Crustal Deformation of Luzon and its Implications on the Stability of the Philippine Survey Network

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ABSTRACT

Tectonic deformation displaces the physical positions of regional or national coordinate reference system and/or survey network reference markers quite significantly when situated within fast-deforming, seismically active Plate Boundary Zone (PBZ) regions. Due to unusually high station velocities that reflect high strains near and within active PBZs, the coordinate positions of such survey reference markers need to be re-evaluated within short time spans to remain useful. Such rapid changes must be measured to assess the nature of deformation, and then construct models to accurately quantify changes and then apply proper component corrections (i.e., in-between surveys) in order to maintain the spatial integrity of geodetic networks as a function of time. To determine the effects of regional tectonic deformation on existing survey networks, we evaluate the GPS velocity field gathered from GPS stations situated in Luzon, a region sandwiched between two active, opposing subduction zones: the Manila Trench and the

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Philippine Trench. This region is traversed by numerous active faults such as the Philippine Fault System, and the (Marikina) Valley Fault System. Using GPS observations, we model the Luzon region as made up of independently rotating but interacting tectonic microplates or blocks, separated by active faults. We then quantify the individual contributions of tectonic block rotation and transient elastic locking strain to estimate the overall deformation field that affects the Philippine Survey Network from its establishment in 1992-1993 to the present. Our preferred block model results show that most stations have been affected by >1 m displacement, with a handful having ~2 m of accumulated displacement in the Sundaland reference frame from their observed initial positions in 1993. Differential inter-block motions of stations dictate that stations need to be reobserved at shorter time spans. Continuum models of residual strain rates further reveal regions of complex internal deformation that may further exacerbate the geometric instability of existing geodetic networks.

Keywords: Geodesy, Crustal Deformation, Luzon, active tectonics, geodynamics, surveying

INTRODUCTION

This study addresses a fundamental issue affecting the stability of survey networks around the globe: mobility of the crustal plates. During the last two decades, studies using GPS observations have shown that significant motions affect vast regions of the Earth, particularly Plate Boundary Zones (PBZs). PBZs are regions that are situated between stable continental plates, characterized by extensive faulting and high level of seismicity and, in many cases, pervasive deformation and volcanism (Stein and Sella 2002). The Philippines is situated in such a region (Gervasio 1967; Hamburger et al. 1982; Barrier at al. 1991; Rangin et al. 1999; Yumul et al. 2008). On August 15, 2003, a stakeholders' conference for professional geodetic engineers and the academia was held by the National Mapping and Resource Information Authority (NAMRIA), specifically to address technical issues pertaining to the upgrading of the Philippine Reference System of 1992 (PRS92). PRS 92 is the first system of 467 GPS-observed geodetic controls marked on the ground by concrete monuments distributed all over the Philippine archipelago (NAMRIA 1992; 2007). The system is primarily used as one of the main geodetic reference networks by mapping professionals and practicing land surveyors for survey controls and demarcation of cadastral property lines.

During the 2003 conference, discussions regarding errors possibly originating from numerous sources were outlined, including datum shifts introduced by changing from a local to a global reference datum, observational errors, among others. Among these possibilities, the participants conjectured that perhaps the largest source of error would be due to tectonic deformation as the Philippines is composed of mobile geologic units. This deformation issue was subsequently discussed in greater detail during the Geodetic Engineers of the Philippines (GEP)–NCR conference of December 2003 (Abad 2003; Galgana et al. 2003). Tectonic motions can change the relative ground positions of survey control points, leading to the destabilization of entire horizontal survey control networks (Pearson and Snay 2007). Thus, it was deemed necessary to quantify the amount of offset introduced by tectonic deformation in order to design an appropriate survey network and to determine the periodicity of observations required to maintain a reliable network (Snay and Pearson 2010; Lopez 2011). At present, the Philippine Geodetic Network is being upgraded by NAMRIA to conform to modern standards, which will incorporate dense GPS and leveling observations and will take into account important geodynamic effects (Cayapan et al. 2016).

Although the amount of tectonic deformation in the Philippines has been roughly quantified in several past publications (Rangin et al. 1999; Yu et al. 1999, 2013; Aurelio 2000; Beavan et al. 2001; Galgana et al. 2007; Hsu et al. 2016) more detailed studies of spatio-temporal variations that specify the contributions of rigid tectonic block motions and the elastic strains along faults and subduction zones are needed. With this information, appropriate corrections can be applied to minimize transient errors affecting the Philippine survey network. This study specifically examines the pattern of active tectonic deformation by quantifying rotation, elastic strain from fault locking and internal strain within tectonic blocks of the northern Philippine island of Luzon. From the residual strain maps, we infer the spatial extent of horizontal positional degradation.

GEOLOGIC AND TECTONIC BACKGROUND

Luzon is situated in an active tectonic deformation zone between the Manila Trench and the Philippine Trench and is traversed by prominent geologic structures such as the Philippine Fault, the (Marikina) Valley Fault System, Macolod Corridor, and the Lubang Fault or Verde Passage Fault System (Figure 1). Deformation of the crust in this region has occurred along fault systems and active magmatic features, such as active volcanoes (e.g., Mount Pinatubo and Taal Volcano), dike systems, maars (e.g., the Seven Lakes in San Pablo, Laguna), collapse craters and caldera systems (e.g., Taal Lake) (Förster et al. 1990; Oles et al. 1991; Torres et al. 1995; Yumul et al. 2008) that dot the region. Eastward subduction occurs along west-bounding Manila

Trench, as the Sundaland Plate dives underneath Luzon, opposing the westward-subducting Philippine Sea Plate underneath Luzon along the east-bounding Philippine Trench. The subduction process along the Manila Trench is devoid of historic large magnitude earthquakes, in contrast to numerous large magnitude events (i.e., $\geq$ Mw 7.0) along the Philippine Trench. Sinistral strike-slip faulting occurs along the PFZ, and this is marked by several moderate- to large-magnitude earthquakes in the past, including the most recent Mw 6.5 Leyte earthquake on July 6, 2017. Located offshore south of the study region is a nearly east-west striking Verde Passage (Lubang)-Sibuyan Sea Fault System (VPSSF in Figure 1). The NNE-SSW trending (Marikina) West Valley Fault (marked MARF) traverses SW Luzon from Bulacan, north of Metro Manila, towards the Cavite-Laguna area, south of Metro

