Earthquake-induced crustal gravitational potential energy change in the Philippine area

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Abstract

The crustal gravitational potential energy change (ΔGPE) caused by earthquakes in the Philippine area from January 1976 to November 2011 was estimated in this study. The active convergence between the Philippine Sea Plate and the Sundaland–Eurasian margin is reflected by the greatest gains in GPE along the Philippine, Negros and Cotabato trenches, whereas the Manila Trench is covered by a GPE loss pattern. Although the Philippine Mobile Belt (PMB) itself is actually affected by the ongoing collision and subduction processes, almost the entire Philippine Fault Zone is dominated by GPE loss, revealing a slightly extensional environment along the fault. The time evolution of the cumulated ΔGPE for different segments along the Philippine archipelago shows distinct patterns. Due to the numerous large underthrusting events that have occurred along the Philippine Trench, the cumulated ΔGPE is regularly increasing in its most southern segment. However, in the middle segments, where the Palawan Block enters into collision with the PMB, the increase in cumulated ΔGPE is relatively small. In the most northern segment, where the North Luzon is located, a decrease of cumulated ΔGPE demonstrates that the seismic characteristic of the Manila Trench is dissimilar from other subduction systems in the world. We suggest that the collision of both the Palawan Block and the Benham Rise with the PMB promotes the rotation of the PMB and facilitates the northward escape of the northeastern Luzon, resulting in a decrease of cumulated ΔGPE in the northern Philippines.

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1. Introduction

The Philippine archipelago, is bounded by oppositely dipping subduction zones (Cardwell et al., 1980; Hamburger, 1982) and encounters multiple collisions (Karig, 1983; McCabe et al., 1985), exhibits significant seismic activity. The area is a complex geological environment, as evidenced by the earthquake focal mechanisms and geological structures that have given it diverse patterns of stress configuration, such as the co-existence of extensional, compressional and shearing systems (Rowlett and Kelleher, 1976; Bautista et al., 2001). Accommodated by several subduction and collision processes, the main stress controlling the deformation of the island has been attributed to underthrusting and shortening mechanisms (Seno and Kurita, 1978; Faure et al., 1989). Additionally, extensive strike-slip features, such as the Philippine Fault Zone (PFZ) (Allen, 1962; Karig, 1973; Lewis and Hayes, 1989; Rangin, 1991; Barrier et al., 1991; Aurelio, 2000), and small-to-large scale extensional structures, such as the Macolod Corridor (Cardwell et al., 1980; Förster et al., 1990; Pubellier et al., 2000), have been revealed by numerous geological analyses.

Previous studies have also suggested that the present geology of the archipelago is marked by the stress directions of different tectonic stages and is largely composed of reactivated pre-existing structures (Barrier et al., 1990; Pubellier et al., 1991, 2000). Therefore, the geological environment of the Philippines records not only the close interaction of the regional and local regimes but also a complex geodynamic history. Generally, seismic activity can help to disclose the present tectonic deformation; however, the distribution of focal mechanisms in the Philippines is so diverse that a broad view of stress configuration is needed to understand the ongoing global tectonic processes.

Earthquake faulting often produces a redistribution of mass. The vertical displacement induced by such a reallocation can cause changes in gravitational energy potential (ΔGPE), suggesting a transfer between the elastic strain energy and the ΔGPE of the Earth. Therefore, the estimation of ΔGPE could serve as a tool for the study of tectonic problems. Generally, the crustal ΔGPE increases in compressive areas and decreases in extensional areas (Okamoto and Tanimoto, 2002). In this study, we evaluated the crustal ΔGPE caused by earthquakes in the Philippine region over the period from January 1976 to November 2011 using the global centroid moment tensor (GCMT) catalog (http://www.globalcmt.org/CMTsearch.html). With this approach, we aim to simplify the...
geological problem and provide a broad view of the tectonic environment without any prior assumptions. We also discuss the space-time evolution of the cumulated ΔGPE with the aim of better understanding the tectonic configuration along the Philippine Archipelago.

