainfall.

[21] The shortening recorded by creep meter CHIH001 amounted to 17.0 mm for 3 years, 1999–2001, that is, 5.7 mm/yr on average. Annually, it revealed a larger amount of shortening, 9.0 mm/yr, in 1999 and less shortening,
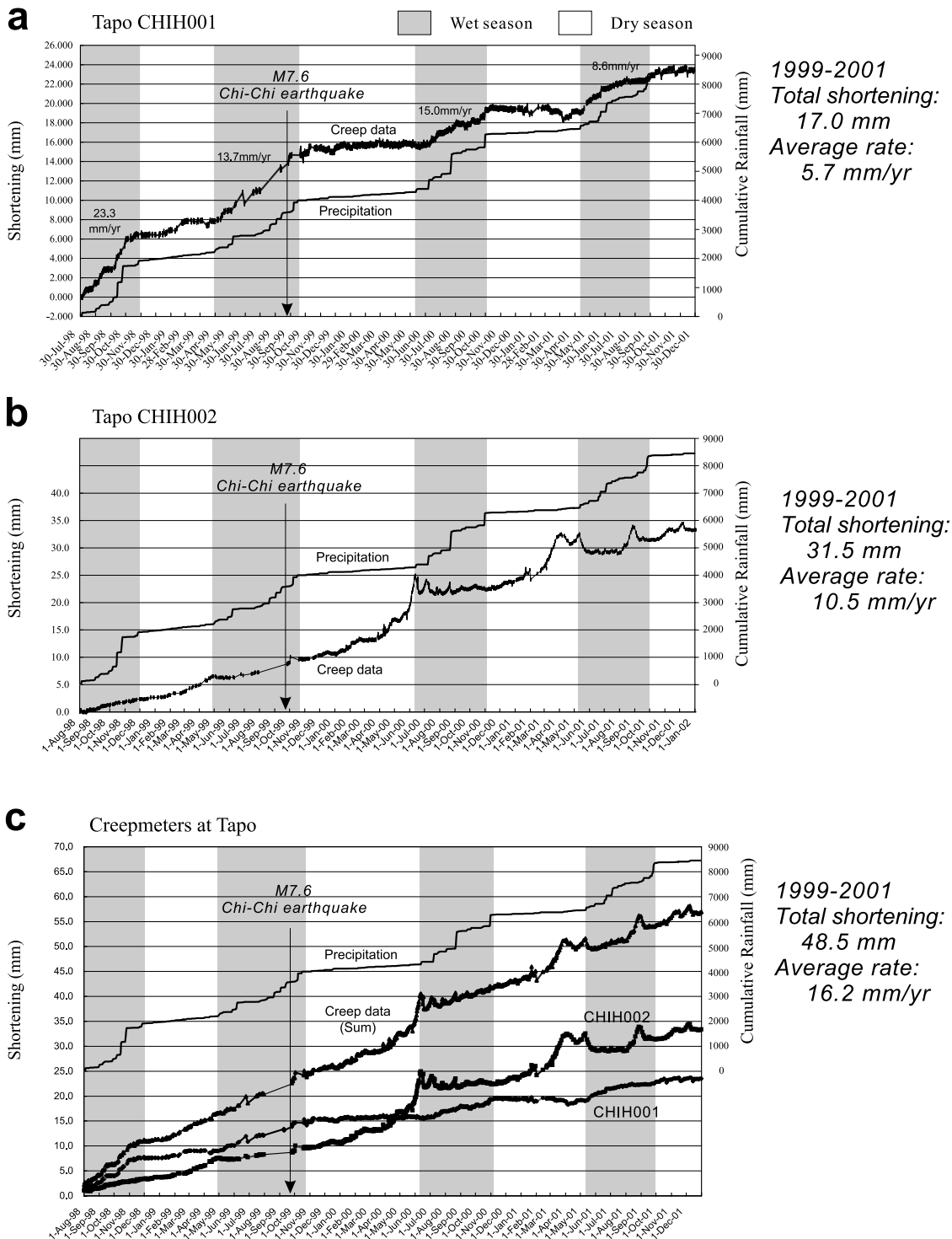
Figure 10. Data of the creep meters at Tapo school site. Two creep meters, (a) CHIH001 and (b) CHIH002, are connected together to measure the displacement in a 10–15 m wide active fault zone situated at the foot of a small hill. (c) Sum of the data of two creep meters represents the total shortening amount. For each plot of the creep meter data, we also provided the daily cumulative precipitation as comparison on the seasonal variation.

Figure 11. (opposite) Data of the creep meters in Chinyuan. Three creep meters, (a) CHIH003, (b) CHIH004, and (c) CHIH005, are located individually on the surface traces in a 100-m-wide active fault zone. Note that the periods of the rapid shortening rates correspond well to the periods of the wet season for each year. For each plot of the creep meter data, we also provided (d) the daily cumulative precipitation as comparison on the seasonal variation.
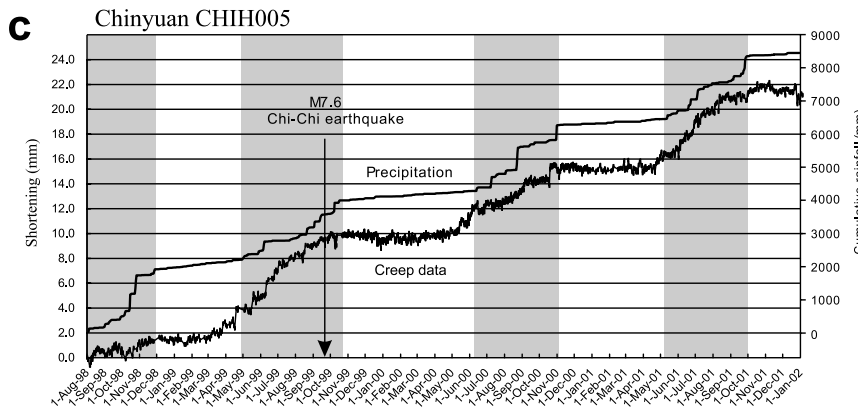
a Chinyuan CHIH003
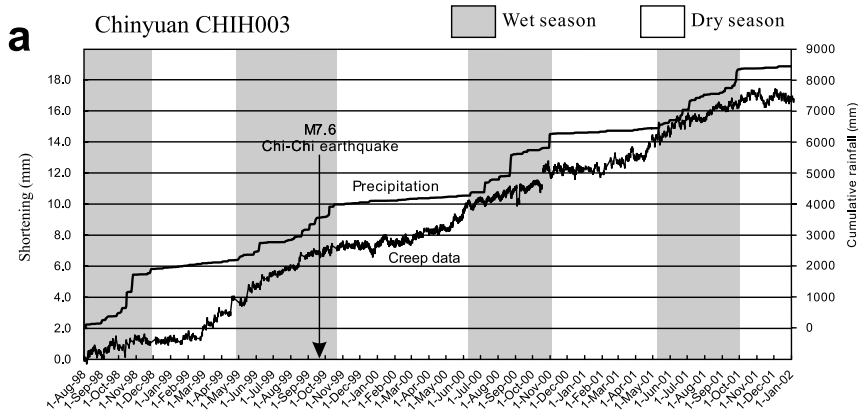
1999-2001
Total shortening:
15.5 mm
Average rate:
5.2 mm/yr