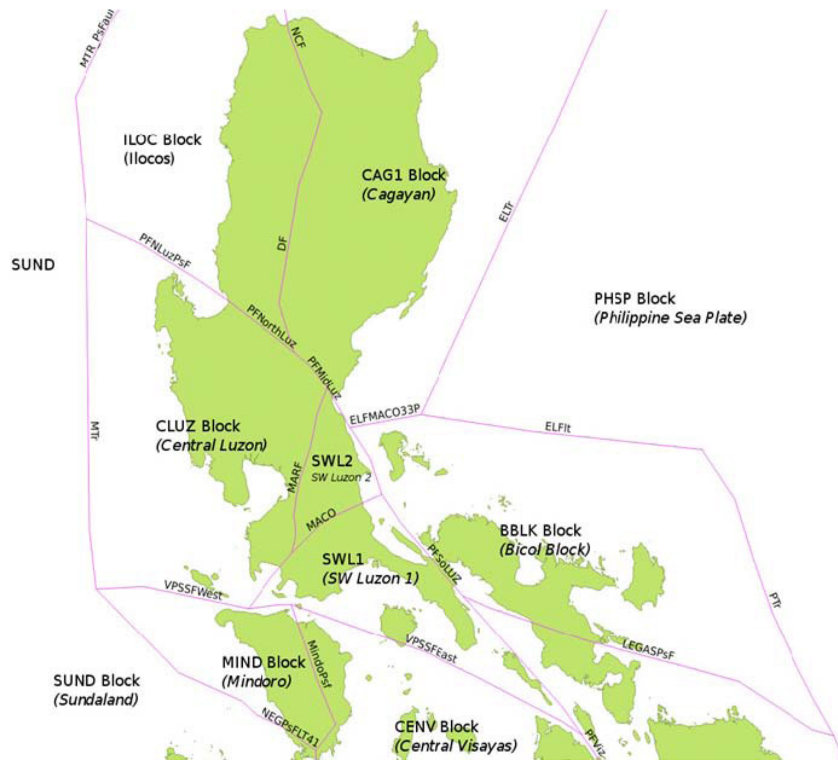

Figure 1. Map of identified tectonic block boundaries, which are generally simplified to follow major faults and tectonic structures and/or alignments of seismicity. MARF = (Marikina) West Valley Fault; MTr = Manila Trench; PTr = Philippine Trench; ELTr = East Luzon Trough; MACO = Macolod Corridor; NCF = Northern Cordillera Fault; PF = Philippine Fault (North Luzon [PFNorthLuz], Mid Luzon [PFMidLuz] and South Luzon [PFSoLuz] segments shown here); DF = Digdig Fault; VPSSF East and West = Verde Passage (Lubang)-Sibuyan Sea Fault, East and West; PsF = Pseudo Fault prefix identifier (used only as line for block boundary geometry with no modeled locking). Note that ELFMACO33P and PFNLuzPsF are Pseudofaults. MIND and CENV are not kinematically modeled and are used only as references.

Manila (Rimando and Knuepfer 2006). These active tectonic structures, which absorb the overall convergence of the Philippine Sea Plate and the Sundaland Plate, appear to significantly influence the overall deformation field of Luzon. The tectonically active nature of this region has important implications on the integrity and maintenance of ground survey markers. Periodic shifts and instabilities are expected to perturb the three-dimensional positions of such monuments.

OBSERVED DATA AND MODELING METHODS

To fully understand the deformation patterns in Luzon, we use a two-step modeling process that essentially combines the result from two major approaches: (1) the Block Modeling technique and (2) the Continuum Modeling technique (Thatcher 1995; Holt and Haines 2000; McCaffrey 2002). The Block Modeling method solves for the kinematic deformation (i.e., through block rotations and elastic strain) of a series of fault-bound plates or tectonic blocks while the Continuum Modeling approach treats the lithosphere as a continuously deforming sheet, which is very useful for areas with dense, complex or even undefined fault geometries. Block models are very useful for assessing regions where the dominant horizontal motions of semi-rigid, relatively intact plates are limited by bounding faults. Continuum models, on the other hand, are exceptionally useful in determining strain rates in areas where faults are diffuse or complex and hard to define, such as orogenic regions—or within areas where the dominant nature of deformation is non-rigid. The sequential use of these two competing methods provides a fresh and unique approach that utilizes the combined strengths of both approaches to overcome the simplifications normally employed in current block-only or continuum-only methods.

Along with seismicity and focal mechanism data, we first use geometric information from active tectonic structures (i.e., active faults, geologic lineations, ridges) to demarcate discrete regions, as input to the first modeling step, i.e., in identifying microplates or tectonic blocks that will be used as input to the block model. These blocks will form the primary elements upon which the unit calculations will be based. Note that the selection of block boundaries, while keeping true to the geologic and geophysical information, are modified by GPS data coverage, the perceived size and geometry of the resulting geodetic network and, more importantly, model stability as dictated by algorithms. The geometries of active faults were derived from published research articles and geologic maps (e.g., Förster et al. 1990; Oles et al. 1991; Pubellier et al. 2005) as well as the alignment of seismicities at depth that define the Wadati-Benioff zones, in the case of subduction zones (Hayes et al. 2012; Smoczyk et al. 2013).

To quantify deformation in Luzon, we combine the published GPS velocity field compilations of Galgana et al. (2007), Kreemer et al. (2014), and Hsu et al. (2016). In particular, the data collection reported by Kreemer et al. (2014) was sourced from earlier velocity solutions that include the contributions of Rangin et al. (1999) and Yu et al. (1999) for Southeast Asia, and Kato et al. (2003) and Nishimura (2011) for the Philippine Sea Plate area. These GPS velocities were in turn collected from separate field observations during the late 1990s and early 2000s through 2015, with Luzon datasets primarily acquired by PHIVOLCS and institutional collaborators (as reported in Galgana et al. 2007; Bacolcol et al. 2013). These datasets were rotated to conform to a common reference frame. Supplementing the GPS data are selected earthquake slip vectors in the same region, used primarily to constrain motions of oceanic plates. These slip vectors were obtained from Centroid Moment Tensor solutions derived from seismic observations that range from 1975 to 2006 (Dziewonski et al. 1981; Dziewonski and Woodhouse 1983).

To determine the plate motions and the rate of deformation along faults, we first use the block modeling approach from the tdefnode software (McCaffrey 2002). The approach utilizes the GPS velocity field and other kinematic information (i.e., earthquake slip vectors and Euler Poles) to model the behavior of tectonic blocks. The block modeling system treats the lithosphere as a series of tectonic plates or small tectonic blocks that are separated by planar faults. These blocks rotate with respect to one another, about their Euler poles. The planar faults that act as boundaries are defined based on the actual geometry of existing active faults, clusters of seismicity, and/or other geomorphological and structural boundaries. The faults are defined through three-dimensional coordinates of nodes along the fault planes, i.e., the faults are represented by a series of strike- and dip-going nodes with spacing being based on fault geometry, which include approximate locking depth and known fault dip angles. In the case of Luzon, for strike-slip faults such as the PFZ, the dip is assumed to be vertical, with the fault interface extending down to 20 km, approximating the values of average locking depth and elastic thickness for the Philippine Mobile Belt (Galgana et al. 2007).

The block modeling software that we use, tdefnode, specifically models elastic block rotations, internal strains, fault locking, and can also use other transient sources such as volcanic sources and afterslip for volcanic source and coseismic analysis (McCaffrey 2002). For this particular analysis, we only use long-term tectonic motion, with transient volcanic deformation sources and areas affected by postseismic motion removed from the datasets. Block translation and rotations are derived from the average motion of GPS stations situated within tectonic plates, while frictional locking along faults produces elastic strain along these block boundaries that counteracts the free movement of the blocks; the remaining strain, on the other hand, is treated as the spatially non-varying average internal block deformation.

