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Strain Rate Distribution in Taiwan before the 1999 Chi-Chi, Taiwan Earthquake Derived from GPS Observations

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Abstract

In order to investigate strain distribution in Taiwan before the 1999 Chi-Chi, Taiwan earthquake, displacement rate vectors estimated by GPS observations in Taiwan were used to derive the principal components of strains. Five years of data for the period from 1990 to 1995 published by Yu *et al.* (1997) were used for this purpose. We employed the Least Squares Prediction technique for the strain analysis. The results suggest that Taiwan might be categorized into four regions of different tectonic backgrounds in terms of strain distributions. I) Central to south of eastern coastal range, where arc-continent collision is predominant and seismicity is very high. II) The southwestern part of the island where strain and seismicity due to subduction of the Eurasia plate is large. III) Northeastern corner of the island where effects from the backarc rifting of the Okinawa trough is eminent and positive dilatation is predominant. And, IV) the Northwestern corner where strain rate is comparatively low. The Chi-Chi earthquake occurred at the central west of the island where these four regions merge.

Key words: Chi-Chi earthquake, Taiwan, Least Squares Prediction, Strain, GPS

1. Introduction

Taiwan is located at the WNW corner of the Philippine Sea plate (PHS). The island is under a complicated strain regime due to the arc-continental collision, subduction of the continental Eurasia (EUR), and effects of backarc rifting of Okinawa Trough (e.g. Seno, 1994. See also Fig. 1). The Philippine trench and the west Philippine trench are approaching from the south. The Eurasian plate is subducting from the west according to Davis *et al.* (1983) and Seno (1994). Although the whole area of the island may be considered as being in the plate boundary region, seismicity and other tectonic activities are mostly concentrated in the eastern coastal range and in the Longitudinal Valley, which run parallel with the coastal range. Thus the plate boundary between PHS and EUR is thought to run along these eastern area (Fig. 1).

The island of Taiwan is divided into several major geologic provinces that run mainly NS or NE-SW. Major thrust faults run along the boundaries of these provinces (e.g., Ho, 1986). The disastrous Chi-Chi, Taiwan earthquake of M=7.5 occurred on September 21, 1999, (Local time) in the central part of Taiwan. The epicenter was located about 80 km west from the seismically most active area along the coastal range, and a surface rupture was observed along the Chelungpu fault with vertical

