



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Earth and Planetary Science Letters 222 (2004) 573–581

EPSL

www.elsevier.com/locate/epsl

Change of crustal gravitational potential energy in the Taiwan orogen by the Chi-Chi earthquake sequence

Shu-Kun Hsu*, Chung-Liang Lo

Institute of Geophysics, National Central University, Chung-Li 32054, Taiwan

Received 25 September 2003; received in revised form 27 February 2004; accepted 1 March 2004

Abstract

The active convergence between the northwest corner of the Philippine Sea Plate and the southeast margin of the Eurasian Plate has given rise to the Taiwan mountain-building and produced numerous earthquakes. Among the earthquakes, the 1999 Chi-Chi earthquake is the largest one recorded in the century. In this study, we examine the crustal gravitational potential energy (GPE) change in the Taiwan orogen caused by the Chi-Chi earthquake sequence, which was catalogued by the regional broadband seismometer array for a whole year. As a result, we find that the crust was going up and down randomly during the earthquake sequence, but an overall cumulative gain of the crustal GPE, $+1.82 \times 10^{16}$ J, was rapidly achieved in 1 month after the main shock. The crustal GPE was nearly still afterwards and reached $+1.90 \times 10^{16}$ J in 1 year. Spatially, although the main surface faulting has occurred in western Taiwan, the crustal GPE gain is mainly distributed in central Taiwan at the area where the existing crustal GPE is high and the existing lithospheric GPE is relatively low. The crustal GPE loss by the Chi-Chi earthquake sequence can also be observed and is generally distributed at both sides of the crustal GPE gain area. The crustal GPE gain mainly found in central Taiwan corroborates that the uplift of the Taiwan orogen is principally taking place in central Taiwan, rather than in the more hazardous western Taiwan.

© 2004 Elsevier B.V. All rights reserved.

Keywords: earthquake; gravitational potential energy; crust; Taiwan orogen

1. Introduction

Earthquakes not only release seismic-wave energy but also generate permanent deformations in the earth [1,2]. Because of the latter, earthquakes give rise to gravitational potential energy (GPE) change. The GPE change is as large as three to four orders

of magnitude greater than the released seismic-wave energy but is balanced by elastic strain energy change [2]. Coseismic, vertically static displacements even infinitesimal can induce a global GPE loss of 2TW and make the Earth more spherical and more compact [3,4]. In orogenic belts, the temporal change of the crustal GPE is associated with mountain-building or collapsing [5–7]. The magnitude of the crustal GPE change may indicate ongoing extensional or compressional tectonics [5,6].

* Corresponding author. Tel.: +886-3-4268316; fax: +886-3-4222044.

E-mail address: hsu@oc.gep.ncu.edu.tw (S.-K. Hsu).

Located on the westernmost edge of the Philippine Sea Plate, the Luzon Arc is colliding north-westwards against the Southeast Asian margin of the Eurasian Plate with a velocity of 7–8 cm/year near Taiwan [8] (Fig. 1), which provides a live example of mountain-building processes [9–15]. Because of the plate convergence, the uplift of the Taiwan mountain belt is intense and is occasionally associated with disastrous earthquakes. Among those, the September 21, 1999, Chi-Chi earthquake is the largest earthquake (M_w 7.6) of the century in Taiwan, that produced a total surface rupture of 85 km long along the east-dipping Chelungpu fault in western Taiwan [16] (Fig. 2a). Thanks to the Broadband Array in Taiwan for Seismology (BATS), the Chi-Chi earthquake sequence was well recorded for a whole year, providing important source parameters of the regional earthquakes [17,18]. Especially the radial components of the seismic moments give us a rare occasion to examine the magnitude and behaviour of the crustal GPE change due to a large earthquake sequence in the young, active orogenic belt of Taiwan.

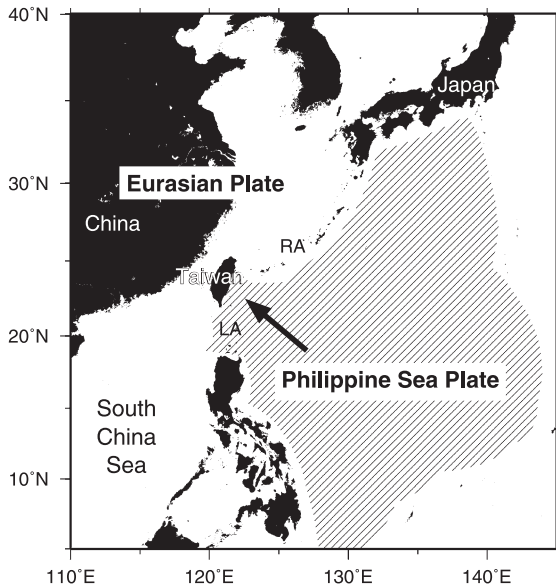


Fig. 1. Geological settings of the Taiwan orogen. The Philippine Sea Plate is converging north-westwards against the Eurasian Plate (indicated by the black arrow). RA denotes the Ryukyu Arc; LA denotes the Luzon Arc.