The observed GPS velocity field at the surface is linked to deformation along fault surfaces at depth through Green's functions that use three-dimensional planar dislocation models (Okada 1985, 1992). To derive values of fault locking strain, the coupling fraction or the ratio of locked to total slip (φ) are either specified or estimated at the fault nodes. The slip deficit rate, a value that quantifies elastic deformation along faults, is estimated by multiplying φ with the slip vector V at the node (V on the other hand is calculated through block angular velocities). Total elastic deformation along the various faults is calculated by integrating over small fault patches (quadrilaterals) in the regions between the nodes for every fault. The rectangular dislocation method (Okada 1984, 1992) is applied to calculate surface velocities while applying backslip at a rate of $-V\varphi$ on each of the fault patches. Multiple forward models of predicted surface deformation are subsequently run using different combinations of fault locking, internal strain and block rotations, and the model with the least overall data-model residual is selected. The optimal parameters are obtained by simultaneous inversions, with the best-fit values calculated and selected by minimizing the residuals between the observed and predicted GPS velocities (McCaffrey 2002). This optimization process is operationalized using simulated annealing and/or grid search, a system that essentially solves for the best value of parameters. In summary, with mathematical inversions, optimal values of block rotation, block internal deformation rates, fault slip rates, the fault locking patterns, slip deficit and tectonic moment accumulation rates along fault and subduction zone interfaces can be obtained.

The continuum modeling process, on the other hand, uses a unique system that delineates the entire Luzon region with smaller 0.2° x 0.2° (grid composed of 22.1 x 22.3 km rectangular areas) polygonal sub-regions that are constrained by GPS velocities; the system then solves for the internal strain rates in these sub-regions. The method specifically quantifies high resolution velocity gradient tensors (spatial derivatives of horizontal velocities) to get an idea how tectonically active regions of the Earth are deforming (Haines and Holt 1993; Holt et al. 2000). The method is most effective in determining rates of strain in regions of complex and/or diffuse deformation, such as orogens and highly faulted regions, and thus can be used to quantify seismic potential (Shen-Tu et al. 1998, 1999; Kreemer et al. 2010). For this study, we use the continuum approach to calculate the residual strains within these smaller regions to get a sense of the spatial distribution of the remaining deformation, as contributed by non-modeled structures or other sources of model misfits. The results can be used as a guide in refining resurveys within smaller regions in Luzon.

RESULTS

Overall, when plotted with respect to a stable Sundaland reference plate, observed GPS velocities trend towards the WNW to NW, at about 20 mm/yr to > 90 mm/yr, indicating a predominantly convergent trend of motions between the Philippine Islands and the Sundaland plate. We obtained a best-fit model that shows a very good fit for the Luzon area (Figure 2), with predicted station velocities that trend NW to WNW at magnitudes ~30 mm/yr and higher with respect to reference plate SUND. Plots deriving predicted motions at grid points are shown with different block

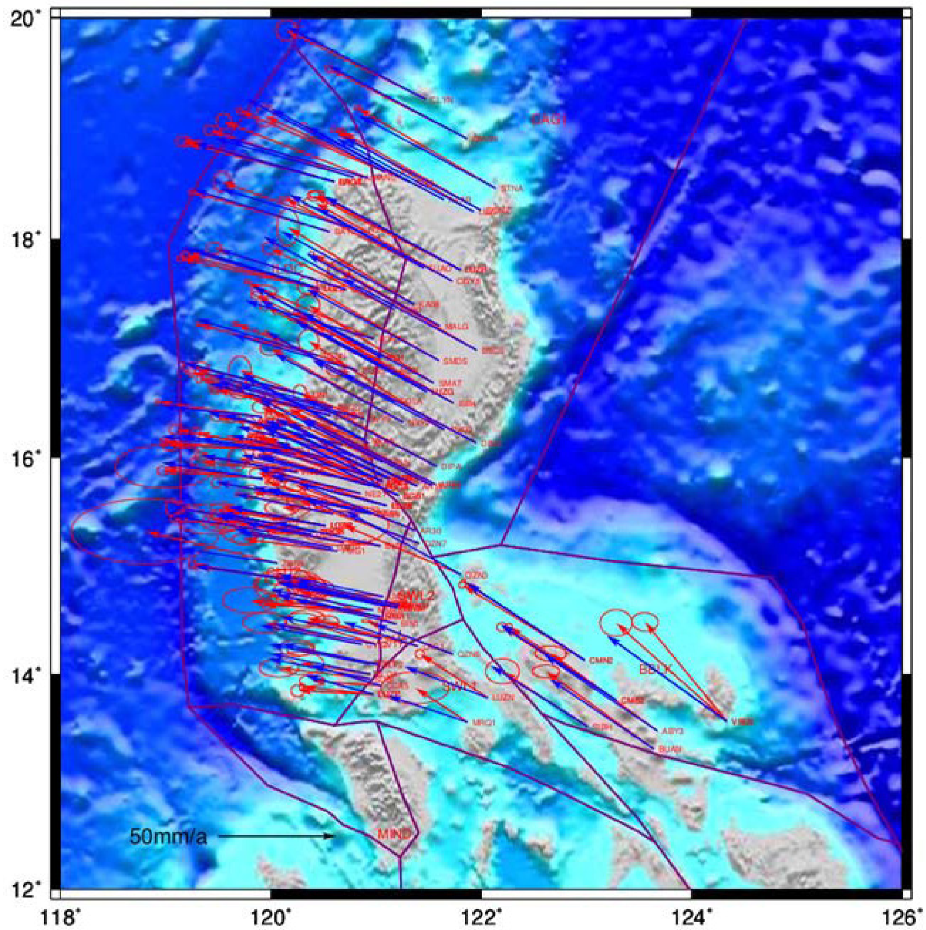

Figure 2. Best-fit block model, showing observed (red arrows with error ellipses) and predicted (blue arrows) velocity vectors in the Sundaland reference frame. The general pattern of velocities indicate rapid counter-clockwise motion of Luzon tectonic blocks with respect to Palawan (part of Sundaland Plate, situated on the left side of the map), where the velocity field increases from the south to the north (>50 mm/yr). Background colors show hillshaded topography and bathymetry: gray indicates surface topography while deeper blues indicate deeper sections of the seafloor, in contrast with lighter blues for relatively shallow areas.

motions (Figure 3) and along profile lines with significant changes in the predicted block velocities (Supplementary Figures 1 and 2). The elastic strain component of the velocity field shows considerable elastic strain near the shallow part (~10 km depth) of the Manila Trench, and along the East Luzon Trough interface (Figure 4). The elastic strain component along the PFZ on the other hand, while significantly smaller than the trenches, is also noticeable (Figure 4; Supplementary Figures 1 and 2). MARF also contributed minute elastic strain components.