b Chinyuan CHIH004
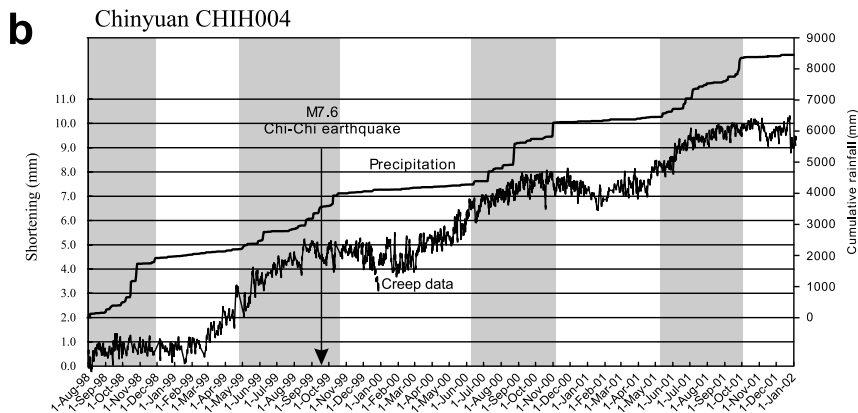
1999-2001
Total shortening:
9.0 mm
Average rate:
3.0 mm/yr

c Chinyuan CHIH005

1999-2001
Total shortening:
20.5 mm
Average rate:
6.8 mm/yr

d Creepmeters at Chinyuan
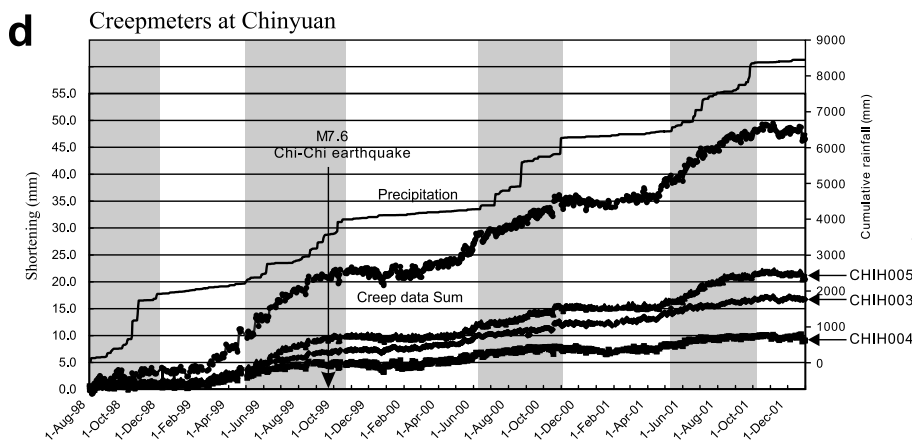
1999-2001
Total shortening:
45.0 mm
Average rate:
15.0 mm/yr

4.0 mm/yr, in 2000 and 2001. Furthermore, the curve shortening-versus-time for creep meter CHIH001 (Figure 10a) clearly shows a seasonal variation of creep motion. Relatively rapid creeping occurred during the wet season (summer-autumn), interspersed with very slow creep motion during the dry season (winter-spring). The only exception is revealed by a short period of rapid motion during the second half of February 1999. This probably is due to moderate precipitation during January and February 1999 (57 and 64 mm, respectively). The creep rates, converted to millimeter per year for consistency, were as follows for the rapid creeping seasons from 1998 to 2001: (1) 23.3 mm/yr from August (beginning of data recording) to mid-November 1998, (2) 13.7 mm/yr from May to early November 1999, (3) 15.0 mm/yr from the end of June to early November 2000, and (4) 8.6 mm/yr from early May through November 2001. In contrast, the creep rates during the slow creep dry seasons averaged 0–1 mm/yr, except for the short period in February 1999 mentioned above.

[22] The shortening of the creep meter CHIH002 is 31.5 mm for the 3 years, 1999–2001, that is, 10.5 mm/yr on average, approximately twice as large as that recorded by the lower creep meter. The shortening amounts for 1999, 2000, and 2001 are 8.5, 14.0, and 9.0 mm, respectively. Creep meter CHIH002 shows movements throughout the 3 observation years, regardless of season. This motion, however, cannot be regarded as steady state except to first approximation. There exist weeks-to-months-long periods with abrupt pulses (or surges) of displacement at least once per year, for instance, March/April 1999, April–July 2000, February–May 2001, and August 2001. One can notice that the abrupt pulses, with amplitudes of displacement up to 6–8 mm, are characterized by first dramatically shortening and then lengthening. Each of these abrupt pulses correspond to events of rapid or abrupt surface movements, which do not correspond to a general simple fault motion. In fact, these pulses of displacements suggest that complicated surface deformation is involved, which we interpreted to be mainly due to rotation of the pier caused by either fault or small gravitational landslides along the slope as discussed in a later section of this paper. It is also worthy to note that for each year the abrupt pulsing periods basically occurred during the second half (or near the end) of the dry season and the beginning of the wet season. This behavior differs from that of the other creep meter stations.

[23] We attributed the total shortening across the surface breaks of the Chihshang Fault at the Tapo site to the sum of the individual shortening on the two connected creep meters CHIH001 and CHIH002. Combining data from these two creep meters, the curve of the summed creep data (Figure 10c) reveals a continuous shortening motion with a surprisingly rather steady rate, except for some pulses of abrupt movement already noticed in the CHIH002 record. We thus obtain the combining total shortening of 48.5 mm in 3 years from 1999 to 2001, that is, 16.2 mm/yr on average. For individual years, the annual creeping rates are 17.5 mm/yr (1999), 18 mm/yr (2000), and 13 mm/yr (2001). Note that the two connected creep meters, CHIH001 and CHIH002, moved in a general complementary way and sometimes even in opposite-sense movements. Before the beginning of each wet season, and without exception during the 3 years of observation, the creep meters started to move, in particular,

CHIH002 (the upper one) crept dramatically. While the upper creep meter recorded a dramatic shortening, and the lower one (CHIH001) revealed a small amount of unexpected lengthening. Then the upper creep meter exhibited a rapid but small lengthening while the lower one began to be shortened. After moving abruptly with a few similar pulses, this upper creep meter became inactive for an unspecified time, while the lower creep meter continued creeping with shortening throughout the wet season. We kept in mind that it was necessary to install these Tapo creep meters on a slope, unlike the other creep meters that could be installed on flat land. This particular behavior deserves discussion in light of the possible presence of other fault strands and local gravity sliding. We will discuss this in detail, in a later section.

7.2. Creep Meters at the Chinyuan Site

[24] The creep data at the Chinyuan site are illustrated in Figure 11 by plots of shortening (in mm) versus time (in months) for three creep meters across three individual surface breaks within a 100-m-wide deformation zone of the N-S trending Chihshang Fault.