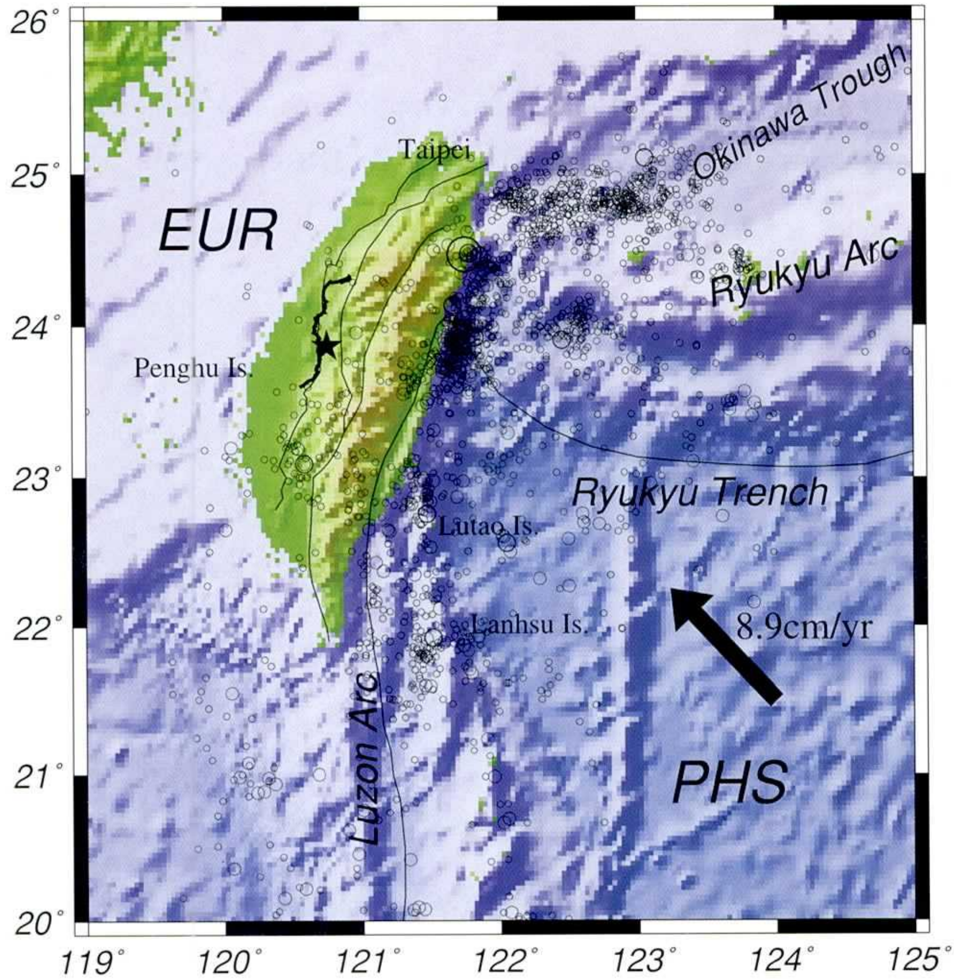

Fig. 1. Geographical map of Taiwan. Shallow earthquakes (d≦30 km) of magnitude more than 4.0 for the period from 1964/01/01–1997/01/31 are plotted according to the ISC database. The 1999 Chi-Chi, Taiwan earthquake is plotted by a star together with the observed earthquake fault shown by a thick line (after Ma *et al.*, 1999). Four major faults are also shown, which were taken from Yu *et al.* (1997). Velocity vector is taken from Kotake *et al.* (1997). EUR: Eurasia plate, PHS: Philippine Sea plate.

thrust and left lateral offsets (Ma *et al.*, 1999) (Fig. 1). In order to help understand the tectonic background of the above earthquake, GPS (the Global Positioning System) data taken from repeated surveys before the earthquake were analysed in the present study to delineate principal components of strains in Taiwan.

The Global Positioning System has rapidly developed and has been used for crustal deformation researches since around 1990 in various areas around the world. In Taiwan, GPS surveys have also been repeated since around 1990. Yu and his colleagues have published a series of papers (e.g., Yu and Chen, 1994, Yu *et al.*, 1997, Yu and Chen, 1998) concerning the displacement field of Taiwan based on GPS observations. In this paper, we use their data and applied the Least Squares Prediction (LSP) technique for strain analyses first developed by Moritz (1962) and was introduced for crustal deformation data by Fujii and Xia (1993) and El-Fiky *et al.* (1997).

2. Data

Among several publications by Yu and his group, we employed Yu *et al.* (1997), because it includes a nationwide data set as a table and data spans over five years,

