Paper:

Development and Operation of a Regional Moment Tensor Analysis System in the Philippines: Contributions to the Understanding of Recent Damaging Earthquakes

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A network of 10 satellite-telemetered broadband stations was established under a cooperative project between Japan and the Philippines, and a source analysis system based on waveform inversion of regional seismograms was adapted to operationalize a regional moment tensor analysis of Philippine earthquakes. This study presents the source information generated by the system for recent damaging earthquakes: the M_w6.7 Negros and M_w7.6 offshore Samar in 2012, and the M_w7.2 in Bohol in 2013. Results show that the Negros event was generated by shallow NE–SW thrust faulting with a small strike-slip component, and that the centroid was located slightly offshore. The Samar event occurred in relation to an outer-trench thrust fault within the Philippine Sea Plate, adjacent to a part of the Philippine Trench that has relatively low seismicity. Our centroid moment tensor (CMT) solutions show that the Samar event triggered distinct clusters of outer-rise normal and thrust aftershocks, which we explain as being consistent with a Coulomb stress change in the area. Finally, we infer that the previously unidentified fault zone that generated the Bohol earthquake has a length of ∼100 km, is oriented ENE–WSW, transects parts of Bohol, and extends offshore towards Cebu. These examples show how recent improvements in Philippine earthquake monitoring could contribute to the characterization of earthquake sources and in the understanding of the seismotectonics of the area.

Keywords: earthquake monitoring, source parameters, waveform inversion, Negros, Bohol, Samar, Philippine Trench

1. Introduction

The Philippine region is known to be an area of complex seismotectonics, which accommodates deformations due to the opposing movements of the Philippine Sea Plate and the Sunda Plate (**Fig. 1**). The Philippine archipelago has 23 active volcanoes and numerous active faults and trenches [1]. The threat of tsunami is very high for most of the Philippine coastline, as both sides of the archipelago are bounded by active subduction zones associated with large earthquakes. Both the Philippine Trench and the North Luzon Trough lie to the east of the Philippines; the former has a history of large earthquake generation (e.g., 1925 M8.2, 1995 M7.5), and the latter is a bathymetric depression interpreted as either an incipient subduction or a remnant suture zone. The western coast of the archipelago is defined by the Manila Trench (1994 M7.2), the Mindoro-Negros collision zone (1948 M8.3), the Negros Trench, the Sulu Trench and the Cotabato Trench (1976 M7.6). Most of the major islands of the Philippines are transected by active faults, the most dominant of which is the $\sim$1,250 km long, arc-parallel, left-lateral strike-slip Philippine Fault Zone (PFZ) (1645 M7.9; 1990 M_w7.7) [2, 3]. The PFZ traverses the major islands of the Philippines and manifests itself in several active splays, thereby dominating the seismic activities in the NW part of Luzon, Central Visayas, and Eastern Mindanao [4, 5]. To assist in improving the preparations for (and the mitigation of) earthquake and tsunami disasters in this country, it is considered important to gain an understanding of the seismic potential of all active faults and trenches.

The integration of routine regional moment tensor analysis in the Philippine earthquake monitoring system is