[25] First, the westernmost creep meter CHIH003 reveals a displacement (shortening) of 15.5 mm in 1999–2001, that is, 5.2 mm/yr on average. Annually, the creep rates on creep meter CHIH003 are quite steady, although slightly decreasing: 6.0, 5.0, and 4.5 mm/yr for each year from 1999 to 2001. The shortening data also reveal a seasonal variation, which also exists for the other two creep meters at the Chinyuan site. This seasonal variation is characterized by a relatively rapid creep rate during the wet season and a slow creep rate during the dry season.

[26] The creep meter CHIH004, located across the middle branch fault in the deformation zone, exhibits a 3-year total displacement (shortening) of 9.0 mm in 1999–2001 (Figure 11b), that is, 3.0 mm/yr on average. For each of the 3 years, the shortening is 3.5, 3.0, and 2.5 mm, respectively. The plot of shortening for creep meter CHIH004, like the other two creep meters at Chinyuan, also shows a clear seasonal variation in the movement of surface faults. In addition to rapid shortening in the wet season, a unique characteristic of fault movement was observed at creep meter CHIH004. Large variations occur on timescales of a few days or weeks (and certainly less than 1 month). These variations result in a narrow sawteeth appearance of the curve (Figure 11b). Their amplitude is generally about 1–2 mm. The reason for these variations remains unclear. Concerning the relation between the creep rate and the rainfall, we observe that the shortening periods at the creep meter CHIH004 approximately correspond to the rainy periods, although they were not perfectly correlated. The onset of creep from quiescence period to shortening period occurred generally a few days to 1 month before the beginning of the rainy season. This implies that moderate rainfall during the transition period from the dry season to the wet season is enough to trigger rapid creeping at CHIH004. We will discuss more in detail the onset of rapid creep in terms of daily precipitation data in a later section.

[27] The easternmost creep meter CHIH005 displays a total shortening of 20.5 mm in 3 years, that is, 6.8 mm/yr on average (Figure 11c). For each individual year, the shortening rates are 8.0, 6.0, and 6.5 mm/yr, respectively, from

1999 to 2001. The creep meter CHIH005 reveals the most obvious seasonal variation in fault motion. Whereas very limited motion occurred during the dry seasons, rapid creep and shortening prevailed during the wet seasons. Again, the rapid creep generally started during the transition period from the dry season to the rainy season, especially in 1999.

[28] To obtain the total deformation record at the Chinyuan site, we simply sum the shortening amounts of the three creep meters to obtain the total shortening of the surface motion on the Chihshang Fault. The three creep meters revealed a total shortening of 45.0 mm in 3 years from 1999 to 2001, that is, 15.0 mm/yr on average (Figure 11d). For each of the 3 years, the annual total shortening was 17.5, 14.0, and 13.5 mm, respectively.

[29] Hereafter we summarize the creep history of the creep meters at the Chinyuan site as the typical pattern of seasonal creep at the Chihshang Fault. From November 1998 to mid-February 1999, no significant displacement occurred. Then the fault started to move with shortening of 18.5 mm in 7.5 months (creep rate 29.6 mm/yr) from mid-February to September 1999. This was followed by the second annual cycle of seasonal variations, a quiet period with very little shortening of about 1.5 mm (creep rate 2.6 mm/yr), which occurred during 7 months of the dry season, from October 1999 to April 2000. The fault moved again at a relatively rapid rate and showed a shortening of 11 mm in 6 months (that is, a creeping rate of about 22 mm/yr), from May to October 2000. Finally, we have the third annual cycle with a quiet period of 5.5 months during the dry season, from November 2000 to mid-April 2001, followed by a period of relatively rapid shortening (13.9 mm in 6 months, that is, a creep rate of 27 mm/yr) during the wet season from mid-April to mid-October 2001.

[30] The surface creep exhibited a relatively higher rate in 1999 and slightly lower ones in 2000 and 2001. With only these creep meter data, we are not able to conclude whether the fault creep displacement underwent a significant decrease with time from 1999 to 2001, using shortening rates calculated at the annual timescale. We shall discuss this aspect in more detail by comparing other available information in later sections. In detail, comparison of the behaviors among the three creep meters reveals a distinct behavior related to the seasonal variation. This behavior involves fast creeping that started from the late dry season and continued throughout almost the whole wet season (that is, for about 6 months) and very little motion during the dry season (for about the 6 remaining months). During the fast creeping periods, relatively higher creep rates prevailed in the first half of the wet seasons and relatively lower creep rates occurred in the second half of the wet seasons. Slight differences in creep behavior could also be recognized among the creep meters. An intriguing case is that of creep meter CHIH004 (the middle one), which revealed systematic short-term variations.

7.3. Comparison Between the Tapo and Chinyuan Sites

[31] To compare the shortening amounts determined at the two sites, Tapo and Chinyuan (Figures 10 and 11), we first depict the first-order difference in creep behavior between the two sites: a steady motion with clear seasonal variation (moving in the wet season and dormant in the dry season) in Chinyuan and a more continuous creep regardless of the season (and with a few abrupt movements) in Tapo. Note, however, that separate consideration of the two in-line Tapo creep meters revealed season dependency as pointed out before. We infer that these differences mainly result from the location of the creep meters. The creep meters at the Tapo site were installed in the $20°-30°$ inclined hill-slope made of Lichi Mélange, above the active fault. Because of this slope and the mechanical weakness of the mélange, the gravitational effect is enhanced at the Tapo site. The creep meters at the Chinyuan site, on the other hand, are situated in a rather flat area with thick alluvial deposits of the recent Quaternary, where no significant gravitational effect or landsliding occurs.

[32] Despite this contrast, we obtained similar amounts of annual shortening from 1999 to 2001 in the Tapo and Chinyuan sites: 17.5 mm at both Tapo and Chinyuan in 1999, 18.0 mm at Tapo and 14.0 mm at Chinyuan in 2000, and 13.0 mm at Tapo and 13.5 mm at Chinyuan in 2001. The reason why a slight discrepancy in the shortening amounts between the sites of Tapo and Chinyuan arose in 2000 remains unclear and arguable. However, we tend to interpret it as a result of the irregularity in motion at Tapo's creep meters, particularly CHIH002. The sudden increase in displacement recorded by this creep meter in June 2000 accounts for the abnormally high shortening amount in the 2000 season (Figure 10b), as compared with the measurements from the other four creep meters. It is worth noting that the creep meter CHIH002 returned to its former trend after this sudden increase in the rate of shortening. We think that this abrupt jump of displacement can be explained by gravitational landsliding that possibly occurred in June 2000, in addition to the tectonic faulting. We will discuss the complicated creep behavior at the Tapo site in a later section. Because of unclear effects at the Tapo site, we used the data from creep meters at the Chinyuan site for the representative surface creep in the Chihshang Fault zone, that is, a shortening of 17.5 mm in 1999, 14 mm in 2000, and 13.5 mm in 2001. The average shortening rate is 15.0 mm/yr, which forms the basis for the amount of creep in later discussions.