2. Geological setting

The Philippine archipelago is characterized by two opposing subduction zones: the East Luzon Trough and the Philippine Trench to the east and the Manila–Negros–Sulu and Cotabato trenches to the west (Cardwell et al., 1980; Hamburger, 1982; Hayes and Lewis, 1984; Rangin, 1989) (Fig. 1a). Both of these subduction zones, characterized by deep bathymetry, low gravity anomaly (Hayes and Lewis, 1984) and association with moderate-to-large magnitude seismic activity, determine the extent of the Philippine Mobile Belt (PMB) (Gervasio, 1971) (Fig. 1a). On its western side, the Sunda Block is moving with respect to Eurasia with a velocity of approximately 6–10 mm/year in the northeast direction. On the eastern side, the Philippine Sea Plate is moving approximately 7–9 mm/year northwestward (Kreemer et al., 2003). The oblique convergence of the Philippine Sea Plate relative to the Sunda Block is principally absorbed by the two series of subduction systems and is accommodated by a left-lateral strike-slip fault zone, named the Philippine Fault Zone (PFZ), lying along a system extending from northern Luzon to the Molucca Sea (Allen, 1962; Barrier et al., 1991; Rangin, 1991; Aurelio, 2000). The Legaspi Lineament and the Verde Passage Fault – Sibuyan Sea Fault (SVPF) are the two large fault branches of the PFZ, which act as transfer faults that connect the main fault to the Philippine and Manila Trench, respectively (Fig. 1a). In Mindanao, the NW trending Sindangan–Cotabato–Daguma Lineament is another left-lateral fault (Yumul et al., 2009) (Fig. 1a).

Several major oceanic bathymetric highs ram the Philippines: the NW Luzon oceanic bathymetric high, the Scarborough Seamount, the Palawan Block, and the Zamboanga–Sulu Peninsula in the west and the Benham Rise in the east (Fig. 1a) (Karig, 1975; Barrier et al., 1991; Pubellier et al., 2000; Bautista et al., 2001; Yumul et al., 2008). The collision between the Palawan Block and the PMB is significant and has produced several indentation-related features, such as microblock rotation, ophiolite emplacement, and seismic gaps (McCabe et al., 1985; Jumawan et al., 1998; Ramos et al., 2005; Yumul et al., 2005; Yumul, 2007). The Zamboanga–Sulu Peninsula, located in the south of the Palawan Block, has collided with the PMB in central Mindanao, resulting in several continental, arc and ophiolite affinities (Querubin and Yumul, 2001; Sherlock et al., 2003). Another major collision event, supported by structural records (Pinet and Stephan, 1990; Ringenbach et al., 1993), gravity and GPS (Rangin et al., 1999; Galgana et al., 2007) data, occurred between the eastern border of North Luzon and the Benham Rise (Sajona et al., 1997; Lallemand et al., 1998; Bautista et al., 2001). The good fit of the shape of the western border of Benham Rise and the sharp bend of the Luzon coastline also suggest a generic relation about their collision (Bautista et al., 2001).

Fig. 1. (a) Tectonic framework of the Philippines. Earthquakes with a $M_w > 7$ from the Global CMT catalog are shown and numbered. Slashed space shows the Philippine Mobile Belt area. (b) Focal mechanisms from the GCMT catalog in the Philippines, with depth indicated by color. The black lines are the main tectonic features (Yumul et al., 2009). The bathymetry is from (Sandwell and Smith, 1997). T: Tablas; R: Romblon; S: Sibuyan; SCDL: Sindangan–Cotabato–Daguma Lineament; CVB: Central Valley Basin. The gray rectangle in the inset figure indicates our study area. EU: Eurasia Plate; PSP: Philippines Sea Plate; MSP: Molucca Sea Plate; SB: Sunda Block; SVPF: Verde Passage Fault – Sibuyan Sea Fault. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
3. Methodology and data

The earthquake-induced gravitational energy change can be calculated by

\[ \Delta GPE = - \int r \rho(r) u(r) g(r) dV \]  

(1)

where \( \rho(r) \) is the density distribution of the Earth, \( u(r) \) is the radial displacement caused by earthquakes and \( g(r) \) is gravitational acceleration (Chao et al., 1995). \( \rho(r) \) and \( g(r) \) are the functions of radius \( r \) of the earth. \( V_c \) shows the calculated volume of the crust which has been obtained by integrating globally the volume in the depth kernel based on the PREM model (Hsu and Lo, 2004).

The Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson, 1981), which assumes a spherically symmetric, non-rotating, elastic and isotropic earth model, was used to compute the normal modes. The six components of seismic moment tensor are \( M_{rr}, M_{pp}, M_{pp}, M_{pp} \) and \( M_{pp} \), where \( r \) is up, \( t \) is south, and \( p \) is east, describe the force couples acting on particular planes. Under the assumption of seismic moment tensor \( M_{rr} + M_{tt} + M_{pp} = 0 \), radial modes are the only type of moment tensors that affect the estimation of \( \Delta GPE \) (Okamoto and Tanimoto, 2002).

Therefore, Eq (1) can be reduced to

\[ \Delta GPE = M_{rr} \int r_0 \rho(r) K(r, r_0) dr \]  

(2)

where \( R_0 \) is the Earth radius, \( R_c \) is the bottom of the crust and \( M_{rr} \) is the radial component of the seismic moment tensor. \( K(r, r_0) \) is the depth kernel, and is defined as

\[ K(r, r_0) = 4\pi r^2 \rho(r) u(r, r_0) g(r) \]  

(3)

In this paper, we extracted \( M_{rr} \) from the GCMT catalog. For the calculation of \( K(r, r_0) \), we adopted the numerical approach developed by Okamoto and Tanimoto (2002), which estimates the direct solution of \( \Delta GPE \) to avoid the truncated error of a harmonic function by using a normal mode summation scheme (Chao and Gross, 1987; Chao et al., 1995; Tanimoto et al., 2002). For the sake of satisfying the assumption of the Earth as a spherical symmetrical model and simplifying the calculation, the surface water layer will be replaced by upper crustal material. The crustal thickness was modified to 35 km to model the thickened crust of the Philippine arc subduction zone (Dimalanta et al., 2002; Dimalanta and Yumul, 2004, 2006; Yumul et al., 2008). For a more detailed explanation of the algorithm, please refer to Okamoto and Tanimoto (2002). We evaluated the crustal \( \Delta GPE \) for the period from January 1976 to November 2011 using the GCMT catalog (http://www.globalcmt.org/CMTsearch.html) (Fig. 1b). In total, 1285 earthquake events were used for the estimation of \( \Delta GPE \) in our study area. The earthquakes have magnitudes \( M_w \) as small as 4.7, and the hypocenter depths are mostly shallower than 200 km (Fig. 1b).

4. Results

4.1. General features of GPE

Fig. 2a shows the distribution of the radial components of the centroid moment tensor (\( M_{rr} \)) solutions from the GCMT catalog, which are presented as the temporal variation. The denser positive \( M_{rr} \) distribution suggests a large amount of energy released by compressive earthquakes. Although there are fewer extensional events, the similar amplitudes of both the positive and negative \( M_{rr} \) suggest that the amount of \( \Delta GPE \) induced by a single extensional event could be as large as that induced by a compressive one. The \( \Delta GPE \) accumulation shows that the energy increment is the predominant change in the system (Fig. 2b). The total crustal \( \Delta GPE \) is estimated to be \( 2.70 \times 10^{18} \) J for the 34 year span, corresponding to a rate of \( 7.77 \times 10^{16} \) J/year; approximately 0.5% of the \( \Delta GPE \) was induced by the 2004 Mw 9.3 Sumatra–Andaman mainshock (Lin et al., 2012, submitted to Tectonophysics). The abrupt increases of \( \Delta GPE \) were mainly caused by earthquakes of a magnitude equal to or greater than 7.0 (events in Figs. 1a and 2b; Table 1), and most of them were shallower than 35 km. Conversely, the large decreases of \( \Delta GPE \) mainly correspond to earthquakes of a depth deeper than 150 km (e.g., No. 6 in Fig. 1a).

4.2. Spatial variation of GPE

To examine the spatial distribution of the crustal \( \Delta GPE \) in the Philippine area, we divided the study area into 0.2° by 0.2° grids. The crustal \( \Delta GPE \) from all of the earthquakes in a grid was summed. Furthermore, as the crustal thickness of the island arcs has been estimated to range from approximately 20 to 35 km (Dimalanta et al., 2002; Dimalanta and Yumul, 2004, 2006; Yumul et al., 2008), the \( \Delta GPE \) distribution may vary in depth. Using 35 km as the depth boundary, we separated all earthquakes into two depth ranges to examine this possibility.