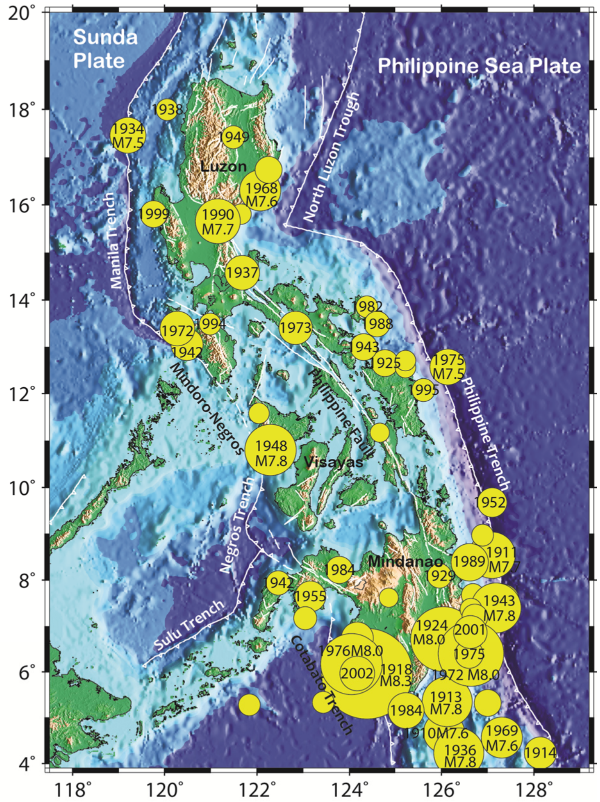

Fig. 1. Significant earthquakes in the Philippines ($M \geq 7.0$, 1900-2009, ISC-GEM Catalogue).

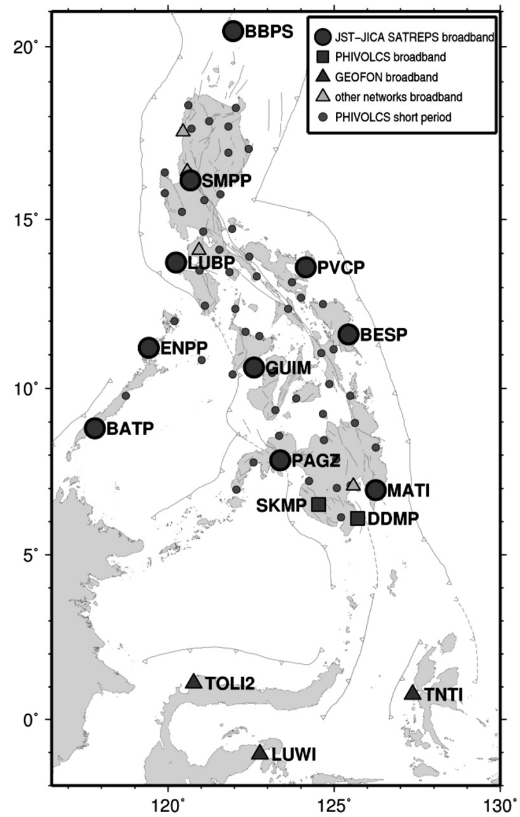

Fig. 2. Seismic stations in the Philippines. SWIFT uses data from the broadband (BB) stations installed under the JST-JICA SATREPS (shaded big circles) and some BB stations of Geofon Program (shaded triangle) and PHIVOLCS (square).

expected to contribute to a better characterization of earthquake sources in the country. Currently, earthquake source characterization is predominantly based on the following information: known surface ruptures of active faults, a short earthquake catalogue that spans $\sim$400 years, and source information that has been available from global CMT (GCMT) solutions [6, 7] since 1976. The improved national earthquake monitoring system is able to provide CMT solutions for moderate-sized events that occur more frequently in the Philippines, but which are less fully resolved by global networks. In areas where the mapping of active faults is hampered by physical conditions such as areas with thick volcanic sediments (in the case of western Mindanao), or by the inherent nature of blind faults, this system can provide information that is critical for an accurate seismic hazard assessment. The new system has now been operating for nearly two years, and has produced valuable earthquake source information, as will be shown by CMT results obtained for the recent damaging earthquakes in Negros on February 6, 2012 (M_w6.7), offshore Samar on August 31, 2012 (M_w7.6), and in Bohol on October 15, 2013 (M_w7.2).