2. Methodology

The estimation of the coseismic crustal GPE change is achieved by the integral

$$\Delta E_c = - \int_{V_c} \rho(r)u(r)g(r)dV, \quad (1)$$

where $\rho(r)$ and $g(r)$ are the mass density and gravitational acceleration functions of radius r of the Earth, respectively; the $u(r)$ is the coseismic, radial displacement induced by an earthquake [3]. The V_c denotes the volume of the crust. To calculate the static displacement $u(r)$ and then the crustal GPE change in Eq. (1), each earthquake faulting is modelled as a point source and we consider the Earth as the PREM [19], which is a spherical, symmetric, non-rotating, elastic and isotropic earth model. The exclusion of the isotropic component from the solution in spherical harmonics analysis is achieved by the assumption that seismic moment tensors $M_{rr}+M_{\theta\theta}+M_{\phi\phi}=0$ [20]. Thus, only the radial component M_{rr} of the moment tensors is involved in the calculation of the GPE. Eq. (1) is then reduced to

$$\Delta E_c = M_{rr} \int_{Rc}^{Ra} K(r; r_s)dr, \quad (2)$$

where the Ra denotes the Earth radius, Rc denotes the bottom of the crust and

$$K(r; r_s) = 4\pi r^2 \rho(r)u_r(r; r_s)g(r) \quad (3)$$

is called the depth kernel [20]; the $u_r(r; r_s)$ is the static radial displacement due to an earthquake at source $r=r_s$. To avoid the spurious oscillation results in the calculation of the static displacement and the crustal GPE, we adopt here the direct solutions from the numerical approach proposed by Okamoto and Tani moto [20], instead of the normal mode summation approaches [3–6]. However, we replace the surface water layer of the PREM with the upper crustal material and modify the crustal thickness to 30 km, a parameter close to the average crust thickness of the Taiwan orogen. The detailed approach of the algorithm can be seen in [20]. In the case the crustal thickness is 30 km, the integrated depth kernel (i.e. $\int_{Rc}^{Ra} K(r; r_s)dr$) or a unit M_{rr} for the crustal GPE change in Eq. (2) is illustrated in Fig. 3. The neutral depth (shallower than which the integrated crustal GPE

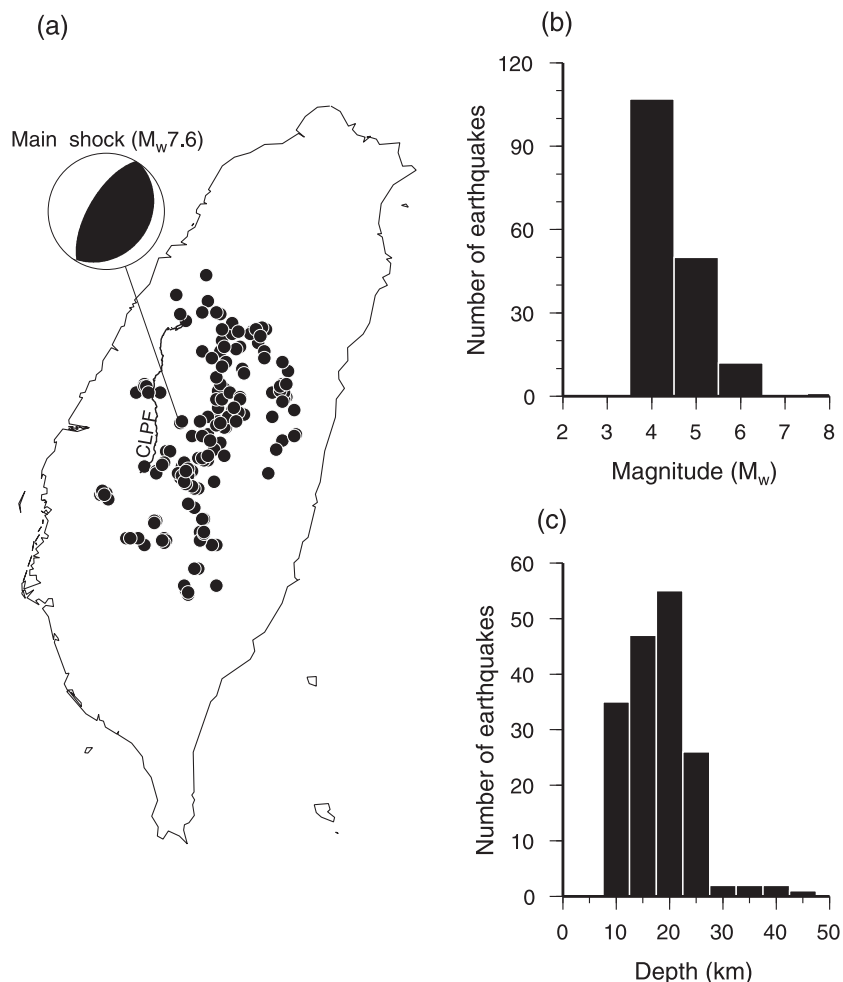


Fig. 2. (a) Epicenter distribution of the Chi-Chi earthquake sequence. Black dots indicate the locations of the earthquakes. The fault plane solution of the main shock (with compressional quadrants in black) is shown. CLPF: the Chelungpu fault. (b) Distribution of the earthquake magnitudes (M_w). (c) Distribution of the earthquake depths.