Fig. 3a shows the spatial distribution of \( \Delta GPE \) calculated from all earthquakes over the study period. With the exception of a gap at the 11°N meridian, there is a continuous and homogeneous \( \Delta GPE \) gain pattern distributed along the Philippine Trench from approximately 5–14°N, demonstrating the active convergence along the Philippine Trench. In contrast, along the Manila subduction system, \( \Delta GPE \) gain was concentrated in three main clusters. The northernmost cluster was off the shore of northwestern Luzon, approximately 40 km landward of the trench. The second cluster was located in the southern part of the region where the Scarborough Seamount, an extinct spreading center of the South China Sea basin, enters the subduction system. The third and most southern cluster was found in the southern termination of the Manila Trench. Around these three clusters, some positive \( \Delta GPE \) was scattered occasionally along the western Luzon coast. Along other subduction systems, such as the Negros, Sulu and Cotabato trenches and East Luzon Trough, the \( \Delta GPE \) is also dominated by positive values. It is notable that some positive \( \Delta GPE \) patterns spread sporadically over the northeastern part of Luzon and the western part of the southern PFZ, including Visayas (Negros, Cebu and Bohol Islands) and Central Mindanao (Fig. 3a).

Successive negative \( \Delta GPE \) patterns exist in the vicinity of both the Philippine and the Manila subduction zones, but the patterns differ for each zone: the former pattern is on the seaward side, along the outer-rise, whereas the latter is mostly along the trench or on its landward side (Fig. 3a). Along the Cotabato trench and its northeastern prolongation, we observed a negative \( \Delta GPE \) distribution at depths greater than 35 km, which was mainly due to deep-seated earthquakes associated with a detached Moluccas slab extending underneath central Philippines (Acharya and Aggarwal, 1980; Cardwell et al., 1980; Quebral et al., 1996). Nearly all of the left-lateral strike-slip faults, including the PFZ and its branches, are characterized by \( \Delta GPE \) loss. Other negative \( \Delta GPE \) features were also present locally, such as in the Central Valley Basin, around the Pinatubo volcanic area. The most remarkable negative \( \Delta GPE \) feature was observed over an area of approximately 200 × 150 km², extending from the western Mindoro, Panay and Romblon in the west to the Masbate in the east, where the continent-arc collision presently occurs.

When comparing the \( \Delta GPE \) obtained from the events shallower and deeper than 35 km, several features are notable (Fig. 3b and c): (1) most \( \Delta GPE \) gain features along the Manila subduction system are located under the forearc, at depths greater than 35 km, whereas the shallow part of the Manila subduction system is dominated by \( \Delta GPE \) loss patterns, especially in its northern portion;
(2) earthquakes that occurred along the PFZ were shallower than 35 km, with the exception of several earthquakes in the northern Luzon Island area; (3) the 11°E meridian seems to be an important boundary for earthquake distribution along the Philippine Trench. South of 11°N, numerous earthquakes occur at all depth ranges, but north of the meridian, the number of earthquakes deeper than 35 km drops dramatically.

4.3. Temporal variation of the crustal ΔGPE

The variation of earthquake activity and ΔGPE from the north to the south is obvious (Fig. 1b) and probably related to the tectonic heterogeneity. Along the western subduction systems, a gap of eastward underthrusting of the Eurasia Plate exists between approximately 10° and 13°N. A seismic gap in the eastern coast of the Philippines is also present between the northern Philippine Trench and the East Luzon Trough (approximately between 14° and 16°N). Based on these distinct geological structures and earthquake distribution patterns, we have divided the study area into four segments along trenches, and the cumulated crustal ΔGPE of each segment is estimated as a function of time (Fig. 4).