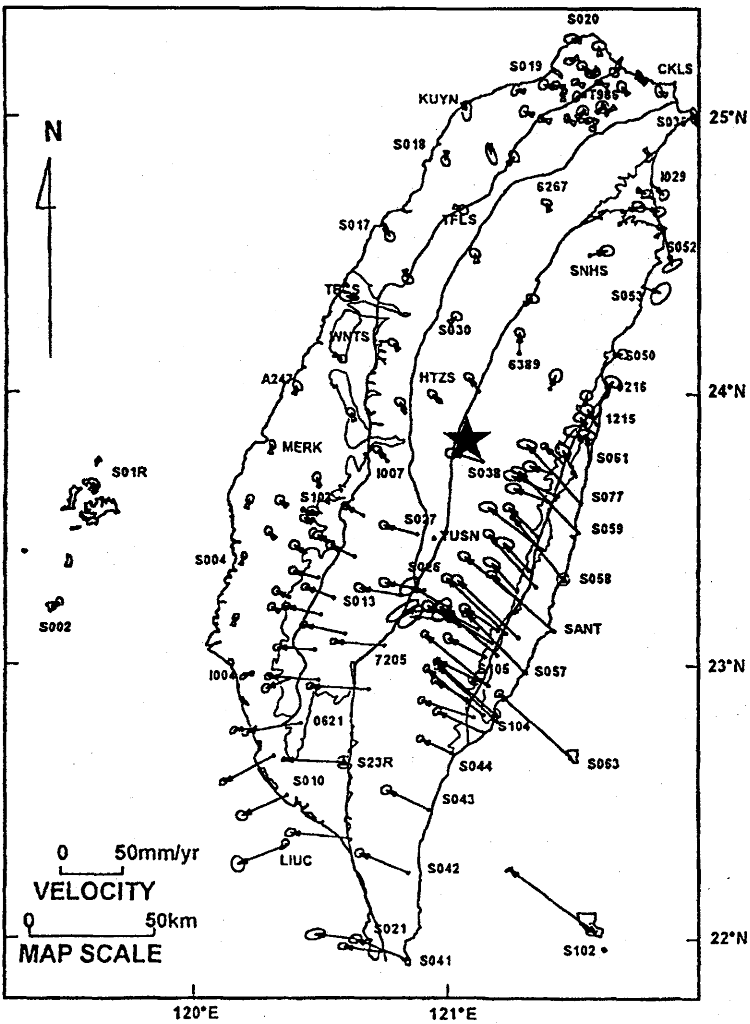

Fig. 2. Velocity vectors estimated by repeated GPS observations (1990–1995), relative to Paisha (S01R), Pheghu Islands (Yu *et al.*, 1997).

which is long enough to obtain reliable velocities at sites. According to Yu *et al.* (1997), the GPS observations had been done at approximately one-year interval between March 1990 and November 1995 using dual-frequency GPS receivers. A total of 131 stations were observed during this time period. Fig. 2 reproduces the velocity field derived from GPS observations (Yu *et al.*, 1997). The site at Paisha Island, Penghu (S 01 R) was held fixed in the analysis. As is readily seen in Fig. 2, large displacements are found in the eastern coastal range. The region is greatly affected by the arc-continent collision between PHS and EUR. The displacements decrease rapidly toward the central mountainous area, except at the southern part of the island. At the northern half of the island, on the other hand, the displacement velocities are not so large as in the south-southwestern area.

3. Analysis

We applied the Least Squares Prediction (LSP) method used by El-Fiky *et al.* (1997). The method is a corollary of the least squares collocation method introduced by Moritz (1962) for gravity data reduction. Assuming that the spatially distributed geodetic data L are given by the summation of tectonic signal S and random noise N, such that,

$$L = S + N$$

where L is assumed to be homogeneous and isotropic, and free from systematic errors. In this study L is the velocity vectors in a plane after the averaged value is pre-subtracted from the dataset. Two components (NS and EW) are treated as independent data sets, so that the cross-correlation between components is assumed to be negligible (El-Fiky *et al.*, 1997).

Then the signal and noise were segregated by assuming that noise in the data is only local in origin and the signal (tectonic deformation in this case) may have spread widely. Thus the spatial correlation of data may be a good measure to extract the signal from noise. Thus the variance-covariance analysis was conducted to obtain the so-called empirical covariance function. We chose the Gaussian covariance function, $C_l(d_k) = C_s(0)Exp(-k^2/d^2)$, from which signal S at any arbitrary point in the field is estimated by the following formula (e.g., Kato *et al.*, 1998 b);

$$S = C_{st} C_l^{-1} L$$

where the matrix C_{st} is composed of elements c_{st} ($1 \leqq s \leqq N$, $1 \leqq t \leqq P$, where P is the number of sites whose signals are to be estimated); c_{st} is given by $c_{st} = C_{us}(0)exp(-K^2_u d^2_{st})$ for EW components and $c_{st} = C_{vs}(0)exp(-K^2_v d^2_{st})$ for NS components, respectively, where d_{st} is distance between the data site and the predicted site. $C_{us}(0)$ and $C_{vs}(0)$ are the estimated variances of each component at $d=0$. K_u and K_v are the fitting parameters of the empirical covariance functions for EW and NS components, respectively. These equations were used to reconstruct velocity vectors (signal) at grid points (7 km $\times$ 7 km) all over Taiwan.