2. Development of a Regional Moment Tensor Analysis System in the Philippines

2.1. Establishment of a Satellite-Telemetered Broadband Network

A network of 10 satellite-telemetered broadband seismic stations was established through a partnership between the Philippine Institute of Volcanology and Seismology (PHIVOLCS) and National Research Institute for Earth Science and Disaster Prevention (NIED), under the framework of a collaboration between the Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA), and within a Science and Technology Research Partnership (SATREPS) project in the Philippines (2010–2014) entitled "Enhancing Earthquake and Volcano Monitoring Capabilities and Promoting Effective Utilization of the Disaster Information in the Philippines" [8]. Under the umbrella of the SATREPS project, ten of the 66 short-period stations of PHIVOLCS were converted into broadband stations during 2011–2012. Each station was equipped with either a Trillium 120 P/PA or a Trillium 240 broadband seismometer, and data were transmitted on a near real-time basis via satellite to the main office of PHIVOLCS. By November 2011, the network had begun to produce useful seismograms. However, signals were intermittent in early 2012 due to the necessary change of the broadcasting satellite, but the network was fully operational by the end of 2012. From 2012–2013, PHIVOLCS established two new satellite-telemetered broadband stations, bringing the present number of available real-time broadband stations in the Philippines to twelve (**Fig. 2**). To improve azimuthal coverage of Mindanao events, some of the shared broadband stations of GEOFON [9] were also used by the system.

2.2. Waveform Inversion Method

To determine the source parameters of Philippine earthquakes using regional data, the technique using the determination of source parameters by waveform inversion of Fourier-transformed signals in the frequency domain, or SWIFT [10] was adopted. The technique performs a simultaneous inversion for the source time function and the source mechanism, even when there are a limited number of seismic stations. Once triggered by an earthquake alert, the system performs a fully automated signal preparation and waveform inversion, and is also able to send notifications via email and publish results on the web. For the Philippine set-up, the earthquake alert system uses the initial hypocenter location and magnitude computation of the automated SeisComP3 of GFZ [11] as installed in PHIVOLCS. In the inversion a double couple focal mechanism is assumed to stabilize the solution by using data from a small number of stations.

In the first step, three-component seismograms were corrected for the instrumentation response, and they were then integrated in time to obtain the displacement seismograms. The waveforms were bandpass filtered according to magnitude. Small events $M_w < 4.5$ were bandpass filtered between 20 and 50 s; $4.5 \leq M_w < 7$ events between 50 and 100 s; and large events $M_w \geq 7$ between 50 and 200 s. The filtered waveforms were then decimated to a sampling frequency of 0.5 Hz. A total data length of 512 s (256 data points in each channel) was used for the inversion. In addition, Green's Functions were synthesized using the discrete wavenumber method [e.g., 12], assuming the standard Earth model ak135 [13], and the hypocenter locations from the automated SeisComP3 were used as initial source locations. An adaptive grid spacing was used for the spatial grid search, with a grid spacing starting from 0.5° and 10 km for horizontal and vertical grids, respectively. In the next step, the grid spacing was reduced to 0.2° horizontally and 5 km vertically, and for the 2012 Negros and 2012 Samar events the final horizontal grid spacing was reduced to 0.1°, while for the 2013 Bohol event the final horizontal grid spacing was 0.05°. At each source location of the spatial grid search, the fault parameters (the dip, slip and rake angles) were searched using adaptive angle steps gradually decreasing from 30°, 15°, 8°, 4°, 2° to 1°. For each combination of source location, fault, and slip orientation angles, the waveform inversion was carried out to estimate the best-fitting source parameters.

The system was first integrated with the earthquake monitoring procedure in the Philippines in 2011, and was then fully operational by 2012. **Fig. 3** shows the CMT solutions obtained from the system operation from between November 2011 and March 2014. Bonita et al. (2014) [14] discuss the reliability of the SWIFT CMT solutions, most of which were obtained using Philippine broadband stations, although for some cases (mostly in Mindanao events) a few of the shared GFZ stations in Indonesia were used (**Fig. 2**).