change and the radial seismic moment M_{rr} have reverse signs [20]) is at 5.46 km below the surface (Fig. 3); while it is at 4.39 km depth in the case of PREM crustal thickness (i.e. 24.4 km). Most of the earthquakes used in this study have epicenter depths deeper than the neutral depth (Fig. 2c).

3. Chi-Chi earthquake sequence and crustal GPE change

Fig. 2a shows the epicenter distribution of the main shock and the 169 major aftershocks of the Chi-Chi

earthquake sequence. The earthquakes have magnitudes (M_w) as small as 3.6 and the hypocenter depths are mostly shallower than 30 km [21] (Fig. 2b and c). However, we use here the Harvard centroid moment solutions [22] for the main shock, because its magnitude was out of the scale of the BATS instruments at that time. Besides, the focal depth of the main shock was adjusted to 8 km and the epicenter is at 23°51' N and 120°49' E according to local studies [23]. As shown in Fig. 2a, the main shock is located in the middle to west of the Taiwan island; whereas, the aftershocks are mainly distributed in central Taiwan. Moreover, the hypocenter depths of the aftershocks

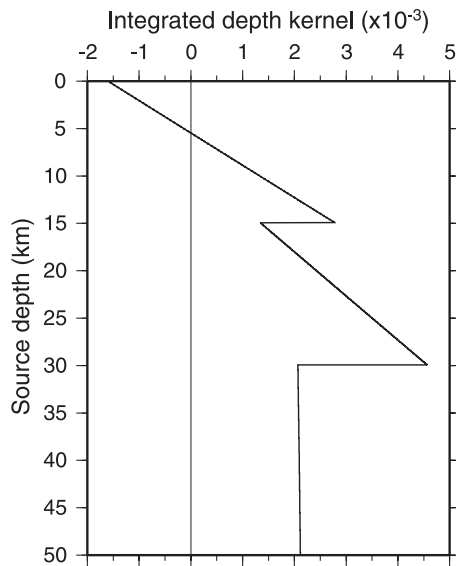


Fig. 3. Diagram showing the integrated depth kernel ($\int_{R_c}^{R_a} K(r; r_s) dr$) as a function of earthquake source depth.

are generally deeper than the 8 km depth of the main shock (Fig. 2c). It implies that the main shock could have simply triggered the release of the elastic strain energy stored beneath central Taiwan due to the plate convergence.

3.1. Temporal change of the cumulative crustal GPE

As shown by the temporal distribution of the radial components of the centroid moment tensor solutions from the catalog of BATS [17] (Fig. 4a), the crust was going up and down during the Chi-Chi earthquake sequence. It indicates that earthquakes occurring in a compressive mountain-building zone are not all thrusting in mechanism. However, the overall calculated crustal GPE change due to the Chi-Chi earthquake sequence rapidly gained and reached 1.82×10^{16} J after 1 month of the main shock (Fig. 4b). Afterward, the crustal GPE change was almost stable for the following 11 months (Fig. 4b). The increasing crustal GPE in central Taiwan as a function of time corroborates that the uplift of the present-day Taiwan orogen is actively taking place.

The uncertainty of the BATS moment tensor solutions may cause error in estimating the crustal GPE change. By examining the uncertainty estimates of the

BATS dataset [17], we can find that the major error in estimating the crustal GPE change may come from the uncertainty of the earthquake source depths. If all the focal depths of the earthquakes used are extremely underestimated, the crustal GPE change may increase to the upper dashed line in Fig. 4b. On the contrary, if all the focal depths are extremely overestimated, the crustal GPE change may decrease to the lower dashed line in Fig. 4b. Thus, the maximum error for the