Fig. 3 (a) and (b) show the covariance plots of each component and the fitted

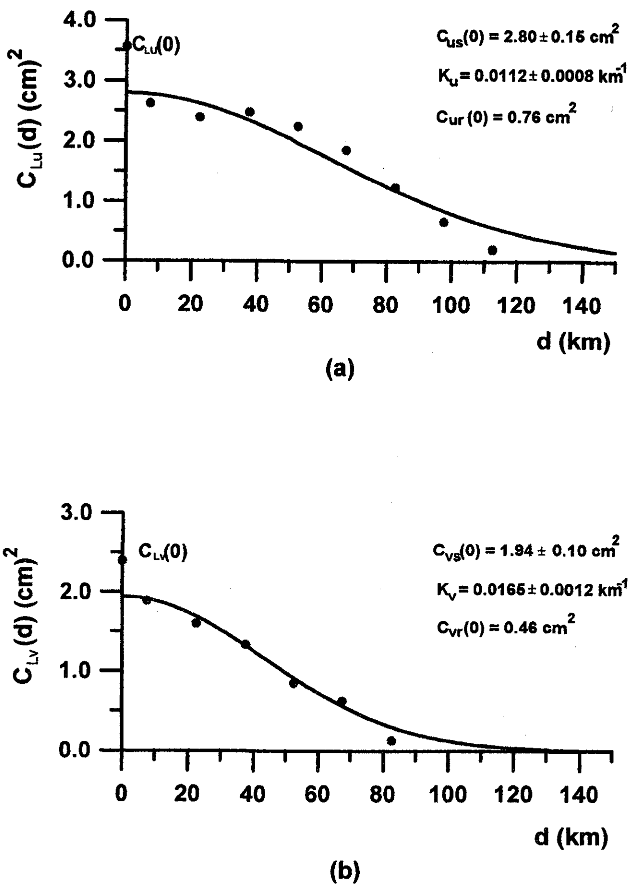

Fig. 3 Variance-covariance of velocity vectors for discrete baseline distances and fitted empirical covariance functions; (a) EW component, and (b) NS component, respectively. Estimated parameters ($C_{us}(0)$, K_u and C_{ur}) for EW component and ($C_{vs}(0)$, K_v, and $C_{vr}(0)$) for NS component for the empirical covariance functions, respectively, are shown.

empirical covariance functions. The figures indicate that the correlation reaches about 100 km for EW component while the correlation is about 80 km for NS component. These are 30 to 50 km shorter than the case of Japan (Kato *et al.*, 1998 b). This might indicate that the correlation distances of deformations (or, in other words, crustal blocks) are a little more fragmented in Taiwan compared with the Japanese islands.

Estimated velocities at grid points were then differentiated in space to obtain crustal strains during this data period, such as dilatations, maximum shear strain and principal axes of strains. Dilatations and maximum shear strains at grid points were contoured using GMT Ver. 3.0 software (Wessel and Smith, 1985), whereas the