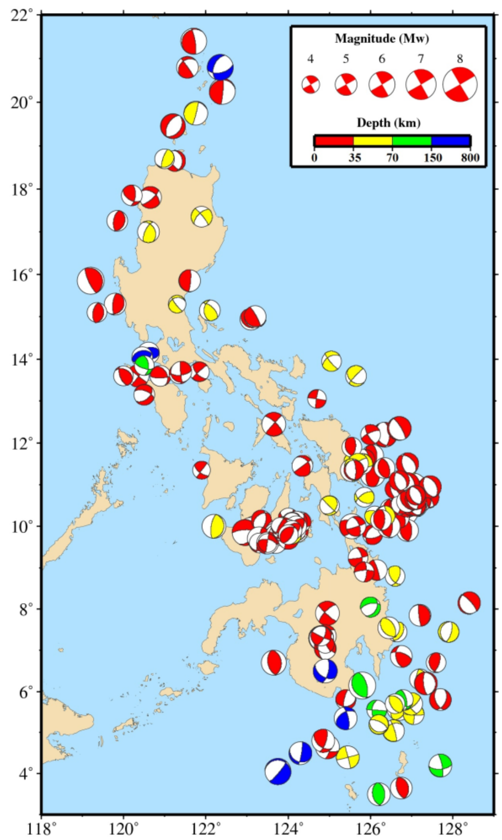

Fig. 3. The focal mechanisms of earthquakes in the Philippines determined using SWIFT within the period of its implementation from November 2012 to March 2014.

3. Moment Tensor Analysis of Recent Damaging Earthquakes in the Philippines

3.1. The 2012 M_w6.7 Negros Earthquake

On February 6, 2012 at 03:49 UTC, a strong earthquake occurred in the Negros area, Central Philippines. The intense shaking devastated communities along the eastern part of the island and generated landslides, liquefaction, sinkholes, ground subsidence, and coastal uplift [15]. A local tsunami with a height of < 1 m was observed on the eastern coast of Negros and on the southwestern coasts of Cebu while there were indications of a tsunami with a height of $\sim$5 m localized in Libertad, Negros Oriental. The earthquake caused 51 deaths (mainly in relation to landslides), 152 people were injured, and 62 were declared missing. Moreover, the damage to infrastructure and dwellings was significant [16].

PHIVOLCS located an inland hypocenter about 3 km from the shoreline (at 9.968°N, 123.165°E, and a depth of 5 km) while global networks located the epicenter offshore: USGS (at 9.964°N, 123.246°E, and a depth of 11 km) [17] and GFZ (at 10.12°N, 123.27°E, and a depth of 11 km) [18] (**Fig. 4b**). There were no known

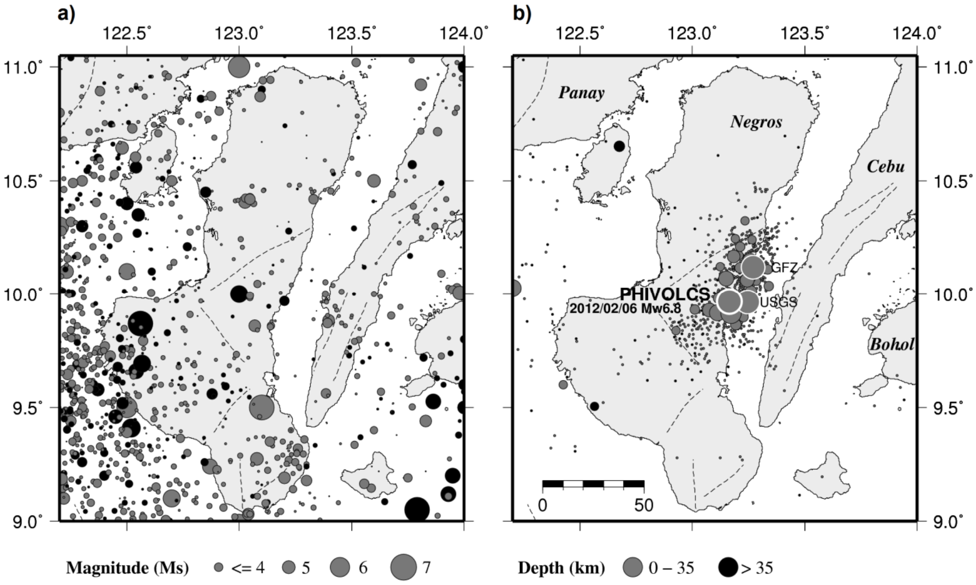

Fig. 4. Seismicity of Negros, Philippines from a) 1900 – February 5, 2012 and b) February 6, 2012 to February 5, 2013. Data source: PHIVOLCS. Dashed lines indicate inferred faults [2].

active faults associated with the hypocenter area [2], no large earthquakes had been documented in the last 400 years [2, 3, 19], and there had been few and sparsely distributed instrumental events (**Fig. 4a**). The Negros earthquake region is in the area of the Central Philippines, where the ground shaking hazard levels are relatively lower than most other Philippine areas located in the proximity of active faults [20]. The geologic hazards of the region have often been associated with the subduction zone west of Negros, and activities of the Kanlaon Volcano in the north.