8. Discussion

8.1. Surface Deformation at the Outcrop and Regional Scales

[33] From the 1998–2001 creep meters data at the Chinyuan sites, we obtained an average shortening rate of 15.0 mm/yr for the Chihshang Fault. This estimate of horizontal displacement is a minimum due to the obliquity of the creep meter orientations relative to the slip vector, as well as to the limited coverage of the creep meters installed within the multibranch fault zone. For instance, the creep meters at Tapo are at an angle of about $40°$ to the slip vector of the fault, whereas the creep meters at Chinyuan are at an angle of $10°-30°$ [Lee et al., 2001]. The previous analyses [Angelier et al., 2000] indicated that the actual surface displacement vectors of the Chihshang Fault are N156°E at Tapo and N145°E at Chinyuan, with a fault trend of N18°E. On the basis of these geometric relationships, we reconstructed the actual horizontal component of the fault creep. The geometric correction yields a fault creep rate of

16.5 mm/yr at the Chinyuan site (21.5 mm/yr at the Tapo site) in 1999–2001.

[34] The previous culture feature measurements at the three sites in Chihshang indicated a rather stable rate of horizontal shortening of 22 mm/yr from 1990 to 1997, which resulted from average rates of 19 mm/yr at the Chinyuan site, 27 mm/yr near the Tapo site, and 21 mm/yr at the third site between Tapo and Chinyuan [Lee, 1994; Angelier et al., 1997, 2000]. The shortening rate of creep meters at Chinyuan (i.e., 16.5 mm/yr, 1998–2001), though a decreasing trend, is considered to be of the same order of magnitude compared with culture feature measurements of 19 mm/yr at Chinyuan since 1990.

[35] The creep meter data are also compatible, in spite of slightly smaller creep rates, with the results of the geodetic trilateration network surveyed in 1986–1988 [Yu and Liu, 1989]. These earlier determinations yielded a horizontal displacement of 20 mm/yr on the Chihshang Fault, based on a rigid-block-model analysis [Lee and Angelier, 1993]. It should be noted, however, that these earlier data and results came from an integration of the displacements across the whole Longitudinal Valley (location see Figure 2a) and consequently are not necessarily comparable to the creep meter data, which reflect local near-fault displacement. Although this observation does not invalidate our general conclusions about a recent decrease in shortening with time, it certainly diminishes the significance of these conclusions. In any case, the data from the 1986–1988 geodetic network suggested that the surface deformation concentrated in a narrow zone with substantial horizontal shortening, which basically reflects the activity of the Chihshang thrust fault [Yu and Liu, 1989; Lee and Angelier, 1993].

[36] Three pairs of GPS stations on both sides of the Longitudinal Valley were deployed to survey the Chihshang area from 1992 to 1999 (location see Figure 2b), yielding a displacement rate of 31 mm/yr [Yu and Kuo, 2001], which is significantly larger than the 22 mm/yr rate obtained from culture feature measurements for roughly the same years, and the 16–17 mm/yr rate obtained from our Chinyuan creep meter data in 1998–2001. The explanation of these discrepancies is multifold. First, it could be that the shortening rate has actually been decreasing during recent years, as noted before. To substantiate this argument, we need to obtain the updated GPS results for recent years. Second, the horizontal shortening on the creep meters across the surface faults could exhibit a smaller amount than the shortening measured by conventional geodesy and GPS covering the entire 5–7 km wide valley. This suggests that additional deformation from GPS measurements might exist in locations other than along the most obvious surface ruptures. It also might be caused by the obliquity of the creep meter orientation to the actual slip vector. Although previous studies have estimated the displacement vectors of the Chihshang Fault, large uncertainties still remain on the determinations of the actual slip vectors for each fault branch at the Chinyuan site [Angelier et al., 2000]. The third possibility is that the strike-slip component is significant on the surface fault at the Chinyuan site. Our preliminary results of a local near-fault geodetic network at Chinyuan indeed indicate a slip vector of N150°–160°E for the Chihshang Fault [Lee et al., 2003]. With this local deviation of fault slip, one would expect a more important strike-slip component and thus a lesser amount of shortening on the Chihshang Fault at the Chinyuan site. This would give an explanation for the discrepancy between the regional cross-valley GPS measurements and the local near-fault creep meter and cultural feature measurements.

8.2. Rainfall Versus Surface Creep

[37] In this section, we summarize the close relationship between seasonal precipitation and fault creep behavior and also discuss the probable effects of rainfall on surface fault movements. Four of our five creep meters, CHIH001 at Tapo and CHIH003, CHIH004, and CHIH005 at Chinyuan, show a strong correlation between the creeping and rainy periods in each year from 1998 to 2001. These four creep meters indicate that the fault crept at a relatively high rate during the wet season, whereas the movement nearly ceased during the dry season. In more detail, however, it seems that each year the fault had begun to move during the transition months between the dry and the wet seasons, that is, about 1 month before the onset of heavy rains.

[38] In order to examine the relationships between the onset of rapid creep and rainfall, we compared the curves of the creep data with the daily precipitation during the dry/wet transition periods for each of the years, 1999–2001 (Figure 12). The combined creep data from the shortening of the three creep meters at the Chinyuan site have been selected for this comparison because of their general agreement with the rainy seasonal variation. Because the daily precipitation measurements at Chihshang were begun in 2000, we restricted the discussions on the transition periods to 2000 and 2001 (Figures 12b and 12c). The plot of 1999 (Figure 12a), which shows the daily precipitation derived from averaging the two nearby CWB metrological stations, was also presented for comparison.

[39] We found that we can roughly divide the onset of creep into two steps during the dry/wet transition period. In the first step, the fault started to creep from quiescence at a rather slow rate. This step seemingly began after a moderate rain in the middle of the dry season. For example, a 20-mm-rain dropped on 6 February 2000 and a moderate rain occurred later in a time span of about a week with daily precipitation of 2–10 mm in late February, resulting in a significant monthly precipitation of 56 mm. The creep data at Chinyuan indicated that the fault began to move at a slow pace around the end of February 2000 (Figure 12b). The similar onset of creep followed by a moderate rain can also be observed in February 2001 (Figure 12c). We thus infer that the onset of this low-rate surface slip was possibly triggered by a moderate rain in the middle of the dry season.