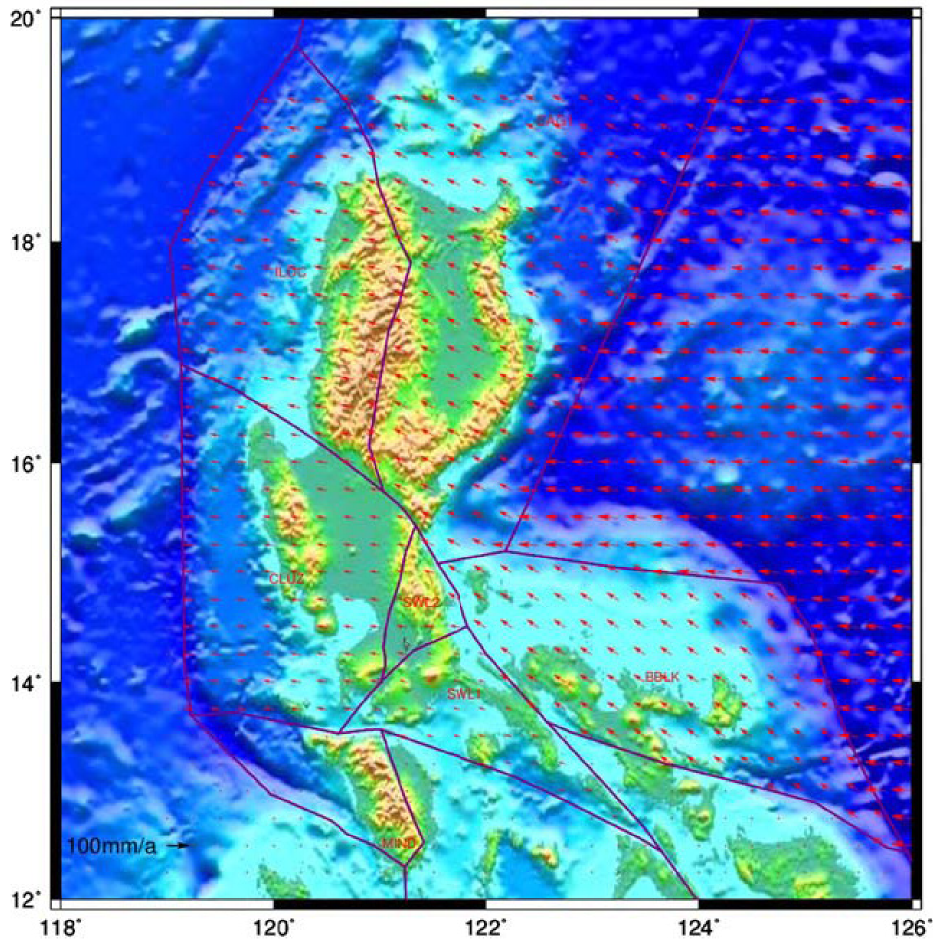

Figure 3. Total predicted (average) block velocity field (rotation) component, plotted at regular 0.2° grid intervals, with respect to Sundaland (SUND). The modeled velocity field illustrates different motions of identified tectonic blocks with respect to adjoining blocks. Background shows surface topography and bathymetry. (Deep sea regions in blue, shallow sea areas in light blue; green to yellow colors show land topography).

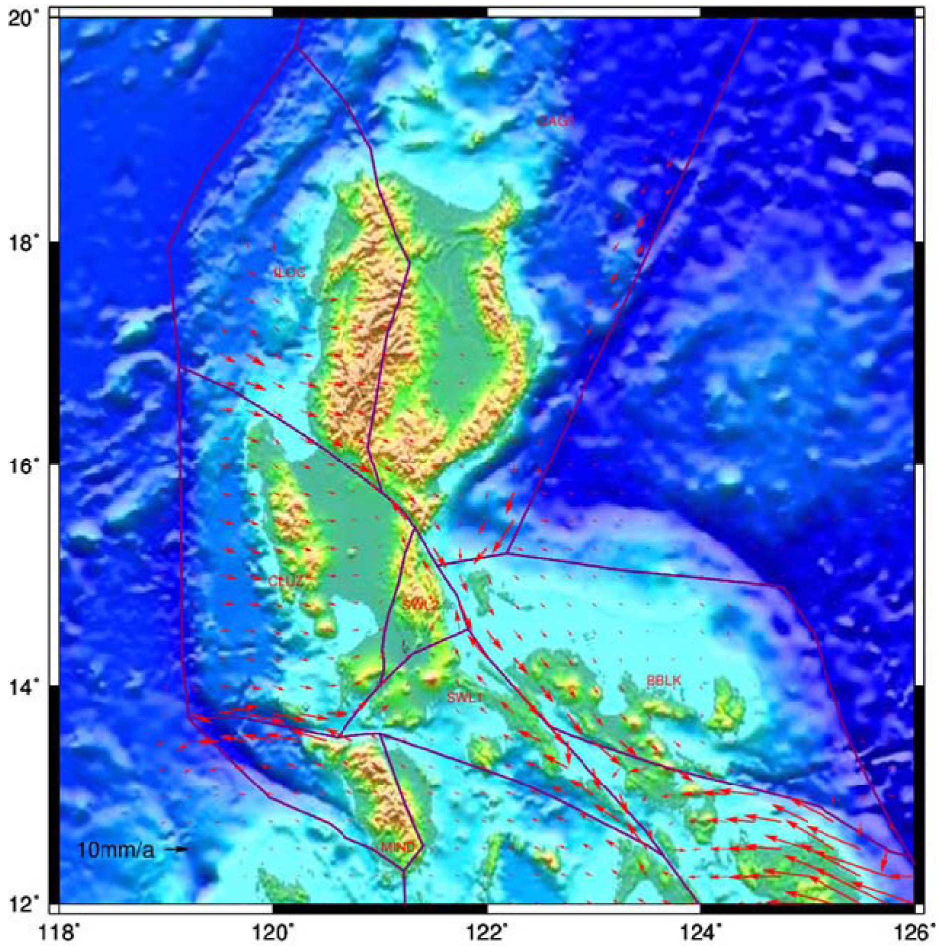

Figure 4. Plot of elastic strain accumulation rate due to fault locking (i.e., V*φ), calculated at regular 0.2° grid intervals. Note larger accumulation vectors near highly locked fault interfaces. This component of slip is due to elastic locking or resistance to motion along identified faults. Background color scheme is the same as in Figure 3.

Based on the high coupling estimates obtained from the best-fit model, elastic strain has been accumulating along the PFZ's Digdig segment in the northern part of Luzon. This implies that about 0.7-0.8 m of unreleased accumulated fault slip is stored at the Digdig segment since its rupture during the Mw 7.8 earthquake in July 16, 1990. The high coupling result in this region translates to high contribution of elastic deformation on the position of GPS stations. Thus, such regions affected by rapid deformation will require shorter period of resurveys, supporting the recommendations of Lopez (2011).

On the other hand, the calculated rate of elastic strain accumulation along MARF is estimated to be 11 mm/yr. The strains trend from N to NNW and show left-lateral strike slip motion with compression (or transpression). According to the Philippine Institute of Volcanology and Seismology (PHIVOLCS), the (Marikina) Valley Fault System was hypothesized to have last generated a Mw 7.2 event in 1658 (Nelson et al. 2000). Assuming a four-meter slip for a Mw 7.2 event (Wells and Coppersmith 1994), we infer that 3.94 meters of accumulated or unreleased fault slip has been absorbed in the system since 1658. This accumulated strain is expected to be released in a future large magnitude earthquake. Overall, the elastic deformation contribution of MARF to GPS station positions is not as significant as the Philippine Fault System scenario. Figure 2 shows the predicted velocities while Figure 5 shows the accumulated displacement per station since 1992.