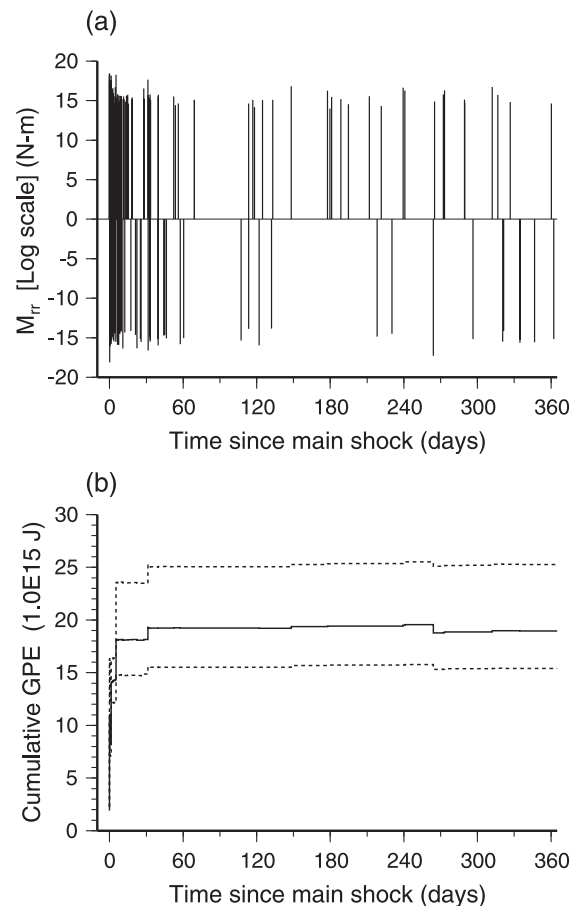


Fig. 4. (a) Distribution of the radial components of the seismic moments (M_{tr}) of the Chi-Chi earthquake sequence as a function of time. The positive values mean thrust faulting and the negative values mean normal faulting. (b) The cumulative crustal gravitational potential energy (GPE) change due to the M_{tr} shown in (a). The dashed lines indicate the maximum error in underestimating or overestimating the crustal GPE change. Note that the accumulation of the crustal GPE change is almost stable after one month of the main shock. M_{tr} : radial component of a seismic moment.

estimation of the total crustal GPE change is about 25%. However, if we consider that the focal depth errors are random within the plus and minus error bars, the estimation error of the crustal GPE change would be greatly diminish.

3.2. Spatial distribution of the crustal GPE change

To examine the spatial distribution of the crustal GPE change due to the Chi-Chi earthquake sequence, we divided the study area into 10-min by

10-min grids. The crustal GPE changes from all the earthquakes in a grid were summed. Fig. 5a and b show the maps of the cumulative crustal GPE change for 1 month and for 1 year, respectively. Except for a major gain of crustal GPE in the grid where the main shock is located, it is surprising to note that the crustal GPE gain is mainly distributed in central Taiwan, close to the western flank of the highest area of the mountain belt (Central Range) and the crustal GPE loss area borders the crustal GPE gain area (Fig. 5).