[40] The second step involved rapid fault creep. In the case of year 2000, surface creep accelerated after a week-long moderate rain in late April to early May and accelerated again after a 22-mm-rain on 21 May 2000 (Figure 12b). In 2001, the rapid creep started after a moderate rain, which lasted for 2 weeks with maximum daily precipitation of 18 mm in April (Figure 12c). We infer that the onset of the surface rapid creep was strongly related to the moderate rain in April/May. It is worth noting that there is no significant difference in the amount of precipitation between the moderate rains in February and those in April/May. The
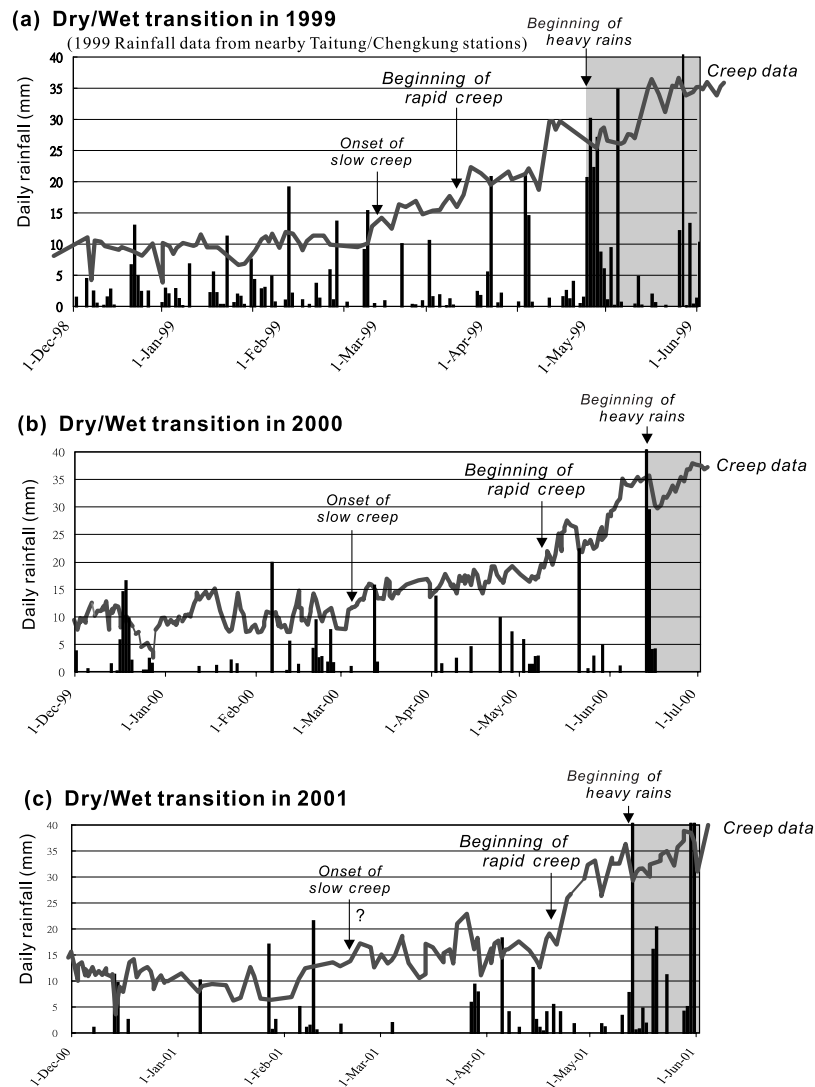
(a) Dry/Wet transition in 1999
(1999 Rainfall data from nearby Taitung/Chengkung stations)

(b) Dry/Wet transition in 2000

(c) Dry/Wet transition in 2001

Figure 12. Detailed creep data at the Chinyuan site with daily precipitation during the transition period of the dry/wet season for each year: (a) 1999, (b) 2000, and (c) 2001. The onsets of rapid creep revealed a close relationship with the onsets of the moderate rainfall. Details are given in the text.

surface creep rate is apparently not in a linear relationship with the precipitation. Further investigation is needed in order to understand this likely more complex relationship between creep rate and rain.

[41] It appears that the duration of the wet season also prolonged the surface fault motion. The durations of the wet season varied for each year from 1999 to 2001: lasting more than 6 months in 1999, only 5 months in 2000, and 5–6 months in 2001. The duration of the rapid creeping period seems to be proportional to the duration of the wet season (Figures 10 and 11). In contrast, the shortening amounts recorded by the creep meters did not show obvious relationship with the amount of precipitation. The annual precipitations are 2119, 2287, and 2149 mm for 1999, 2000, and 2001, respectively, and the shortening amounts are 17.5, 18, and 13 mm at Tapo and 17.5, 14, and 13.5 mm at Chinyuan for the same years. Quantitatively, we cannot discern any relationship between the amounts of rainfall and the amounts of fault creep, partly because no significant

variations existed for either the annual precipitation or the amount of fault shortening in these 3 years.

8.3. Fault Motion and Landslide at Tapo

[42] The landsliding or gravitational phenomenon cannot play any role at Chinyuan, where the fault trace runs across flat land. In contrast, it may significantly affect creep meter records at Tapo, because there the connected creep meters CHIH001 and CHIH002 were installed on a hill flank with a slope of $20°–30°$. This suspicion arises from the creep behavior of the creep meter CHIH002, which revealed several sudden pulses of displacement.

[43] Field observations at this site show that the main fault plane of the Chihshang Fault emerges at the surface under the lower situated creep meter CHIH001. This location of the surface fault trace, which is characterized by a sharp slip surface with the Lichi Mélange mudstone in the hangingwall and the alluvium deposits in the footwall, has been identified from an earlier excavation [*Chu et al.*,
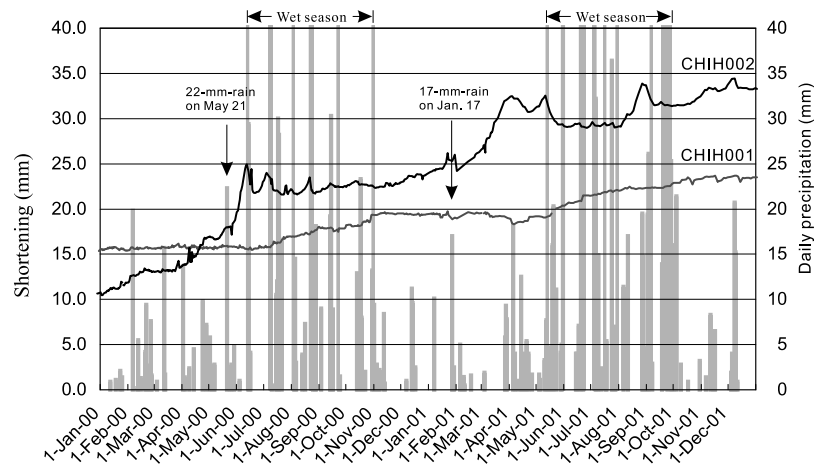
Figure 13. Detailed creep data at the Tapo site and daily precipitation in 2000 and 2001. The onsets of the rapid creep and the beginning of the abrupt pulses on the upper creep meter CHIH002 showed a close relationship with a moderate amount of rainfall in the dry/wet transition periods. Details are given in the text.

1998]. As a consequence, we anticipated that a large part of the fault creep should have been recorded by the lower creep meter rather than the upper one. However, in our data, near-continuous creeps on the upper creep meter suggest that at least one slip surface emerged under the upper creep meter CHIH002. Recent field observation indicates that a few surface breaks are developing under CHIH002 and also near the middle connected pier. Two interpretations are possible. First we consider the new surface breaks as small gravitational landslide surfaces based on its surface feature. Also, evidence of ancient significant landsliding can be observed tens of meters south of the creep meter site. In fact, landslides and gravitational cracks are not uncommon on the hangingwall hills along the Chihshang Fault. This apparently is also due to the nature of the material comprising the hillslope, known as the Lichi Mélange, which provides little mechanical friction when water content is high. However, another possibility that the main Chihshang Fault might branch out to rupture the surface under CHIH002 cannot be excluded. In this case, at least one rupture under CHIH002 is a fault surface instead of landslide or gravitational slip breaks, so that a significant part of the displacements recorded on the creep meter CHIH002 could be attributed to slipping on a tectonic fault surface. To distinguish between these two possibilities, a careful examination of the creep curves of the creep meters has been carried out.