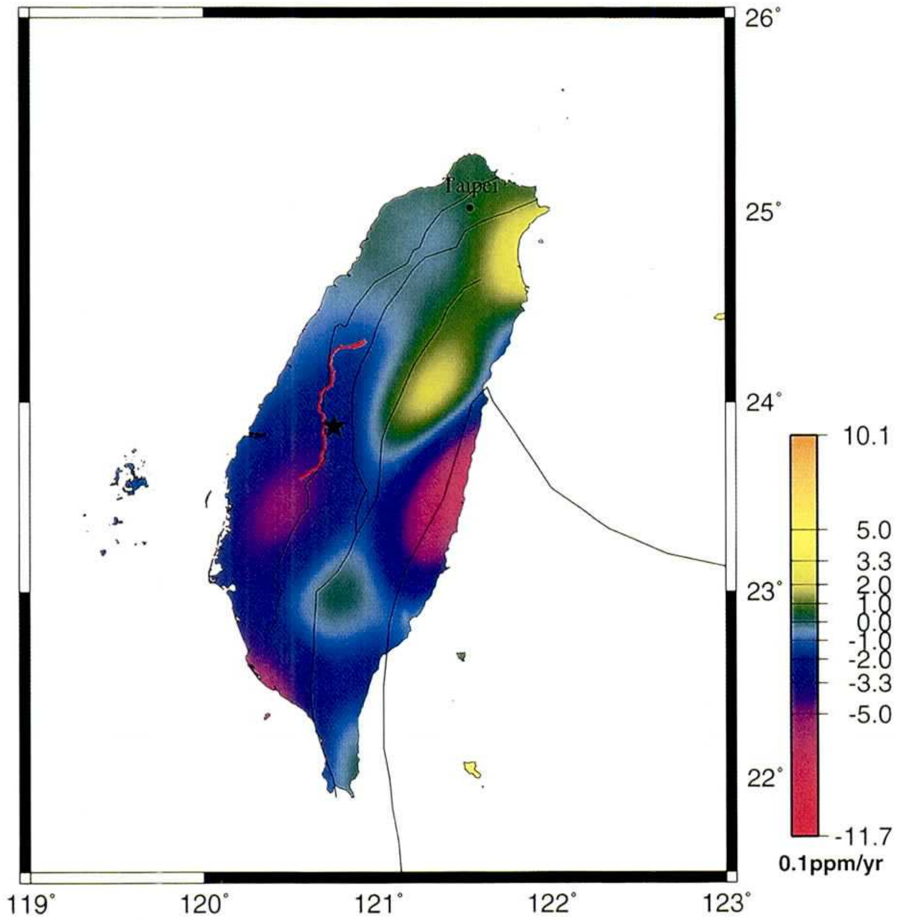

Fig. 4. Dilatations of the Taiwanese islands estimated by the Least Square Prediction method for the period 1990-1995. Major faults and the Chi-Chi, Taiwan earthquake faults are shown in black and red, respectively. The star is the epicenter of the earthquake.

principal axes were estimated at the data point and plotted by orthogonal bars using the same graphical tool.

4. Results

Figs. 4 to 6 show the results obtained of principal components of strains. Also shown in the figures are the major faults in the island. Fig. 4 shows the dilatation (or areal strain). As shown in Fig. 4, Taiwan is separated into two areas: the southern part where strong compression is predominant and the northern part where extensive areal strain prevails. The largest areal compressions reaching more than 1ppm/yr are seen along the central eastern coast where the arc-continent collision is taking place. Positive dilatation in the northern part is presumably due to the