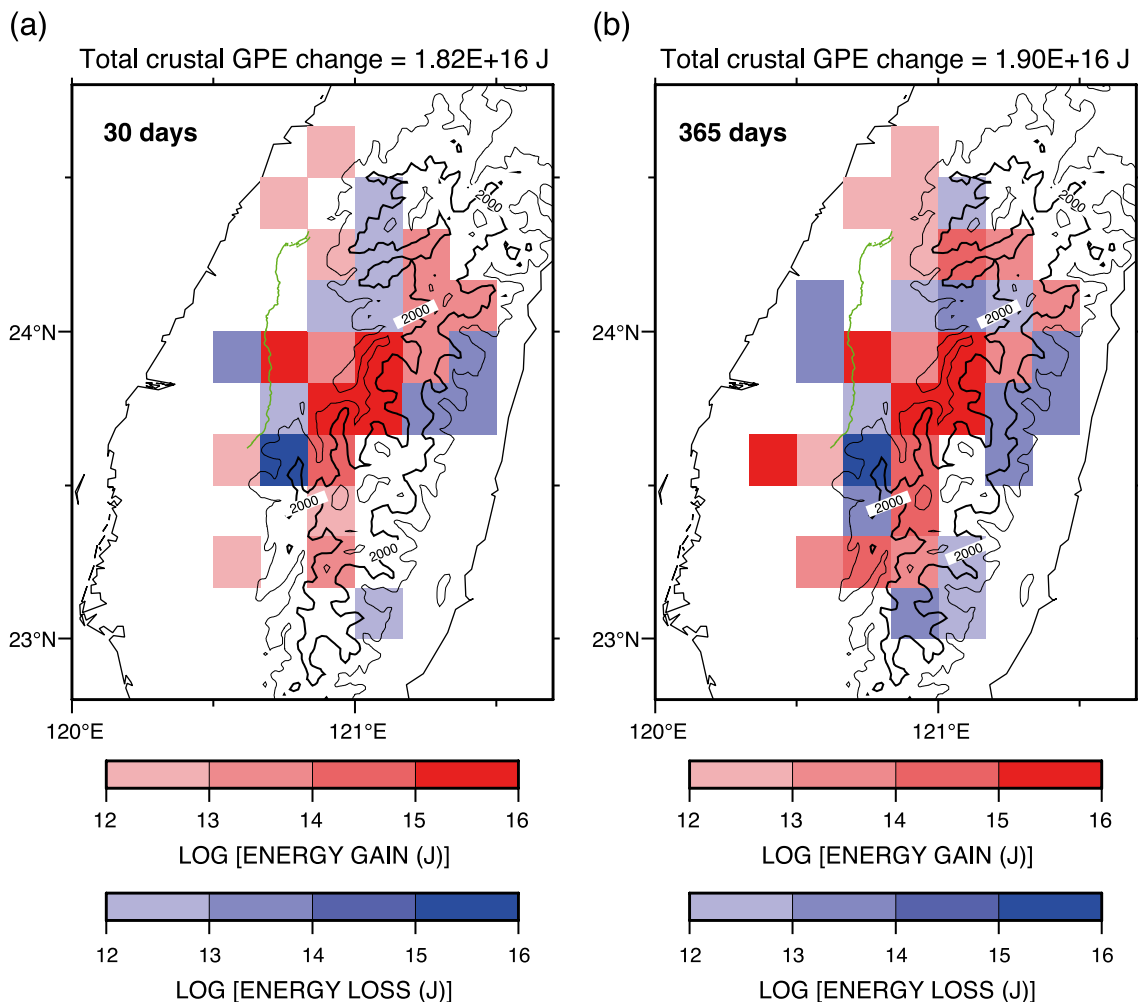


Fig. 5. (a) Spatial distribution of the crustal gravitational potential energy change in the Taiwan orogen due to the Chi-Chi earthquake sequence after 1 month and (b) after 1 year. The energy gain is mainly distributed in central Taiwan. The topography is plotted in contour interval of 1000 m for reference. The green line indicates the location of the Chelungpu fault.

By contrast, on the basis of the Global Positioning System (GPS) measurement, the major coseismic surface rupture due to the Chi-Chi earthquake occurs in western Taiwan along the east-dipping Chelungpu fault and the hanging wall is generally several meters higher than the footwall (Fig. 6) [24]. The main crustal GPE gain area seems irrelevant to the surface upthrusting area and even exhibits a little surface subsidence (Fig. 6). As shown in Fig. 6, the difference between the potential energy peak (central Taiwan) and the surface vertical displacement peak (western Taiwan) reported by the GPS observation is remarkable. This phenomenon can be explained by the relationship between the earthquake source depths and the integrated depth kernel values (Fig. 3) and indicates that earthquakes in western Taiwan generally display shallower and gentler dipping-angle character than those in central Taiwan (cf. [21]). The distribution of the crustal GPE gain in central Taiwan suggests that the uplift of the Taiwan orogenic belt is probably due to the long-term accumulation of static displacement and is mainly taking place in central Taiwan, rather than in the more hazardous western Taiwan.

4. Discussion

4.1. Existing crustal and lithospheric GPE in the Taiwan orogen

The change of crustal GPE is in fact added to the existing crustal GPE. To understand the existing crustal GPE per unit area in Taiwan, we used the tomographic P-wave velocity model of Rau and Wu [25] and converted the velocities into density structures on the basis of the Nafe–Drake curve [26] for the crust shallower than 10 km and the experimental results [27] for the crust deeper than 10 km to the Moho surface. The Moho surface in Taiwan is assumed here to be the 7.4 km/s velocity layer as inferred from the wide-angle seismic profiles across the Taiwan island [28]. Relative to an asthenospheric column whose top is at 2.4 km below sea level [7,29], the calculated crustal GPE (ΔGPE_c) is overwhelmingly positive in central Taiwan (Fig. 7a). The positive ΔGPE_c in central Taiwan reflects the high topography. Although the ΔGPE_c is positive everywhere, it displays relatively low values on both sides of the Central Range. The Chelungpu fault is located at the west relatively low ΔGPE_c zone (Fig. 7a).