The broadband network was in the process of being established during the Negros 2012 event. However, as shown in **Fig. 5(a)**, SWIFT was able to provide CMT solutions for the mainshock and one of its aftershocks by using six stations, and the results are consistent with those obtained by global networks GCMT and GFZ. The focal mechanism of our mainshock shows a shallow reverse faulting with a small strike-slip component. The fault is oriented NE–SW (strike, dip, rake) = (49°, 41°, 131°) / (180°, 60°, 60°), lying almost parallel to the eastern coast of the island. The estimated scalar seismic moment was $M_0 = 1.54 \times 10^{19}$ Nm, corresponding to $M_w 6.7$. **Fig. 5(b)** shows that there is a good waveform fit between the observed and synthetic seismograms for the mainshock, with a normalized residual of 0.10.

Our source centroid is located slightly offshore from Negros (123.3°E, 10°N) at a depth of 5 km, and is close to the PHIVOLCS hypocenter. The aftershocks reported by PHIVOLCS (**Fig. 4b**) were distributed over a region with a width and length of $\sim$25 km and $\sim$50 km, respectively, and were oriented almost parallel to the eastern coast of Negros. Most of the PHIVOLCS aftershocks were plotted close to the coast of Negros, while those reported by USGS NEIC were shown to be mostly offshore along the narrow Tañon Strait, with some epicenters plotted on Cebu Island. Our results agreed well with those

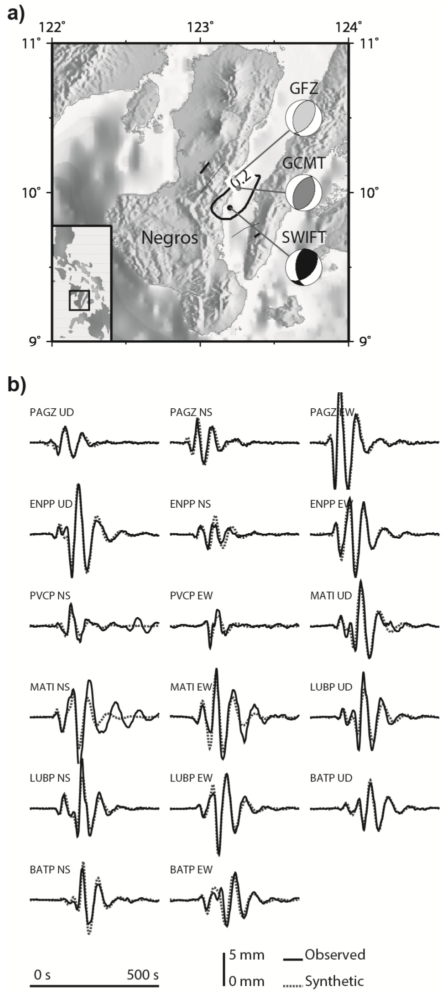

Fig. 5. Waveform matches obtained from the waveform inversion of the $M_w 6.7$ Negros earthquake of February 6, 2012. a) Contour plot of the horizontal residual distribution around the best-fitting source centroid. b) Solid black and dashed gray traces represent the observed and synthesized seismograms, respectively. The station code and component of motion are indicated at the upper left-hand side of each seismogram.