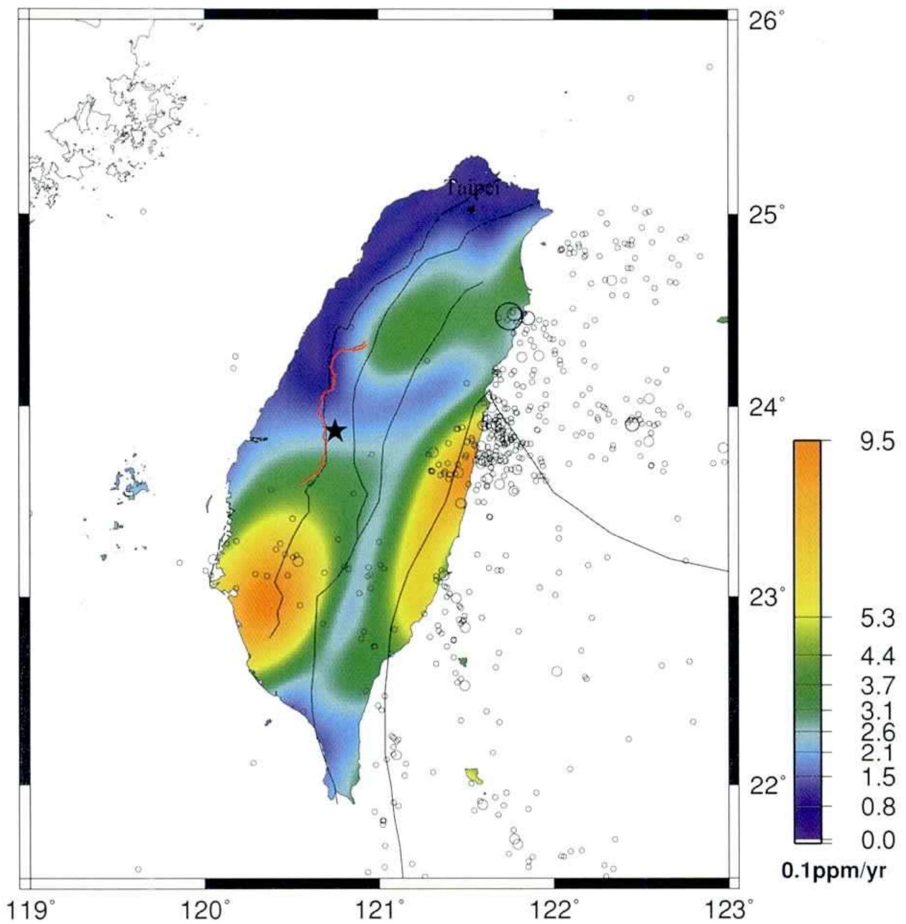

Fig. 5. Maximum shear strains of the Taiwanese islands estimated by the Least Square Prediction method for the period 1990–1995. Shallow earthquakes (d≦30 km) of magnitude greater or equal to 4.0 for the period from 1990/01/01 to 1995/12/31 are plotted (ISC database).

effects of the back-arc rifting of the Okinawa trough extending from east (Kato *et al.*, 1998 a).

Fig. 5 shows the distribution of maximum shear strain. Shear strain in Taiwan is mostly accommodated at the coastal range, which runs north to south in the eastern part of the island, and the southwestern area. Seismicity in the same time period as GPS surveys shows high consistency with high shear strain areas. The largest earthquake in this period of M7.1, however, occurred in the northeastern corner where shear strain is not very large. Large co-seismic effects of more than a few centimeters due to this earthquake cannot be seen from the time-series plots at nearby GPS sites in Yu *et al.* (1997) paper.