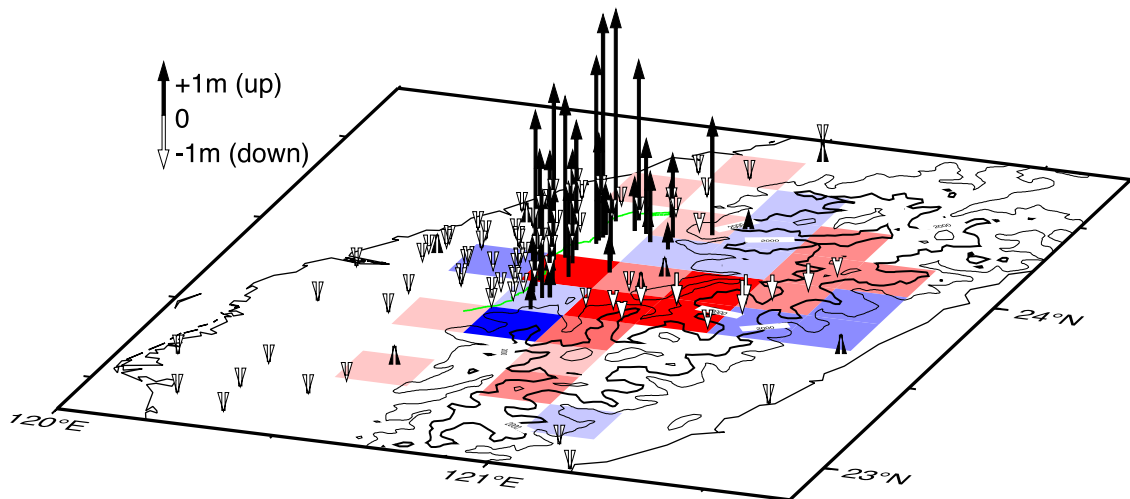


Fig. 6. Superposition of the Chi-Chi coseismic, surface vertical displacements observed by the Global Positioning System [24] on the crustal gravitational potential energy change in Fig. 5a. Black arrows indicate upward surface motions while the white arrows indicate downward surface motions. Note that the area of the crustal gravitational potential energy gain (red colors) and the area of the major upward surface displacements (close to the Chelungpu fault areas) are not consistent in spatial distribution.

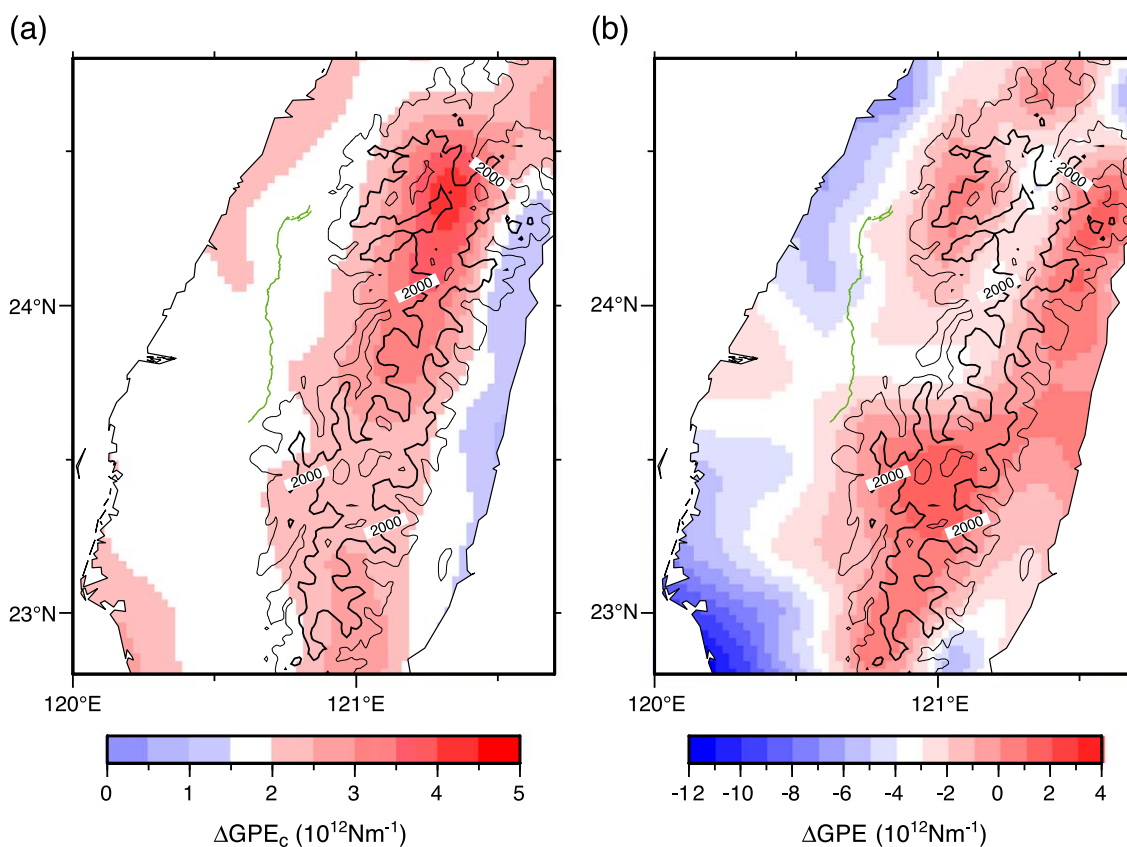


Fig. 7. Distributions of the calculated crustal (a) and lithospheric (b) gravitational potential energy in central Taiwan, relative to a reference asthenospheric column [29]. The green line indicates the location of the Chelungpu fault. See text for details.