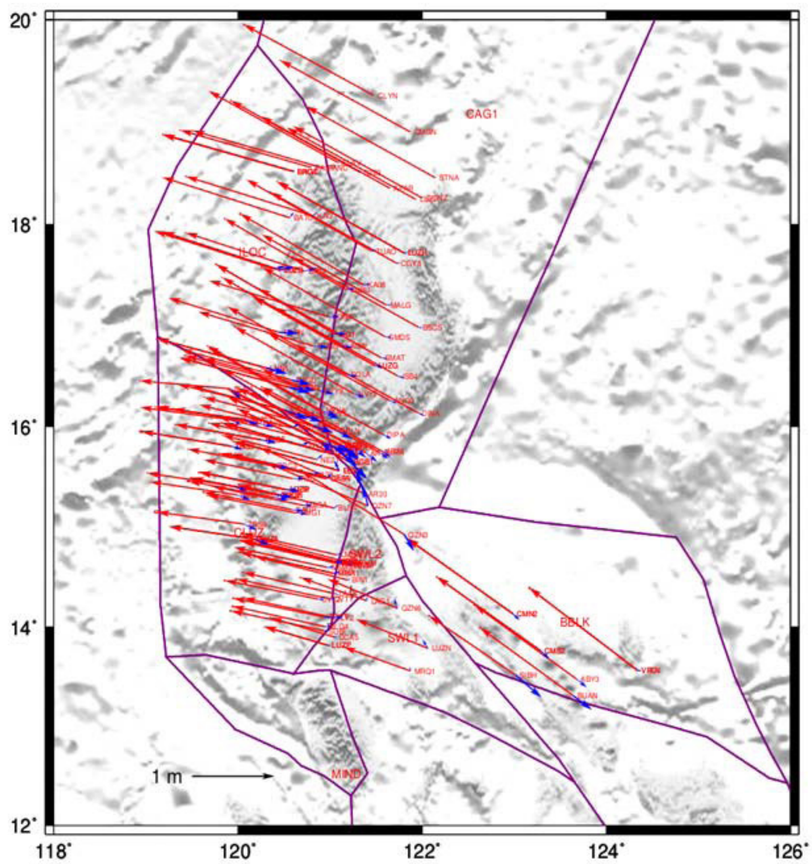

Figure 5. Accumulated Sundaland-based displacements (in meters) along station locations (red arrows), projected from 1992 to 2018; displacements reach values greater than 1 m, with northern stations displaced more than 1.5 m. Motion-resisting elastic strain component per station of the total displacements due to fault locking are represented by smaller blue vectors. Grayscale background shows hillshaded surface topography and bathymetry.

Although low coupling is predominant along the western Luzon subduction interface, the Manila Trench segment underneath Bolinao peninsula appears to be continuously storing elastic energy, which may lead to a potential megathrust seismic release (see Yu et al. 2013; Wang and Bilek 2014; Hsu et al. 2016). This strong locking is due to the high-frictional contact produced by asperities in the form of subducting seamounts along the western coast of Luzon (Hsu et al. 2012, 2016). According to these recent studies, the seamounts prevent the smooth subduction of the South China Sea crust underneath Luzon along the Manila Trench, thus acting as a strain or elastic energy absorber. On the other hand, locking along the southern bend near Mindoro is unresolved due to the absence of GPS stations in the inversions; however, the locking there is inferred to be high, due to the low velocities and the nature of the Palawan-Mindoro collision zone. In contrast, the region near the Lubang Fault (or Verde Passage Fault) is predicted to be accumulating elastic strain at a very rapid rate (~20-40 mm/yr); however, our model in the southernmost Luzon region is not well-constrained and thus necessitates certain simplifications on the blocking geometry to maintain model stability. To be able to properly model this region, better constraints—by adding GPS data and geologic or structural information within the central Philippine region—would be necessary. Thus, the positions and velocities of GPS sites near Bolinao, Mindoro, and along the VPSSF are likely to be affected with high levels of stored elastic strain due to strong locking along the segments of the Manila Trench and the VPSSF (Figure 4). Thus, the periodicity of resurveys of GPS sites near these regions need to be shorter to fully capture the error and then account for the elastic strain effect.

THE CONTINUUM DEFORMATION FIELD

We then use the continuum modeling technique to determine the remaining strain rate or deformation field of the Luzon region. The main philosophy of using this approach is the realization that there are components of deformation that are not sufficiently captured by the block model in particular areas with minor mapped and unmapped faults as well as other tectonic structures that may contribute to the deformation field. After obtaining the best-fit block rotations and elastic locking strains using the block modeling approach, the residuals were used as input to the continuum model. The residuals represent overall model-observation misfits or, essentially, intra-block strain rates that can contribute additional but relatively minute rates of deformation to the survey network. These signals actually contain the contributions of minor structures and could be spatially mapped over smaller regions using grids (Figures 6 and 7, Suppl. Figure 3). The residual velocities range from 0.14 mm/yr to 17 mm/yr, with larger rates in the SW Luzon area—presumably from larger data-model misfits—and with smaller magnitudes in the central to the northern Luzon regions (Figure 7). The resulting continuum model shows highly variable strain rates that range from 89-144 ns/yr in the southwestern Luzon region and slightly higher rates that range from 89 to 277 ns/yr in the northwestern (i.e., Ilocos-Abra) region (Figure 7). The direction of residual deformation shows a mostly scattered but predominantly near E-W principal compressional strain rate axes with some N-S extensional strain rate axes in the Central Luzon area (Figure 7 and Suppl. Figure 3).

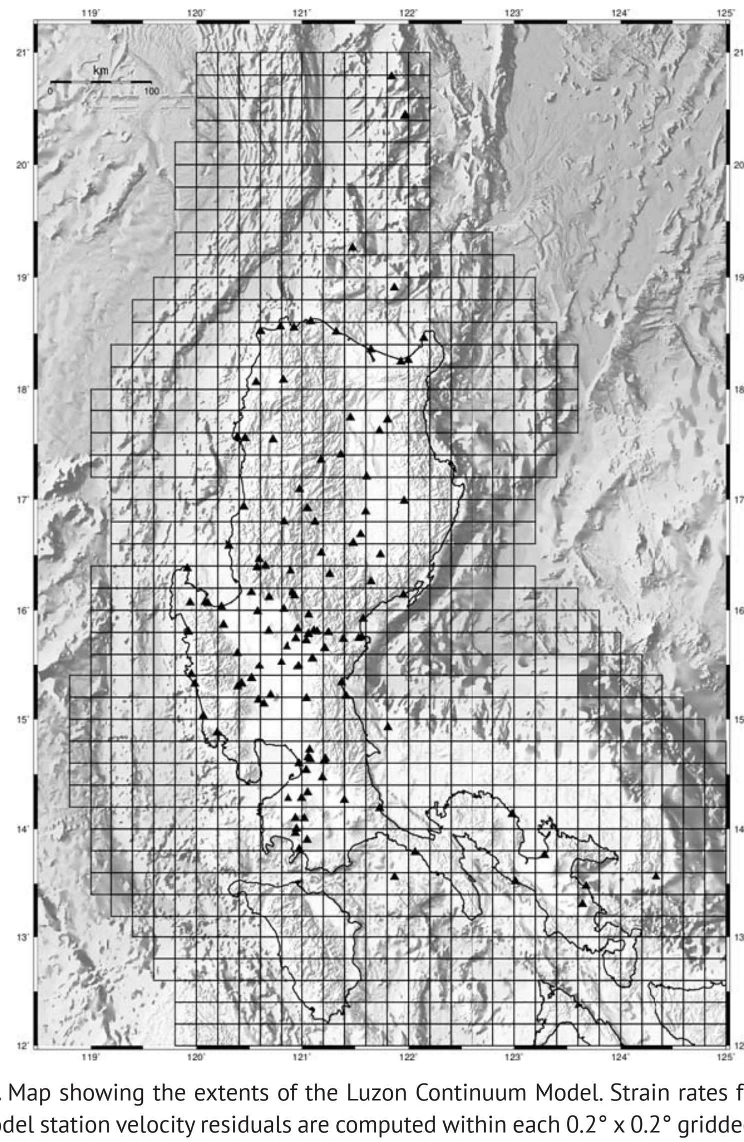

Figure 6. Map showing the extents of the Luzon Continuum Model. Strain rates from input block model station velocity residuals are computed within each 0.2° x 0.2° gridded box. The modeled region has a total of 888 gridded boxes (black lines) and contains 152 measurements or model residuals from GNSS station locations (solid black triangles). Background shows hillshaded surface topography and bathymetry in grayscale.