The time evolution of the cumulated ΔGPE for the four segments along the Philippine archipelago shows distinct patterns for each area. Due to the numerous large underthrusting events along the Philippine Trench, the cumulated ΔGPE regularly increases with time in the southernmost segment (Segment D). A crustal ΔGPE of 2.53 × 10¹⁸ J, approximately 93% of the total crustal ΔGPE of the entire Philippine area, is present in this segment. Moreover, the cumulated ΔGPE distribution is similar to that of the entire Philippine area, suggesting that the main crustal ΔGPE of the Philippine region occurred in this segment. In Segment C, where the Palawan Block collides with the PMB, the cumulated ΔGPE did show an increase, but the total amplitude of the increase was only 2.26 × 10¹⁷ J, approximately a tenth of that seen in Segment D. Further north, in Segment B, an even smaller ΔGPE of 1.08 × 10¹⁷ J was obtained. Finally, a surprising decrease in ΔGPE appeared in the northernmost segment (Segment A), where North Luzon Island is located. The cumulative values of ΔGPE in this segment dropped from 1.72 × 10¹⁷ to 1.00 × 10¹⁷ J.

5. Discussion

5.1. ΔGPE patterns along the subduction systems

With the exception of the Manila Trench, nearly all of the trenches around the PMB are characterized by GPE gain for all depth range. Along the Manila subduction system, GPE gain was concentrated in three main clusters, with a depth deeper than 35 km (Fig. 3). The assembly of compressive earthquakes along the Manila Trench may be related to the subduction of the extinct spreading center in its central part and the collision of the Palawan Block in its southern part. The former tectonic process may induce the large aseismic zone between 15.5°N and 18.5°N along the trench, resulted from its high temperature and/or topographic characteristics. Whereas the later may form the southern slab boundary for the Manila Trench system and earthquakes happen...
there because of sudden stress change. In any case, the influences of these two tectonic procedures are well expressed by the changes in trench morphology and seismic activity around the area.

As mentioned in the previous section that a seismic gap exists at 11°N meridian along the Philippine Trench. Several studies show that subduction of a topographic feature such as a seamount could...
lead to the segmentation of the subduction zone, which could favor aseismic creep and small earthquakes (Singh et al., 2011; Wang and Bilek, 2011). In the eastern part of the gap of 11°N, one topographic high is observed on the oceanic plate. We thus suggest that the subduction of this topographic feature may result in an aseismic environment and cause the presence of the seismic gap of 11°N.

The distribution of ΔGPE along the subduction systems demonstrates that the GPE gain released along the Philippine Trench (Segment D, 2.53 × 1018 J) is approximately 25 times that released along the Manila Trench (Segment A, 1.00 × 1017 J), suggesting a relatively weak compressive environment along the Manila Trench. This result is consistent with the low seismic activity observed along the trench (Rowlett and Kelleher, 1976; Hamburger, 1982), even if it is referred to be the principal structure that absorbed the majority of the Eurasia–Philippine Sea plate convergence (Kremer et al., 2000; Galgana et al., 2007). Based on the resolved coupling values estimated from the geodetic and focal mechanism data, the Philippine Trench has a relatively higher coupling than the Manila Trench (Galgana et al., 2007). We therefore suggest that plate convergence may occur aseismically along the Manila Trench and produce relatively low ΔGPE values. Moreover, the shallow part of the Manila subduction zone is characterized by GPE loss (Fig. 3b) and high angle normal fault sequences (Ku and Hsu, 2009), suggesting that the dominant extensional force was caused by the decoupling effect along the trench (Christensen and Ruff, 1988).

As the PMB area encounters a number of subduction and collision processes, it is expected to receive a good deal of compressive stress (Aurelio, 2000; Bautista et al., 2001). This mechanism may be illustrated by the scattered positive ΔGPE in the eastern Luzon, the Visayas (including theNegros, Cebu and Bohol Islands) and the central Mindanao. These intrablock compression regimes should be linked to the convergence between the Philippine Sea Plate and the Sundaland–Eurasian Plate. Except the Manila trench, all the other subduction zones around the PMB are coupled (Galgana et al., 2007; Yu et al., 2011), the compressive force could thus be transferred from the trenches or collision zone into the PMB area and incite compressive type earthquake activity. However, regardless of the origins of the stress, these intrablock GPE gain patterns seem to be restricted by the negative ΔGPE along the PFZ (Fig. 3b).