For the mantle lithospheric part of the GPE (ΔGPE_m) in the Taiwan orogen relative to the reference asthenospheric column, we assumed a linear variation of mantle densities and a contrast density of 50 kg/m^3 between the average mantle lithosphere density and the asthenosphere [7,29]. Combining the crustal and mantle lithospheric parts, the calculated lithospheric GPE (ΔGPE) is obtained (Fig. 7b). A continental column in isostatic assumption but with greater GPE (positive ΔGPE) should be in a state of higher horizontal deviatoric tension, and a column with lower GPE means less horizontal deviatoric tension [7]. Because most earthquakes in central Taiwan show thrust faulting [18,30], a regional compressive field across the Taiwan orogenic belt can be assumed. Therefore, the lower ΔGPE zone in western Taiwan (Fig. 7b) should have a relatively larger net compression. It can explain why the Chi-Chi earth-

quake sequence took place there in first place. It is also noted that except for the main shock area, the main crustal GPE gain areas caused by the Chi-Chi earthquake sequence generally coincide with the ΔGPE_c high but with relatively ΔGPE low areas in central Taiwan where the horizontal deviatoric stress is supposed to be relatively greater (cf. Figs. 5 and 7).

4.2. Isostasy and GPE

Although the positive ΔGPE appears in most of central Taiwan (Fig. 7b), it does not exhibit tension but compression as evidenced by earthquake focal mechanisms [30]. It indicates that the central Taiwan orogenic belt is not in isostatic balance. In the light of the Chi-Chi earthquake sequence analysis, it also shows that the total crustal GPE in central Taiwan is increasing. Hence, the intrinsic (buoyancy) forces of

central Taiwan are probably less than the externally compressive forces from the convergence of the Luzon Arc (and the Philippine Sea Plate). It can be inferred that after the external forces disappear, the intrinsic deformation would emerge. It provides a simple mechanism for the current post-collision extension in northeastern Taiwan and its adjacent westernmost Okinawa Trough [31,32]. Accordingly, the state of temporal change of the crustal GPE and the present-day Δ GPE seem to be a good pair for indicating the state of the continental isostasy. That is, for an isostatic continental lithosphere the Δ GPE and the temporal change of the crustal GPE should have reversal patterns.

5. Conclusion

We have examined the temporal and spatial change of the crustal GPE caused by the 1999 Chi-Chi earthquake sequence in the active orogenic belt of Taiwan. The overall cumulative crustal GPE change has rapidly and mostly gained in the first month after the main shock. Then, the crustal GPE change was almost still. Spatially, although the major surface rupture occurred in western Taiwan, the gain of the crustal GPE due to the Chi-Chi earthquake sequence is mainly distributed in central Taiwan. The loss of the crustal GPE has also taken place and generally bordered the major crustal GPE gain area. The crustal GPE gain area, in fact, coincides with the existing crustal GPE high, which is along the Central Range of Taiwan. It is consistent with the fact that the uplift of the Taiwan orogen mainly occurs in central Taiwan. Moreover, the crustal GPE gain area due to the Chi-Chi earthquake sequence is generally distributed in a relatively low area of the existing lithospheric GPE (Δ GPE), at which the horizontally deviatoric compression is intrinsically greater.

Acknowledgements

We are grateful to L.-Y. Chiao and B.F. Chao for their fruitful discussions. W.-T. Liang helped prepare the BATS data. Comments from Honn Kao and one anonymous reviewer significantly improved the manuscript. The figures were prepared with the

GMT software [33]. This study was under the grant of National Science Council, Taiwan, R.O.C. [KF]