[44] First, one can observe that the creep rate recorded on the lower creep meter CHIH001 has decreased after the first year. In addition, the average creep rate of 5.7 mm/yr on CHIH001 is only one third of the representative creep rate of 15–20 mm/yr on the Chihshang Fault. Although earlier field evidence had indicated that the location of the main fault was under CHIH001, it is obvious that part of the active fault surface creep was being transferred to another place, probably to a slip surface under the upper creep meter CHIH002, which revealed a creep rate of 10.5 mm/yr. Furthermore, the total shortening rate of 16.2 mm/yr on the two creep meters at Tapo is comparable, though a bit larger, to the rate of 15.0 mm/yr at Chinyuan. As a result,

the landslide probably plays a limited role, and a more important part of the active surface fault creep could be attributed to slipping on a fault strand under the upper CHIH002, rather than to the main fault surface under the lower CHIH001. While summarizing the overall motions on the connected creep meters CHIH001 and CHIH002, we found that the total shortening proceeded at a rather steady creep rate (Figure 10c). This also suggests that the tectonic fault motion played a bigger role than the possible landsliding on the overall displacements. Otherwise, the creeping rate would be rather irregular. We also found that the two creep meters moved in a complementary manner: the lower creep meter CHIH001 moved steadily during the wet season; the upper CHIH002 crept rapidly during the dry season considering the general trend. This complementary creep behavior implies that the individual slip surfaces under the two creep meters have merged downward into a main fault surface probably at a very shallow depth.

[45] One can notice that the two creep meters often moved in a curious opposing sense during the periods of abrupt pulses. While the upper creep meter CHIH002 accelerated its rate of creep with a dramatic shortening when pulses began, the lower creep meter CHIH001 remained dormant or even moved by lengthening (Figure 13). Whenever the upper creep meter exhibited a subsequent small amount of rapid lengthening, the lower creep meter revealed, in contrast, a slight shortening during the same period. We speculate that these opposing motions between the upper and lower creep meters might be partly due to the rotation of the shared pier, which connects the two creep meters. We observed lately that this connected shared pier had indeed tilted slightly toward the uphill direction for slightly less than half a degree after more than 3 years of installation. Geometrically, the tilt of the middle connected pier would yield opposing motions on the two creep meters with a larger displacement on the upper creep meter and a smaller displacement on the lower creep meter, by supposing that the slip surface occurred on the base of the pier or below it. We thus infer that there exists a slip surface, fault, or landslide, along or near the base of the

middle pier. An intriguing point, which can be inferred from the plots of the creep data is that a relatively larger tilt toward uphill occurred first, followed by an opposing-sense smaller tilt toward downhill. We tend to interpret this forward-and-backward tilt of the pier as a balance of mechanics within the whole system of the connected creep meters.

[46] The tilt of the middle pier is not the only possible cause, though it might be the major one, for the abrupt pulses. Landsliding, for example, under CHIH002 could produce pulses. A dilation of abundant clay minerals in the fault zone during the period of high water content could also possibly produce the effect of pulses. As discussed above, the overall creep behavior and shortening amount suggest that the tectonic fault motion played a significant role, and the local landslide played a limited but not ignorable role. Thus we consider the series of abrupt pulses of displacements to be a result of a combination of tectonic fault surface creep and local gravitational landslide. The landslide was restricted mainly to the upper part of the creep meter, based on the creep behavior of the lower creep meter. The lower creep meter CHIH001 revealed a steady creep in the wet season and quiescence in the dry season. This suggests that the contribution of landslide on the lower creep meter was very limited. In the curve of the summed creep data (Figure 10c), jumps on shortening amount can be observed during the pulses of displacement, compared to the general trend of the creep rate. We interpret these jumps of shortening, ranging from 1 to 3 mm, as the amount of shortening caused mainly by landsliding.

[47] We have also plotted the creep curves of the two creep meters at Tapo together with the daily precipitation (Figure 13). The series of abrupt pulses of displacement, which occurred generally after a few months of quiescence, started annually in the dry/wet transition. Considering the rainfall data, it seems that a moderate amount of rain is enough to induce movement of rapid creep near creep meter CHIH002. For instance, a major pulse began soon after a 22-mm-rainfall on 21 May 2000, and a similar pulse occurred after a 17-mm-rainfall on 27 January 2001 (Figure 13). Open fissures located adjacent to the CHIH002 on the clayey hillslope could effectively bring the rain into the ground and enhance the prompt response of the surface creep in the upper creep meter.

[48] Further detailed investigation is required, including borehole analyses and measurements, in order to define the fault strands and landslide surfaces, to quantitatively characterize the fault motion and landsliding, and to understand their behaviors and their responses to the rainfall or groundwater. However, this is beyond the scope of the present paper.

8.4. Surface Creep Locking Depth and Subsurface Seismicity

[49] Several clues indicate that the creep motion took place only at very shallow crustal level on the Chihshang Fault. First, an elastic half-space dislocation model based on the 1983–1988 cross-valley trilateration networks has yielded a rather shallow locking depth of 1.5 km for the Longitudinal Valley Fault in the middle part of the valley near Yuli [Yu et al., 1990]. In addition, as discussed above, the surface creep on the creep meters responded promptly to the rainfall near the end of the dry season. Moderate rainfall seemed to trigger

creeping in only a few days. This implies that the creep zone is probably shallow. As a consequence, we consider the seasonally varying surface creep of the Chihshang Fault to be a fault motion confined to a shallow crustal level and maybe above the water table. However, the creep meter data do not offer much insight into the depth of creep. The locking depth of the surface seasonal creep of the Chihshang Fault could not be precisely defined until further investigations, such as strainmeter measurement and dense geodetic networks including GPS measurements across the fault zone, are carried out.

[50] Figure 14 shows the seismicity recorded by Central Weather Bureau (CWB) seismic network from 1998 to 2001, which coincides with the observation period of the creep meter. This map reveals a cluster of seismicity with focal depths in the range 10–25 km close to the eastern side of the Chihshang Fault. To first approximation, this cluster of seismicity corresponds to the earthquake activity on the Chihshang Fault, as shown by both the location of the seismicity and the geometry of the fault, although the uncertainty of location ranges between 1 and 5 km in depth. The cluster falls on an east-dipping curved surface, with dense seismicity from 12 to 22 km in depth (Figure 14b). The upward extension of this seismogenic feature closely coincides with the surface location of the Chihshang Fault. This fault patch exhibits a listric geometric surface with an eastward inclination of $60°–65°$ in the upper 10 km, which decreases gradually to about $45°$ around 15-km depth and becomes nearly flat at about $10°$ at 20–25 km in depth. Two moderate earthquake sequences of magnitude 5 occurred on this fault patch in 1992 and 1995. The 1992 earthquake sequence, with $M = 5.2$ main shock and numerous aftershocks, took place 3–10 km northeast of Chihshang. The 1995 earthquake sequence, with $M = 5.4$ main shock and aftershocks, occurred 2–15 km east of Chihshang. A recent study with detailed relocation [Chen and Rau, 2002] indicated that these two earthquake sequences reveal very similar listric fault geometry and more concentrated clusters on the fault (Figure 14c), compared with the seismic cluster of 1998–2001.