5.2. Extensional regimes revealed by GPE loss distribution

The most remarkable GPE loss patterns, mainly contributed by strike-slip earthquakes, are present around the area of 10–13°N, at which the Palawan Block enters the PMB. These GPE loss patterns surround not only the suture zone of the collision, including the western Mindoro, Romblon, western Panay and west of Masbate areas, but also extend to its rear, along the SVPF and the PFZ. Several previous studies have proposed that the collision between the Palawan Block and the PMB is ongoing and that the excess force could reach as far as the east of the Sibuyan Island (Faure et al., 1989; Pineda-Ofreneo, 1991; Yumul et al., 2003), affecting the PFZ (as evidenced by its abrupt bend at 13°N) (Bautista et al., 2001). The consistency of the area influenced by the collision and its negative ΔGPE distribution suggest that the lateral intrusion effect caused by the Palawan Block collision may result in GPE loss. Paleomagnetic studies and the morphology of the islands in the central Philippines reveal that these islands have rotated (McCabe et al., 1982, 1987; Yumul, 2000): northern Luzon and Mindoro rotated counterclockwise, and several islands of Central Philippines, such as Panay, Negros, Leyte and Bohol, rotated clockwise due to the collision of the Palawan Block with the PMB (McCabe et al., 1982; Yumul et al., 2003). The magnitude of the colliding force, as well as the degree of rotation, depends largely on the distance from the indenter: the nearest areas have the largest colliding force and rotated angle, and the farthest areas have the smallest angle. The discrepancy of rotation angles could generate an extensional mechanism between the areas suffering distinct collision effects (Fig. 5). Further south, in the prolongation of the Zamboanga–Sulu Peninsula, the existence of the low ΔGPE along the PFZ suggests that the collision of the Zamboanga–Sulu Peninsula and Central Mindanao may also create the same effect, inducing GPE loss events in its rear along the PFZ. However, the affected area may be too small or the intrablock rock strength too high, as we do not observe a clear GPE loss pattern between the indenter and the PFZ.

Another local negative GPE structure is observed in the Central Valley Basin, around the Pinatubo volcanic area (Fig. 3). By revising the focal mechanism distribution in this area, we found most contribution for the ΔGPE calculation coming from left-lateral strike-slip events. Closer to Mont Pinatubo, a northwest trending Iba fracture zone, sub-parallel to the Philippine Fault and possibly related to differential movement on its two sides, is suggested (de Boer et al., 1980). This Iba fracture zone could be the origin of these left-lateral events. Thus, we suggest that the stress environment in the Central Valley Basin is identical to that along the Philippine Fault system. Influenced by the rotation effect resulted from the collision between Palawan Block and PMB, these strike-slip systems process with not only left-lateral movement, but also with slightly extensional component.

The Luzon area, bounded by two subduction systems in its west and east and one continent-arc collision process in the south, should be greatly compressed, as suggested by former studies (Pinet and Stephan, 1990; Ringenbach et al., 1993). However, the cumulated ΔGPE evolution with time displays a decreasing pattern, inferring a regional extensional environment. Several previous works of this nature have been performed along some subduction systems (Ookamoto and Tanimoto, 2002; Tanimoto et al., 2002). Because of the different cell spacing used in these studies, it is difficult to do a quantitative comparison of ΔGPE. Based on ΔGPE distributions, we found that most subduction zones were characterized uniquely by GPE gain pattern along the Trench, however, in contrast, for the portion shallower than 35 km along the Manila Trench, only negative ΔGPE pattern is observed (Fig. 3). Moreover, with the discharge of compressive stress stored along the subduction systems, an increase of cumulative ΔGPE with time should be expected, such as along the Philippine Trench (Segments B–D in Fig. 4) and the Sumatra subduction system. Unexpectedly a decreasing pattern of cumulated ΔGPE is observed in the Luzon area (Segment A in Fig. 4). All these comparisons argue that the Manila subduction system process a different characteristic from other subduction systems, which should be resulted from some special geological environment.