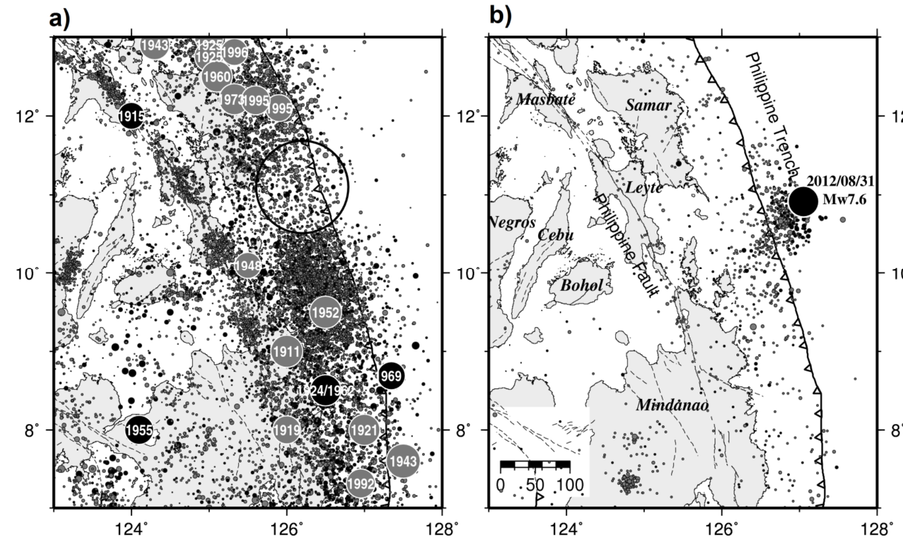

Fig. 6. Seismicity of Samar, Philippines from a) 1900 – August 30, 2012 and b) August 31, 2012 to August 30, 2013. Data source: PHIVOLCS. Dashed lines indicate inferred faults [2] while big circle in **Fig. 6(a)** shows an apparent seismic gap along Philippine Trench.

reported by PHIVOLCS, indicating that the fault can be found close to the eastern coast of Negros. This would explain the devastation of many of the coastal towns aligned along the inferred fault orientation.

Several fault mapping campaigns were conducted to document co-seismic ruptures [e.g., 15, 21, 22], but their results did not indicate the discovery of any surface rupture inland or near the shore of Negros. The PHIVOLCS Quick Response Team suspected that the surface rupture would have been offshore to the east of the island, which would explain the < 1 m coastal uplift that was observed for a length of about 2 km along the eastern coast. The offshore sonar studies of Daag et al. (2012) [21] detected near-shore undersea slumping, and this was proposed to explain the small and locally observed tsunami. However, the studies found no distinct evidence of ruptures on the seafloor, which led researchers to conclude that the Negros event was caused by a blind fault. In this case, therefore, the use of seismic data can be used as a primary basis for the improvement of seismic hazards assessments within the area.

3.2. The 2012 M_w7.6 Samar Earthquake

On August 31, 2012 at 12:47 UTC, a strong earthquake damaged towns along the eastern coast of Samar Island. The earthquake caused damage along the eastern coast of Samar and produced a < 1 m tsunami. For this event, SWIFT was able to provide CMT solutions for the mainshock and 32 of its aftershocks ($M_w > 4.4$). The mainshock was located both by PHIVOLCS and USGS as being offshore from Samar, and seaward of the Philippine trench axis. PHIVOLCS estimated the event hypocenter at 10.919°N, 127.053°E, at a depth of 51 km, and located about 148 km east of Guiuan, Eastern Samar. The hypocenter area was adjacent to an area of the Philippine Trench (9.5°N–11.5°N), which, as shown by **Fig. 6(a)**, is an apparent seismic gap with a seismicity that is sig-