[51] Between 1998 and 2001, the Chihshang Fault zone experienced a period with steady repeated microearthquakes. No earthquake sequences of magnitude greater than 5, however, occurred. We noticed that seismic activity occurred every month throughout the year, without significant seasonal variation from 1998 to 2001 (Figure 15). An average of 20–30 recorded earthquakes occurred along the Chihshang Fault each month, with few exceptions. In other words, when the surface creep meters showed little or no fault motion during the dry seasons, microearthquakes were still occurring in the deeper part of the Chihshang Fault. With rapid creep recorded on the surface creep meters during the wet seasons, no significant increase or decrease in deeper seismic activity could be noticed. Therefore no direct correlation can be established between creep activity near the surface and seismic activity at crustal depths of 10–25 km. This discrepancy of temporal occurrence between surface creeping and subsurface seismicity on the Chihshang Fault leads to the following interpretations.

[52] The Chihshang Fault moved in a basically steady way at least during recent years; however, different behaviors took place at different depths. Repeated microearthquakes ruptured on the deep part of the fault, especially
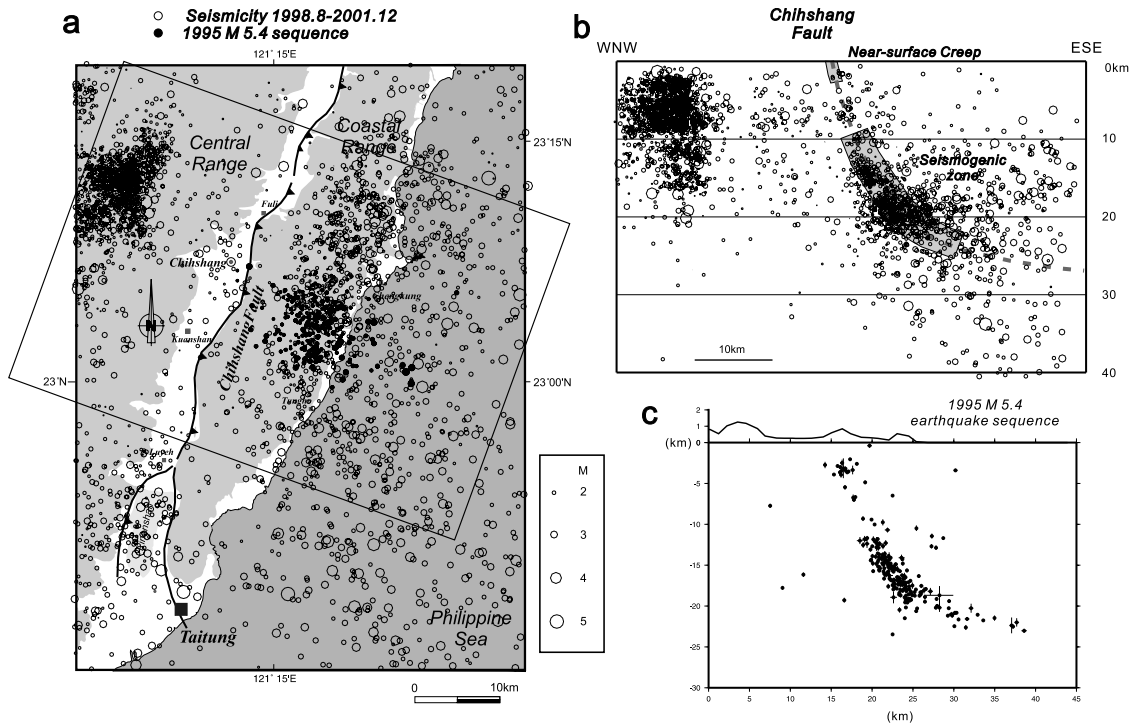
Figure 14. (a) Map of seismicity in Chihshang and the surrounding areas. Open circles designate seismicity from August 1998 to December 2001; solid circles designate the main shock and the aftershocks of the 1995 M5.4 earthquake. (b) Cross-sectional view of the 1998–2001 seismicity, showing a cluster of repeated microearthquakes occurring around the Chihshang Fault at depths of about 10–25 km. (c) Cross-sectional view of the seismicity of the 1995 M5.4 earthquake sequence. The lengths of the cross indicate the standard error of the location of the earthquakes.

around 10–25 km depths, suggesting that crustal stress was released in a rather constant manner through time at this level. The slip corresponding to these repeated microearthquakes did not propagate immediately up to the surface level; otherwise, the surface motion recorded by creep meters would not have ceased during each dry season. The stress accumulated at the upper crust levels did not reach a critical condition during the dry season and hence
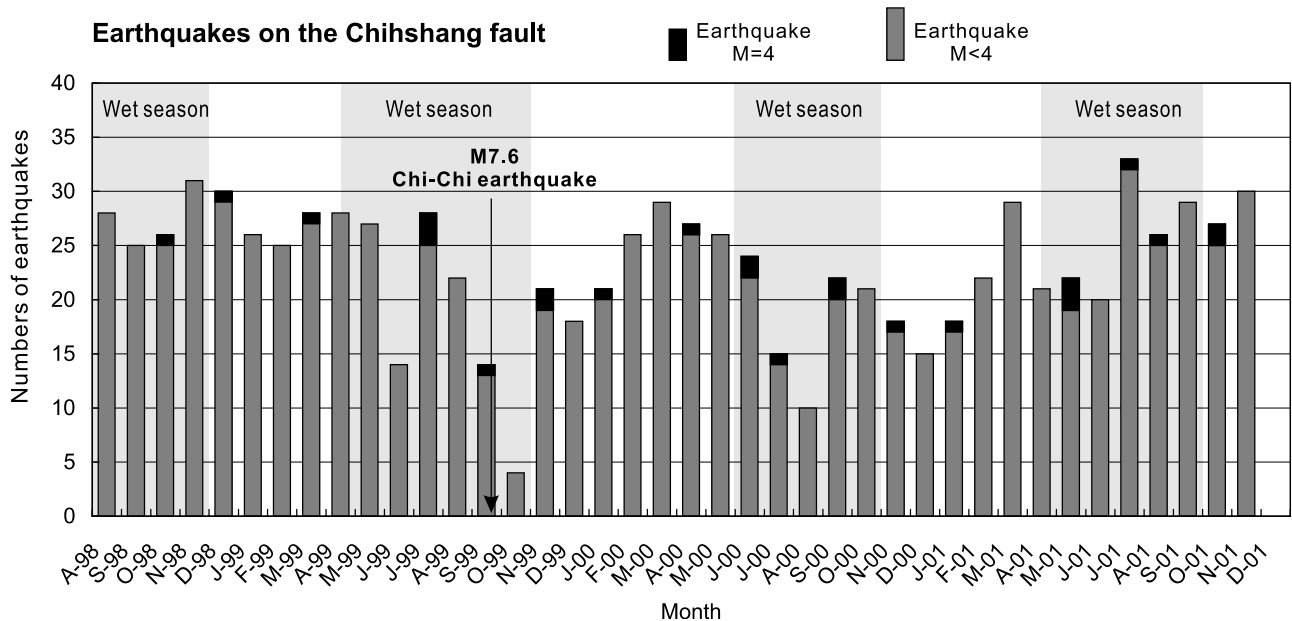

Figure 15. Numbers of earthquakes which occurred along the Chihshang Fault zone each month from August 1998 to December 2001. The seismicity remained generally steady, though slightly varied, except for 2 months quiescence after the Chi-Chi earthquake occurred on 21 September 1999.

could not induce large surface slip. The accumulated stress was largely released, if not completely, when the wet season came. We infer that the rainfall played an important role in triggering or facilitating fault creep near the surface, where the hangingwall of the Chihshang Fault is mainly composed of soft recent deposits and the mélange mudstones as indicated by local geological studies [e.g., *Page and Suppe*, 1981; *Chang et al.*, 2000].