References

- [1] H. Kanamori, The energy release in great earthquakes, *J. Geophys. Res.* 82 (1977) 2981–2987.
- [2] F.A. Dahlen, The balance of energy in earthquake faulting, *Geophys. J. R. Astron. Soc.* 48 (1977) 239–261.
- [3] B.F. Chao, R.S. Gross, D.-N. Dong, Changes in global gravitational energy induced by earthquakes, *Geophys. J. Int.* 122 (1995) 784–789.
- [4] B.F. Chao, R.S. Gross, Changes in the earth's rotation and low-degree gravitational field induced by earthquakes, *Geophys. J. R. Astron. Soc.* 91 (1987) 569–596.
- [5] T. Tanimoto, T. Okamoto, F. Terra, Tectonic signatures in coseismic gravitational energy change, *Geophys. J. Int.* 149 (2002) 490–498.
- [6] T. Tanimoto, T. Okamoto, Change of crustal potential energy by earthquakes: an indicator for extensional and compressional tectonics, *Geophys. Res. Lett.* 27 (2000) 2313–2316.
- [7] C.H. Jones, J.R. Unruh, L.J. Sonder, The role of gravitational potential energy in active deformation in the southwestern United States, *Nature* 381 (1996) 37–41.
- [8] S.-B. Yu, H.-Y. Chen, L.-C. Kuo, Velocity field of GPS stations in the Taiwan area, *Tectonophysics* 274 (1997) 41–59.
- [9] J. Suppe, Mechanics of mountain building and metamorphism in Taiwan, *J. Geol. Soc. China* 4 (1981) 67–89.
- [10] L.S. Teng, Late Cenozoic arc–continent collision in Taiwan, *Tectonophysics* 183 (1990) 57–76.
- [11] C.-Y. Lu, K.J. Hsu, Tectonic evolution of the Taiwan mountain belt, *Pet. Geol. Taiwan* 27 (1992) 21–46.
- [12] S.-K. Hsu, J.-C. Sibuet, Is Taiwan the result of arc–continent or arc–arc collision? *Earth Planet. Sci. Lett.* 136 (1995) 315–324.
- [13] J.-C. Sibuet, S.-K. Hsu, Geodynamics of the Taiwan arc–arc collision, *Tectonophysics* 274 (1997) 221–251.
- [14] F.T. Wu, R.-J. Rau, D. Salzberg, Taiwan orogeny: thinned or lithospheric collision? *Tectonophysics* 274 (1997) 191–220.
- [15] J.-C. Sibuet, S.-K. Hsu, How was Taiwan created? *Tectonophysics* 379 (2004) 159–181.
- [16] K.-F. Ma, C.-T. Lee, Y.-B. Tsai, The Chi-Chi, Taiwan earthquake: large surface displacements on an inland thrust fault, *Eos Trans. AGU* 80 (1999) 605–611.
- [17] H. Kao, Y.-H. Liu, W.-T. Liang, W.-P. Chen, Source parameters of regional earthquakes in Taiwan: 1999–2000 including the Chi-Chi earthquake sequence, *TAO* 13 (2002) 279–298.
- [18] H. Kao, J. Angelier, Stress tensor inversion for the Chi-Chi earthquake sequence and its implications on regional collision, *BSSA* 91 (2001) 1028–1040.
- [19] A.M. Dziewonski, D.L. Anderson, Preliminary reference earth model, *Phys. Earth Planet. Inter.* 25 (1981) 297–356.
- [20] T. Okamoto, T. Tanimoto, Crustal gravitational energy change

- caused by earthquakes in the western United States and Japan, *Earth Planet. Sci. Lett.* 195 (2002) 17–27.
- [21] H. Kao, W.-P. Chen, The Chi-Chi earthquake sequence: active, out-of-sequence thrust faulting in Taiwan, *Science* 288 (2000) 2346–2349.
- [22] A.M. Dziewonski, T.A. Chou, J.H. Woodhouse, Determination of earthquake source parameters from waveform data for studies of global and regional seismicity, *J. Geophys. Res.* 86 (1981) 2825–2852.
- [23] C.-H. Chang, Y.-M. Wu, T.-C. Shin, C.-Y. Wang, Relocation of the 1999 Chi-Chi earthquake in Taiwan, *TAO* 11 (2000) 581–590.
- [24] S.-B. Yu, et al., Preseismic deformation and coseismic displacements associated with the 1999 Chi-Chi, Taiwan, earthquake, *Bull. Seismol. Soc. Am.* 91 (2001) 995–1012.
- [25] R.-J. Rau, F.T. Wu, Tomographic imaging of lithospheric structures under Taiwan, *Earth Planet. Sci. Lett.* 133 (1995) 517–532.
- [26] J.E. Nafe, C.L. Drake, Variation with depth in shallow and deep water marine sediments of porosity, density and the velocities of compressional and shear waves, *Geophysics* 22 (1957) 523–552.
- [27] N.I. Christensen, W.D. Mooney, Seismic velocity structure and composition of the continental crust: a global view, *J. Geophys. Res.* 100 (1995) 9761–9788.
- [28] Y.-H. Yeh, R.-C. Shih, C.-H. Lin, C.-C. Liu, H.-Y. Yen, B.-S. Huang, C.-S. Liu, P.-Z. Chen, C.-S. Huang, C.-J. Wu, F.T. Wu, Onshore/offshore wide-angle deep seismic profiling in Taiwan, *TAO* 9 (1998) 301–316.
- [29] A.H. Lachenbruch, P. Morgan, Continental extension, magmatism and elevation: formal relations and rules of thumb, *Tectonophysics* 174 (1990) 39–62.
- [30] Y.-H. Yeh, E. Barrier, C.-H. Lin, J. Angelier, Stress tensor analysis in the Taiwan area from focal mechanism of earthquakes, *Tectonophysics* 200 (1991) 267–280.
- [31] J.-C. Sibuet, B. Deffontaines, S.-K. Hsu, N. Thureau, J.-P. Le Formal, C.-S. Liu, The ACT party, Okinawa Trough backarc basin: early tectonic and magnetic evolution, *J. Geophys. Res.* 103 (1998) 30245–30267.
- [32] K.-L. Wang, S.-L. Chung, C.-H. Chen, S. Ryuichi, T.F. Yang, C.-H. Chen, Post-collisional magmatism around northern Taiwan and its relation with opening of the Okinawa Trough, *Tectonophysics* 308 (1999) 363–376.
- [33] P. Wessel, W.H.F. Smith, New improved version of generic mapping tools released, *EOS Trans. Am. Geophys. Union* 79 (1998) 579.