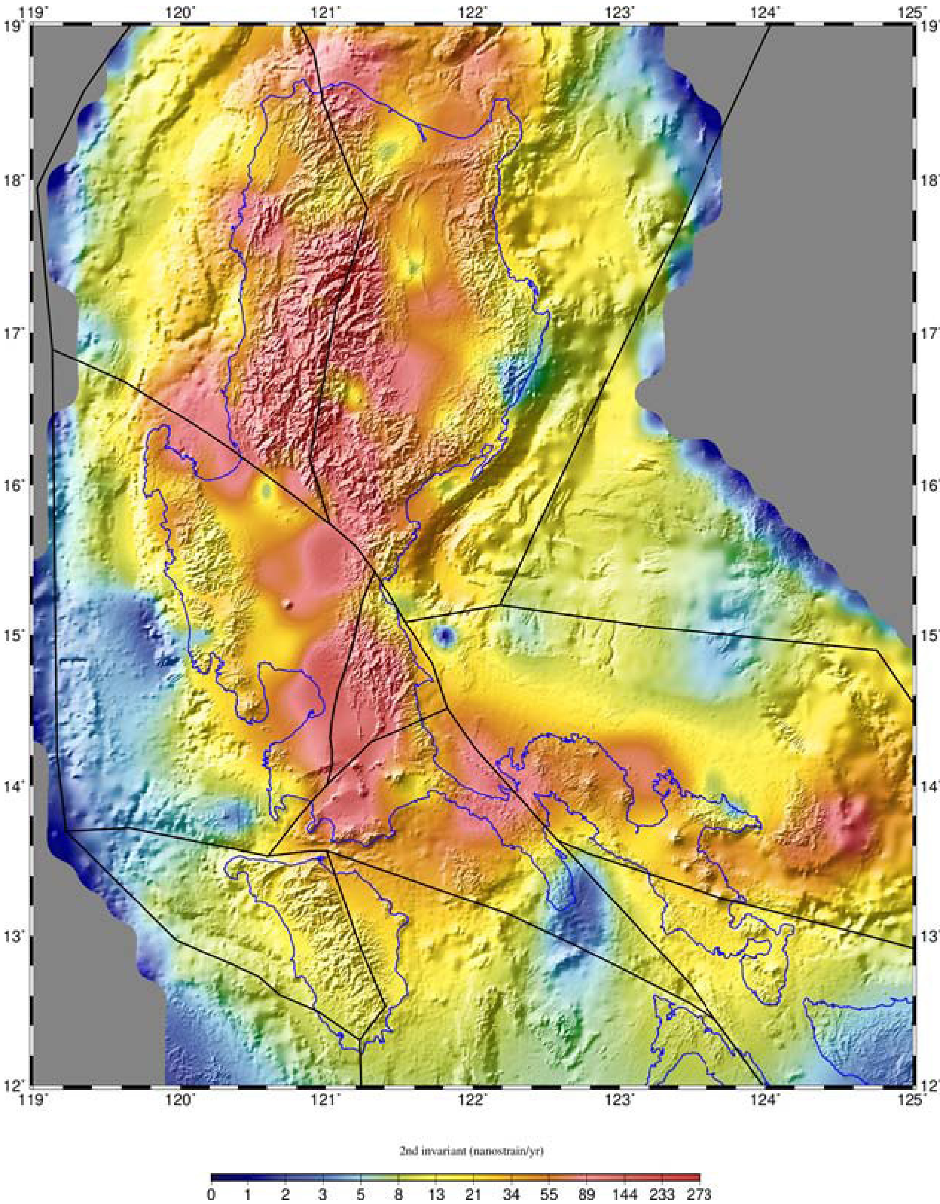

Figure 7. Map of spatially-varying residual strain rates in the Luzon region. Block model boundaries are shown for reference. These were calculated from residual velocities after removing the deformation signal (rotation and fault-locking elastic strain) from the block model. Colors show strain rate magnitudes, in ns/yr (blue = very low; yellow = low; orange = moderate; red = high; hillshaded topography with bathymetry is shown as background shadows). See also Suppl. Figure 3 for the directions of the residual strain rate axes.

DISCUSSION

Overall, the measured tectonic deformation field may be influenced by a combination of several factors. First, rigid block rotation and translation contribute significantly to this deformation field as the microplates or tectonic blocks of Luzon rotate counterclockwise with respect to the Sundaland Plate, with active rotation rates noted to be among the highest in the world (Rangin et al. 1999; Aurelio et al. 2000; Galgana et al. 2007; Bacolcol et al. 2013). Second, the locking patterns along faults and subduction zones due to high friction fault patches create localized deformation field that respond to such regions (Hsu et al. 2013, Wang and Bilek 2014). Third, related to such areas are those that have recently released stress through earthquakes and are undergoing elastic rebound processes (such as those along the Philippine Fault) (Duquesnoy et al. 1994; Bacolcol 2003; Besana and Ando 2005), and/or long-term viscoelastic response due to underlying mantle flow (Khazaradze et al. 2002; Pollitz et al. 2006). Fourth are processes associated with short- to medium-term deformations such as those associated with active volcanism (Bartel et al. 2003; Galgana et al. 2014), surficial creep processes, and hydrological processes (Amelung et al. 1999), which may have not been fully removed in GPS filtering.

Although not addressed directly using horizontal GPS measurements, geodynamic effects on vertical controls might be likely, since local gravitational anomalies might produce significant deviations from the regional geoid model. For instance, the subducted slab of Sundaland plate underneath western Luzon produces positive gravity anomalies (Lewis and Hayes 1983; Hayes and Lewis 1984) while the presence of Central Luzon Valley, Laguna de Bay and the Macolod Corridor contributes to generally negative gravity anomalies due to thick, low density sediments and/or crustal thinning (Bischke et al. 1990; Förster et al. 1990; Featherstone 2000; Ebbing and Olesen 2005). However, one complication is the presence of igneous intrusions (Lagmay et al. 2003), which may result in localized positive gravity anomalies. While such tectonic structures may contribute to either positive or negative anomalies, their combined persistent gravitational effects will have direct implications as to how the geoid is computed in this region. The vertical signal, in turn, although significantly smaller than the horizontal component signal, may contribute some noise to the deformation data.