[53] It may seem surprising that no major effect of the 21 September 1999, M_w 7.6, Chi-Chi earthquake of western Taiwan could be found in the records of the creep meters at Chihshang in eastern Taiwan. Nevertheless, the Chi-Chi earthquake did influence the seismicity of the Chihshang Fault, which experienced a period of quiescence for more than 1 month after the main shock (Figure 15). The seismicity began to return to normal rates about 2 months after the Chi-Chi earthquake. Indeed, a study of Coulomb stress change [*Hu and Ma*, 2001] indicated that the Chi-Chi earthquake has induced a minor stress relaxation in eastern Taiwan. Consequently, there has been a very slight stress drop for the Longitudinal Valley Fault, consistent with 2 months of quiescence after the Chi-Chi earthquake. The Chi-Chi earthquake was able to release a much greater amount of stress accumulated in the Taiwan mountain belt, including that accumulated in the Chihshang area. Thus no rupturing of microearthquakes occurred on the Chihshang Fault for some time after the Chi-Chi earthquake. On the other hand, this temporary quiescence in the deeper seismogenic zone did not immediately affect the surface creep zone, which still kept a steady creep near the end of wet season in 1999.

8.5. Comparison With Other Creeping Faults

[54] Seasonal, precipitation-induced variations of creep behavior have also been observed elsewhere on active faults. For instance, the creep meters at Parkfield across the San Andreas Fault recorded higher creep rates more frequently during the wet season than during the dry season [*Schulz*, 1989; *Langbein et al.*, 1990; *Roeloffs*, 2001]. *Roeloffs* [2001] showed that rainfall effects on creep are complex in that each local individual creep meter may have a unique way of responding to rain. After removing seasonal variations and the obvious heavy rainfall-induced creep, high creep rates are still more likely during the wet season than during the dry season [*Roeloffs*, 2001]. Thus seasonal variations with high creep rates during the wet season appear to be a common behavior for a reverse fault like the Longitudinal Valley Fault as well as a strike-slip fault like the San Andreas Fault. The clearly rainfall-induced seasonal variation on all creep meters in the Chihshang area (excepting those subjected to landslide-induced movements) indicates that the rainfalls certainly played an important role in affecting the creep rate of the fault, in good agreement with the regional lithology and geological condition already mentioned.

[55] Again in the San Andreas system, the Hayward Fault revealed a surface creep rate of about 5 mm/yr, that could be explained by the configuration of a creeping zone from the surface down to 5 km depth, a locked zone of 5–10 km depth, and an aseismical slip below 10 km [*Bürgmann et al.*, 1998; *Lienkaemper et al.*, 2001; *Simpson et al.*, 2001]. Using a three-dimensional (3-D) dislocation model *Simpson*

et al. [2001] suggested that varied locking depths from 4 to 12 km for the Hayward Fault could explain variations in creep rate. In contrast, the Chihshang Fault exhibits a seismogenic zone with abundant microearthquakes (10–25 km in depth) between the lower ductile aseismic slip zone and the upper surface creep zone. Despite the lack of precise data, the reverse Chihshang Fault in eastern Taiwan exhibits a shallower creeping zone (probably 1.5 km or less as mentioned above), compared to the strike-slip Hayward Fault.

[56] *Savage and Lisowski* [1993] pointed out that the surface creep rate of the Hayward Fault should be influenced by the aseismic slip at depth on the Hayward Fault and other faults in the San Francisco Bay area, although the surface creeping zone is separated by a locked region from the aseismic slip at depth. If this is correct, surface creep can serve as monitors of deformation at depth on the main fault and on other nearby faults. As for the Chihshang Fault, even though the surface creeping zone and the deep slipping zone are not connected, the long-term changes in surface creep rate might also be due to changes of slip, seismic, and aseismic, at depth. This tentative interpretation, which may well account for the apparently decreasing creep rate on the Chihshang Fault during the last few years, has obvious implications in terms of increasing earthquake hazard, and should take precedence over our forthcoming studies.

9.   Conclusions

[57] The daily data from creep meters across the Chihshang thrust fault from 1998 to 2001 has led to the following results and interpretations.

[58] 1. Two sites about 2 km apart showed different behaviors but similar annual shortening rates across the Chihshang Fault. The Tapo site revealed shortening of 17.5, 18, and 13 mm for 1999, 2000, and 2001, respectively. The Chinyuan site exhibited 17.5, 14.0, and 13.5 mm of shortening, for the same years, respectively.

[59] 2. Four of the five creep meters indicate a seasonal variation of fault creep rates, showing a close relationship with precipitation: relatively rapid shortening during the wet season and very low creep rates during the dry season. That is, most of the surface fault creep occurred during 5–6 months from April/May through October for each year. In addition, only a moderate amount of rain is enough to trigger fault surface movement during the transition period from dry to wet season in February–April.

[60] 3. Abrupt pulses of displacement on the creep meters at Tapo, particularly the upper creep meter (CHIH002), are mainly attributed to rotation of the middle connected pier, caused by fault branching and/or local gravitational landsliding. Although this unexpected effect of pier tilting at Tapo appeared to be limited, we considered the creep data at the Chinyuan site, which is located in a landslide-free flat area, as the most representative data for motion on the Chihshang Fault.

[61] 4. The average annual displacements recorded on the Chinyuan creep meters (15.0 or 16.5 mm/yr with corrections for the obliquity of creep meter and fault motion) is similar to, or slightly less than, those from the cultural feature measurements of 1986–1997, which in turn are smaller by 14–15 mm than annual displacements from the

GPS across-valley measurements of 1992–1999. We interpret this discrepancy to mean that either the fault creep rate has been significantly decreasing during the last few years or that additional shortening occurred in places other than the observed surface ruptures of the Chihshang Fault.

[62] 5. The crustal seismicity, which occurs on the Chihshang Fault zone at depths of 10–25 km, has no obvious seasonal variation. As a consequence, we conclude that the energy/strain released by earthquake ruptures in the seismogenic zone did not transfer immediately up to the surface along the Chihshang Fault and that most of the stress accumulated in the near surface was released as creep along the fault during the rainy seasons. This reveals mechanical decoupling of stress/strain release between the near-surface creeping zone and the seismogenic zone at depth.

[63] 6. Although the surface creeping zone of the Chihshang Fault and the deep slipping zone are not connected, it is possible that changes in surface creep rates might be affected by slip at depth. The decrease in the fault surface creep rate during the last few years could indicate slip deficit at depth, thus causing an increase in seismic hazard on the Chihshang Fault zone. Further investigation is thus warranted.

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