Finally, Fig. 6 shows the principal components of strains. As is in the Japanese

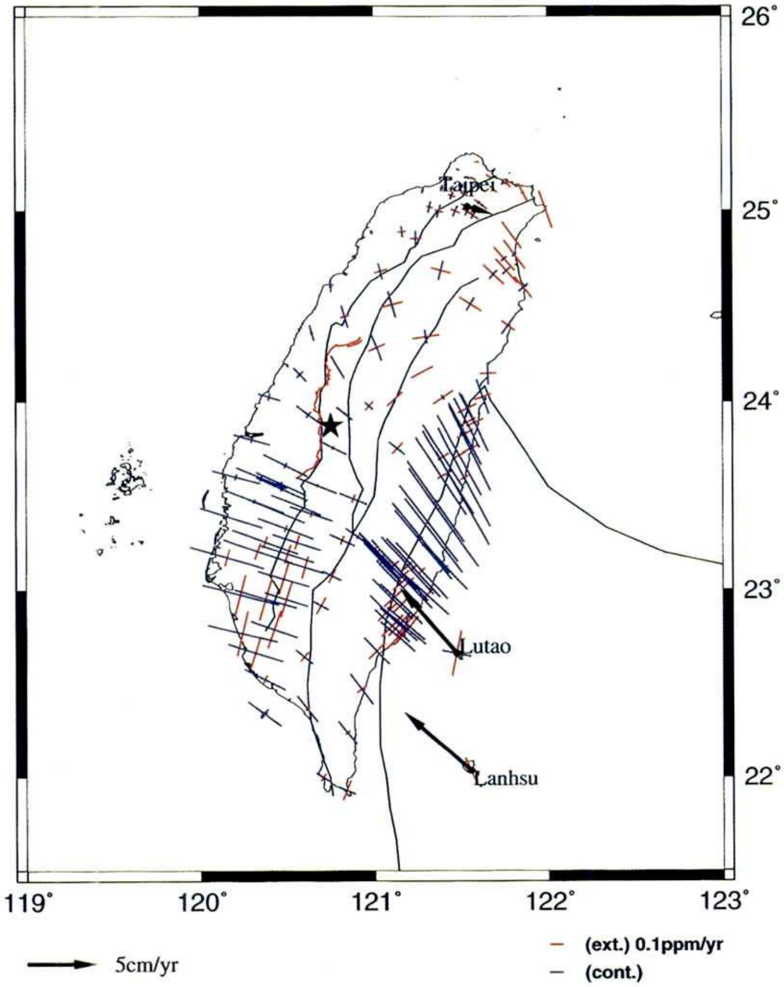

Fig. 6. Principal axes of strains of the Taiwanese islands estimated by the Least Square Prediction method for the period 1990–1995. Blue bars indicate compression and red ones are extension, respectively. Vectors are displacement rate estimated by Kotake *et al.* (1998), relative to the stable Eurasia continent.

islands, the direction of maximum compression is parallel with the direction of the converging oceanic plate. Inserted velocity vectors are those obtained by Kotake *et al.* (1998). Although their results refer to the Eurasia stable continent fixed reference frame, which is different from the Penghu fixed reference in this analysis, their difference may be small (e.g., Kato *et al.*, 1998a). Directions of compressive strain along the coastal area are mostly the same as the direction of PHS plate motion, as is seen in Lutao or Lanshu. This result strongly confirms that the large compressive strain along the eastern coast is the result of compression due to PHS. Another highly compressive area is seen at the southwestern corner of the island, where the direction of compression is rotated about 30 degrees counterclockwise to ESE-WNW. The Chi-Chi, Taiwan earthquake seems to have occurred in the north of this high strain area.

5. Discussion

Before the advent of GPS surveys, conventional geodetic surveys had been done mostly in the eastern area of the island using triangulation and distance measurements using electromagnetic distance measuring instruments (EDM). Sheu and Sato (1984) analysed the triangulation surveys from 1917 to 1979 and showed that the Coastal Range and Longitudinal Valley area is deforming at a rate of 2-3 ppm/yr, which is one order of magnitude larger than for the Japanese islands. Distance measurements using EDM at three local areas along the Coastal Range since 1981 showed a little more diverging crustal shortening from 1.2 to 8.4 ppm/yr (Yu and Lee, 1986). The present result of 0.6-0.9 ppm/yr is significantly smaller than the old results above. There may be a couple of reasons for these differences. The old triangulation results include the period of large earthquakes in the region. M 7.3 and M 7.1 earthquakes in 1951 are examples. Since the focal mechanisms of these earthquakes are thrust types in the region, deformations due to such earthquakes are in a sense accelerating the strain rate over a long time span. Large errors inherent to triangulation surveys compared with GPS may account for some of the discrepancies in velocity estimates, although their quantitative evaluation is difficult.

The strain field in Taiwan may be interpreted as converging plate boundary deformation. However, the strain rate is three to four times larger than for the Japanese islands. This may be interpreted naturally. Regional GPS results such as Kato *et al.* (1998 a) suggest that the continental rigid block is approaching very close to the west of the island of Taiwan whereas the Philippine Sea plate is colliding along the eastern coastal range. The compressive deformation is thus accommodated in the narrow island area of about 150 km in distance compared with about 300 km in Japan. Moreover, differing from Japan where oceanic plates subduct beneath the island and coupling rates changes from nearly 100% to as low as 30% (e.g. Ozawa *et al.*, 1999 ; El-Fiky and Kato, 1999, El-Fiky *et al.*, 1999), Taiwan is a field of arc-continent collision and the strain transfers are nearly 100%. This may be one of reasons why strain rate and seismic activity are so high in Taiwan.