The predicted information derived from the best-fit models can be used to guide the amount of corrections applied to the observed velocity field of geodetic observations. Since the amount of correction per component of the deformation field will vary depending on the cyclicity of the component phenomenon, such modeled information can provide more accurate estimates for significantly long deformation cycles. For example, the correction for the annual block rotation field can be uniformly applied for the control network average velocity field, as compared to the correction for the average annual elastic locking strain field that may vary significantly through time, depending on the proximity of active faults. Another solution is to selectively apply rotations only to fast-moving blocks for inter-block adjustments, with little or no intra-block corrections. In both cases, since the modeled deformation field is geometry-dependent, care must be taken to accurately represent major faults and fault splays (i.e., alignment and depth), as these would have significant impact on tectonic interpretations of the region. Periodic observations are therefore needed in order to correctly define block motions and fault locking behavior, the two parameters that will influence the accuracy of the deformation model.

IMPLICATIONS OF EXCESS INTRABLOCK STRAINS

The second part of the modeling process involves using the block model residual rates to generate a continuous deformation field. This is used to determine areas with high concentrations of strain rates, which may represent the excess locking strain from unmodeled faults and/or excess rotational velocities from microblocks. In the case of Luzon, the northwestern and southwestern area exhibits high strain rates (Figure 7 and Supplementary Figure 3), which would mean that the blocks there may not be adequately modeled (i.e., kinematically) or even physically represented using a sufficient number of blocks and faults. The latter in this case represents an inherent weakness of the block modeling approach: that strain rates produced by faults on the ground may not be fully captured, especially if these faults are not recognized in the block model (Thatcher, 1995). In the case of northern Luzon, while the entire region may be predominantly characterized as rotating blocks and elastic strain, the actual physical manner of deformation may be that of an assembly of tectonic units that are subject to viscoelastic or even plastic form of straining (Figure 7 and Suppl. Figure 3). To be specific, the ILOC block (representing northwestern Luzon) contains several active splays of the Philippine Fault. Further dividing this region into numerous, smaller blocks tends to produce inherent instabilities using the block modeling algorithm due to the resulting block geometries, hanging wall-footwall interface and adequacy of resulting station coverage along the forearc. Hence, we elected to use the easternmost boundary and treat ILOC as an internally deforming block. As presented in Figure 7 and Suppl. Figure 3, high rates of residual deformation in Luzon appear to be scattered within the interior of the island. These high, excess strain rates will contribute significantly to the degradation of survey networks in areas where they are found. It is thus imperative to quantify these excess strains and determine their spatial extent in order to fully develop a dynamic geodetic network solution—one that incorporates fault elastic strain and spatially mapped internal block deformation. This will produce more robust results than those with solutions based on simple block model corrections.

MODEL IMPLICATIONS ON THE STABILITY OF THE SURVEY NETWORK

The block and continuum models presented here present an initial assessment of differential block velocities and internal strains experienced by Luzon during the past two and a half decades. These models fundamentally show that the Philippine Coordinate System, through its ground survey reference markers, will continuously experience rapid deformation at spatially variable rates.

To stabilize the Philippine Survey Network, periodic resurveys are needed to further understand and refine corrections for plate translation, interplate and intraplate strains. Furthermore, geodetic networks may need to be segmented into semi-independent, tectonic block-based controls, from which lower order property and other survey control networks (within individual tectonic zones) should be based. This is to minimize the amount of deformation introduced by differential motions made by crossing different tectonic blocks and/or elastic strain concentrations near fault zones. Furthermore, regions near major fault systems (e.g., PFZ) may need to be adjusted with time-dependency (matched with interseismic cycle and earthquake strain release patterns at those localities) because of potentially higher relative motion across the fault. Tectonic blocks with high internal strains will require dense and more frequent resurveys to fully assess the spatial and temporal nature of deformation, including most especially the identification of contributing active geologic structures. As a consequence of rapid plate motions, the main Philippine Reference Monument (or active GPS survey station) may need to be relocated to Palawan Island, situated in the tectonically stable Sundaland block, instead of its current location in Marinduque Island which is traversed by several active fault systems, and is subjected to creep processes and high elastic strain due to fault locking and plate deformation.

CONCLUSIONS

This research examines the nature and extent of a fundamental source of errors in the Philippine geodetic network, specifically those introduced by rapid crustal deformation. Due to active plate tectonics, crustal movements of Luzon continuously introduce positional errors to ground-based survey reference markers, which will eventually render them inaccurate, necessitating periodic resurveys and/or application of positional corrections in between resurveys. Specifically, our block and continuum modeling experiments here show the amount and spatial extent of deformation within the island of Luzon, providing a guide to pinpoint areas where crustal strain is relatively high. As shown by block modeling experiments, plate motions contribute from 20 to as much as 100 mm/yr differential motion of Luzon tectonic blocks with respect to Palawan (part of Sundaland), plus the deformation induced by locking along faults and subduction zones, as well as internal deformation within tectonic blocks. In particular, our models imply the existence of multiple, internally deforming tectonic blocks that compose Luzon, with these blocks being bounded by faults and subduction zones. Our models quantify the amount of block rotation as well as the amount of elastic strain along the plate interfaces, including the excess deformation. The best-fit model results, in particular, show the predicted velocities along PRS92 stations, with all components of deformation taken into consideration. For block stations near the Philippine Fault in Nueva Ecija and around North-Central Luzon, a significant amount of tectonic plate motion (most have >1 m displacement with respect to Sundaland) has already been accumulated since 1990, displacing PRS92 stations from their original positions (see Figure 5).

While we can remove most of the fast deformation signals using pre-quantified rotations and elastic strain rates through block models, misfits via residual strain rates introduce complications. The continuum (residual) deformation field plays a vital element in the entire modeling process. Residual strain rates that represent data-model misfits could be physically a manifestation of unmodeled excess rotation rates and/or elastic strain rates from unmodeled faults. Other local sources, such as volcanic and hydrological cycle-related deformation, can also contribute to the degradation of the survey network. As our extended model shows concentrations of high strain rates in Luzon, it becomes necessary to identify regions where block models fail. Such regions are subject to higher errors and/or deformations that need to be surveyed with finer grids to correctly account for the motion. Eventually, the sequential use of these techniques is necessary for a complete assessment of the deformation field.

Although the results here present a comprehensive pattern of deformation within Luzon, the models used will greatly benefit from a densified, updated set of GPS observations, as well as expanded tests of resolution and sensitivity to fully assess their strength and limitations. Furthermore, the study only examines the tectonic deformation component that contributes significantly in the overall error field. The application of corrections for other systematic error sources, such as global reference system corrections, rapid horizontal and vertical crustal motions, volcano-induced deformation, and hydrological effects will significantly improve future studies of the region.