Ringenbach et al. (1993) suggested that the PMB is necked by the Benham Rise and the Palawan Block, resulting in a V-shaped disposition of the basins in the North Luzon (Fig. 1a). Under this necking effect, the western PMB was considered to be accreted to the Eurasian margin (Barrier et al., 1991; Ringenbach et al., 1993), whereas the eastern part traveled northward along the PFZ. The slight northward escape of the northeastern Luzon block may be provoked by the left-lateral motion along the PFZ. This northward escape of crustal material may therefore create an extensional environment in the North Luzon (Pubblieri et al., 2000) and induce a decrease of ΔGPE. We suggest that the collision between the oceanic bathymetric highs (the Palawan Block and/or the Benham Rise) and the PMB significantly influences the geological environment of the Philippines. Due to the northwestern motion of the Philippine Sea Plate, the southern part of the archipelago is less affected and shows a typical ΔGPE distribution pattern for a subduction zone. However, the northern part of the
collision area is largely affected by the collision and has had its tectonic properties altered.

The 2004 great Sumatra–Andaman and the 2011 Tohoku earthquakes attract our attention on the tsunamigenic potentials along the subduction systems all around the world. The Manila subduction system, excepted by some studies to have a giant earthquake of \( M_w \approx 9 \), was identified as a high-potential earthquake zone (Kirby et al., 2006; Liu et al., 2007). In our results, a weak compressive stress state, generally considered as undertaking a low coupling mechanism, dominates the northern Philippine area. Compared to the high compressive environment characterized by numerous underthrusting events along other high seismic potential subduction systems, the probability for the occurrence of a megathrust event in the northern Philippine area should be not high. Therefore, a relatively low tsunamigenic potential along the Manila subduction zone is suggested. Even so, it should be noted that most large earthquakes happened in the northern Philippines are inland and characterized by shallow hypocenters; heavy destruction produced directly by an earthquake still should not be ignored.

6. Conclusions

To develop a broad view of the present stress configuration in the Philippines, we calculated the earthquake-induced \( \Delta \text{GPE} \) using the \( M_r \) values obtained from the focal mechanism in the GCMT catalog for the period from 1976 to 2011. The main conclusions of this study are summarized in Fig. 5. Except for the Manila Trench, all of the trench systems around the PMB (Philippine, Negros and Cotabato trench) are characterized by a continuous \( \Delta \text{GPE} \) gain pattern (light green shadows), displaying active convergent processes. Along the Manila Trench, the \( \Delta \text{GPE} \) gain distribution is grouped into three clusters, and the \( \Delta \text{GPE} \) gain obtained from these events are low related those obtained from the Philippine Trench. Three intra-block areas, the Eastern Luzon, the Visayas (including the Negros,
Cebu and Bohol Islands) and the central Mindanao, show positive ΔGPE (light blue shadows). These intrablock compressive regimes (yellow arrows) are probably linked to the convergence of the Philippine Sea Plate and the Sunda or Eurasia Plate. Remarkable GPE loss patterns, primarily contributed by strike-slip earthquakes, are present around the area of 10–13°N, at which the Palawan Block enters the PMB, as well as along nearly the entire Philippine Fault Zone, revealing a slightly extensional environment (light red shadows). The necking effect produced by the collision of the Benham Rise and the Palawan Block with the PMB (pink triangles) has rotated the islands on the western side of the PFZ between the Mindoro and Panay (black bending arrows) while also inducing the slight escape of the northeastern Luzon block (black arrow in North Luzon). These changes of relative block movements could have generated the extensional mechanisms, as shown by the yellow arrows, along the Philippine Fault Zones and the southern Mindoro. Similarly, the GPE loss observed along the southern PFZ, in the northeastern prolongation of the Zamboanga–Sulu Peninsula, could also be due to the collision of the Zamboanga–Sulu Peninsula and the Central Mindanao.

The time evolution of the cumulated ΔGPE for the four segments along the Philippine archipelago shows that the cumulated ΔGPE has been regularly increasing with time in Segment C (the most southern segment), which is consistent with the numerous large underthrusting events that have occurred along the three trenches (Philippine, Negros and Cotabato Trench). Meanwhile, the cumulated ΔGPE drops significantly northward of Segment C (about 10–13°N). The North Luzon area (Segment A) even displayed a decrease in cumulated ΔGPE, suggesting a slightly extensional environment of the Manila Trench. This sudden reduction of ΔGPE suggests that the collision between the oceanic bathymetric highs (the Palawan Block and/or the Benham Rise) and the PMB significantly influences the geological environment of the Philippines, especially in the northern region.

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