It is interesting to note that this high strain is mostly absorbed by a narrow tectonic band in the eastern coastal range. Compared with high deformation area in the coastal area, strain in the northwestern area is mostly negligible. One possible reason for such a low strain in the northwestern area might be the high rigidity of rocks in the region relative to the deforming areas in the coastal range. However, verification of this idea needs additional data such as heat flow or velocity structure. Since the northern area of Taiwan is an area of high volcanic activity in Pleistocene and the area is the western extension of the Okinawa Trough (Fig. 1), tectonic activity is very high in the northern area. Another possibility for such a strain rate difference might come from different tectonic settings. Suppose that the Eurasian continental crust subducts from west in the western part of Taiwan, such a hard embedded material might support the upper soft crust so that the strain at the surface is small. Seno (1994) suggested, however, that there is no clear evidence of the subducting Eurasian plate beneath the northern Taiwan. Therefore, the latter possibility might not be the case. No matter what the reason is, the northwestern part of the island could be considered as part of the continental rigid block, recognizing that the displacement rate at the Taipei GPS site is not significantly different from continental China (e.g. Kato *et al.*, 1998).

The comparison of recent seismicity and the pattern of maximum shear strain in Figure 5 indicates that the high strain accumulation and its release is concentrated in the eastern coastal range and the south western part of the island. These are areas of plate interactions; the former is the plate collision between PHS and EUR, while the latter is the area of subduction of the EUR beneath the PHS. Note that the high strain in Figure 5 might include slight co-seismic effects, although they are not so significant in the strain pattern.

6. Conclusion

Displacement rate data based on GPS observations before the 1999 Chi-Chi, Taiwan earthquake were investigated to delineate background strains of Taiwan. The Least Square Prediction technique was applied for this purpose.

Summing up the results obtained, Taiwan might be categorized into four regions with different tectonic backgrounds in terms of strain distributions. I) Central to south of the eastern coastal range, where arc-continent collision is predominant and seismicity is very high. II) Southwestern part of the island where strain and seismicity due to subduction of the Eurasia plate are large. III) Northeastern corner of the island where the effects from the backarc rifting of the Okinawa trough are eminent and positive dilatation is predominant. And, IV) Northwestern corner where the strain rates are comparatively low. The Chi-Chi earthquake occurred at the central western area of the island where these four regions merge and the strain rates before the earthquake were relatively low. The generating mechanism of such an unusual earthquake may have to be examined in the future.

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1999年台湾集集地震発生前のGPS観測から得られた台湾のひずみ速度分布

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1999年台湾集集地震がどのようなひずみ場の中で発生したかを調べるため，この地震が発生する前にGPS観測によって取得されていた変位速度データを解析した．データは，Yu *et al.* (1997) によって発表された，1990年から1995年にかけて台湾内でほぼ毎年繰り返されたGPS観測による観測点の変位速度リストを用いた．このデータに我々が開発してきた最小二乗予測法を適用し，空間的になめらかな変位場を得た後，面積ひずみ，最大ずりひずみ及びひずみの主軸の，それぞれ5年間の平均的なひずみ速度を求めて図化した．その結果，台湾島内がひずみ速度分布から見て以下の4つの地域に分けられることが見て取れた；I）東部沿岸地域の中央から南部にかけてのひずみ速度が非常に大きい地域，II）台湾南西部の，ユーラシアプレートの沈み込みによる影響と見られるひずみ速度の大きな地域，III）台湾北東部の伸張ひずみが卓越する地域，及びIV）台湾北西部のひずみ速度が比較的小さい地域．集集地震はこれら4つの領域のちょうど交わる台湾中西部で発生した．