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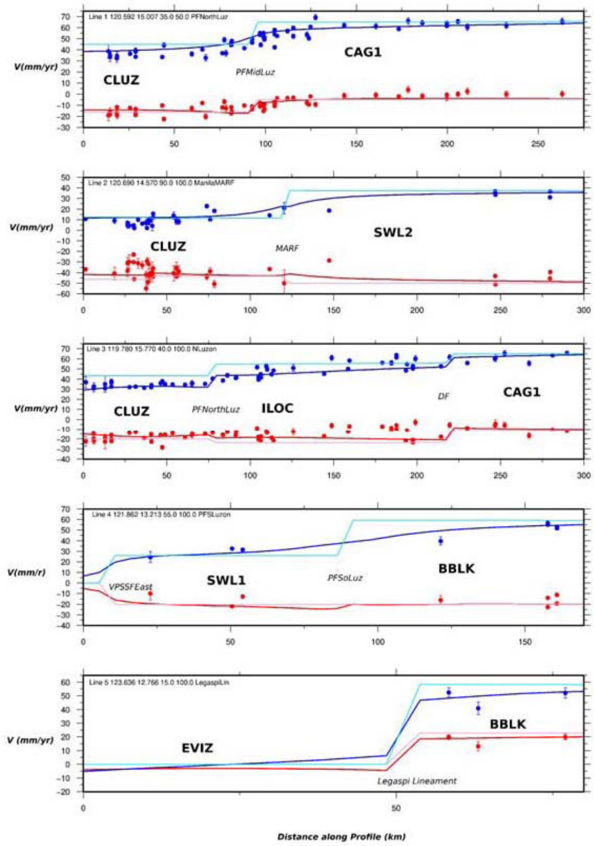
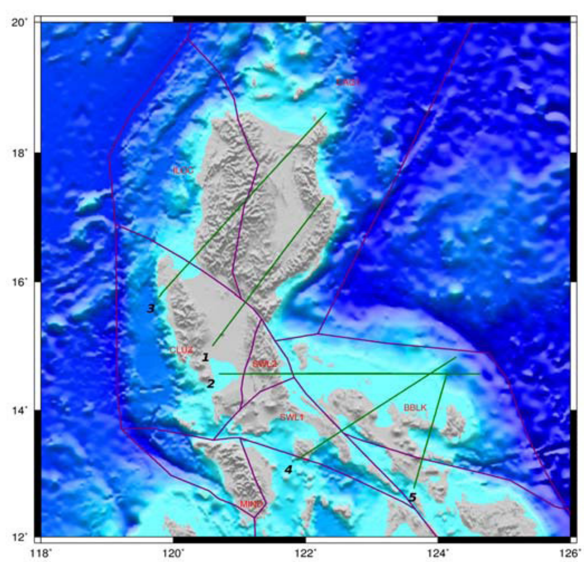
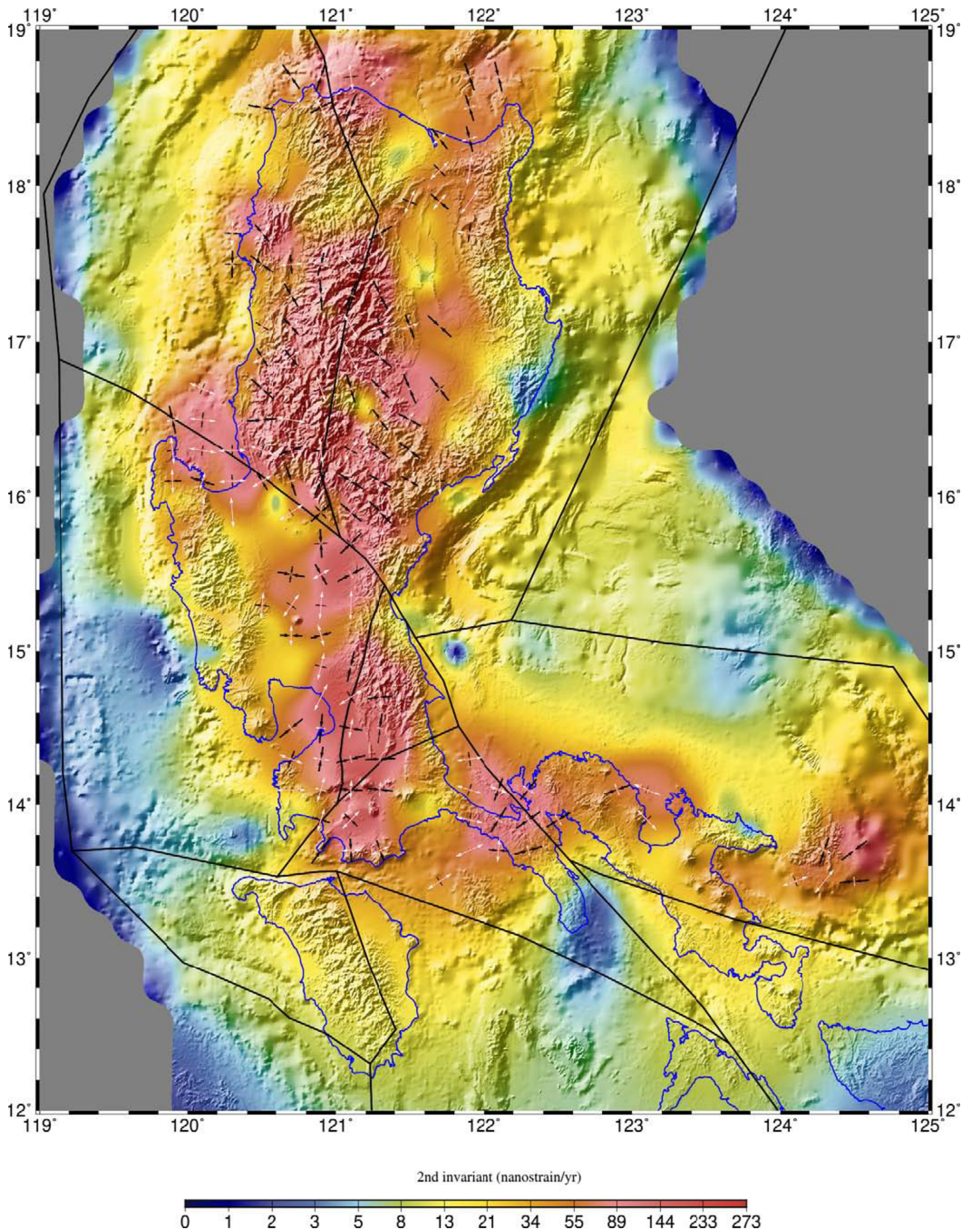
SUPPLEMENTARY FIGURES



Supplementary Figure 1. Model profiles across faults. Blue lines represent fault-parallel component motions, while red lines represent fault-perpendicular component motion (with offsets in their origins for visualization purposes). x-axis shows the distance along the profile line in km, y-axis shows the rate of motion in mm/yr. Curves show combined elastic strain and rigid block motion, while straight lines show only rigid block motion. Dots represent GPS data with 2 sigma error bars. Blocks and faults are named.



Supplementary Figure 2. Map of profile lines. Plots of profile lines across faults from where the model information and GPS data were obtained. Number marks the starting end of each profile line. Data were included at offset distances from either side of the profile line (i.e., 50 km Profile 1 and 100 km for Profiles 2 to 5).



Supplementary Figure 3. Map of spatially-varying residual strain rates in the Luzon region, plotted with the normalized residual strain rate axes. Axes with significant residual strain rates, i.e., those above 55 ns/yr are shown. Block model boundaries are shown for reference. White vectors indicate the principal extensional strain direction, while black arrows indicate principal compressional strain directions. Colors show strain rate magnitudes, in ns/yr (blue = very low; yellow = low; orange = moderate; red = high; hillshaded topography with bathymetry is shown as background shadows).