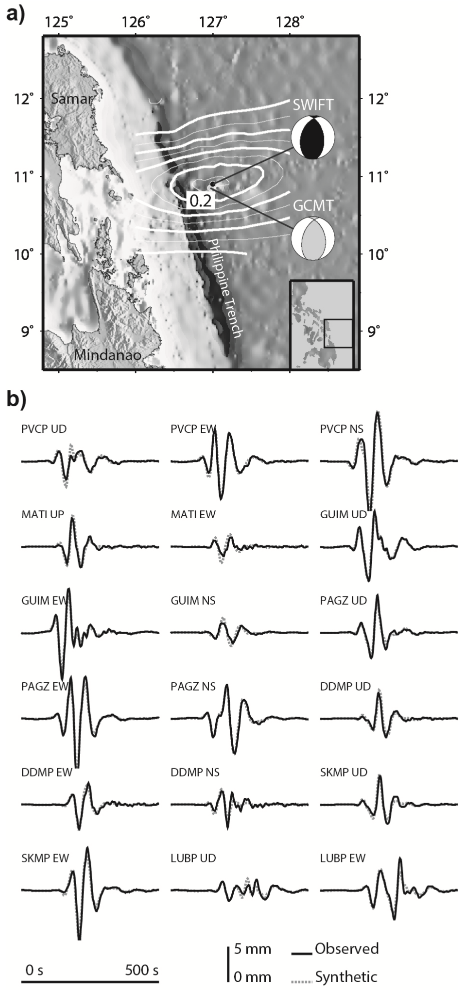

Fig. 7. Waveform matches obtained from the waveform inversion of the M_w7.6 Samar earthquake of August 31, 2012. a) Contour plot of the horizontal residual distribution around the best-fitting source centroid. b) Solid black and dashed grey traces represent the observed and synthesized seismograms, respectively. The station code and component of motion are indicated at the upper left-hand side of each seismogram.

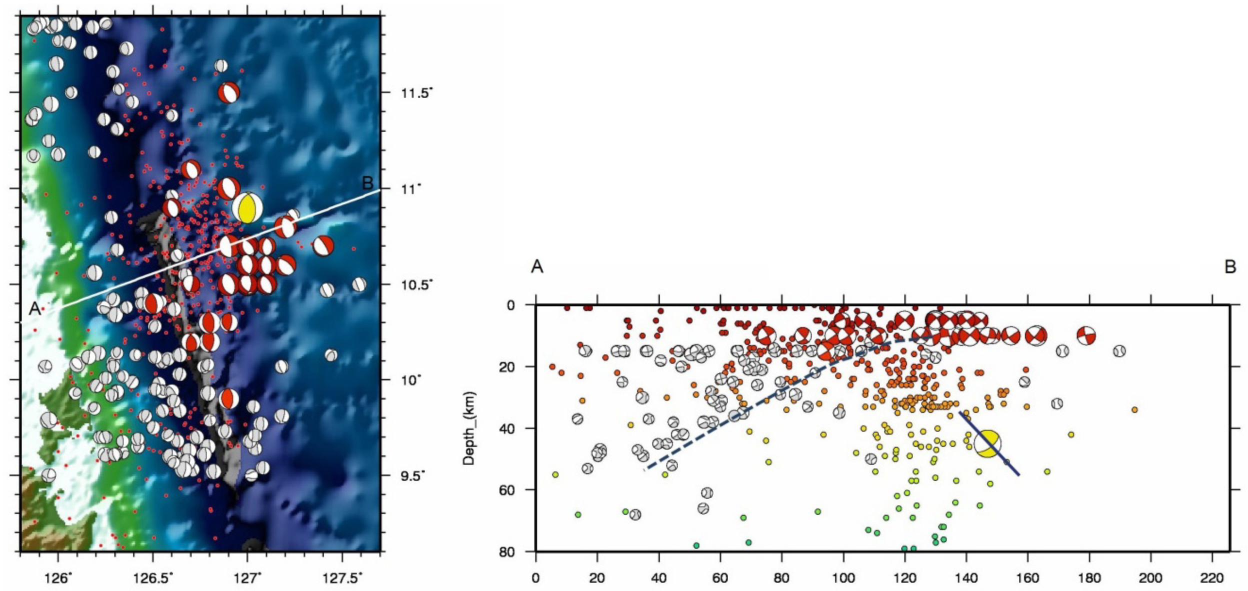

Fig. 8. Map and cross section (indicated as white line in map view) of the SWIFT moment tensor solutions for the 2012 Samar earthquake and its main aftershocks (in red CMT). Global CMT solutions from August 3, 2012 to January 2013 are in gray while PHIVOLCS hypocenters are in solid circles colored according to depth.

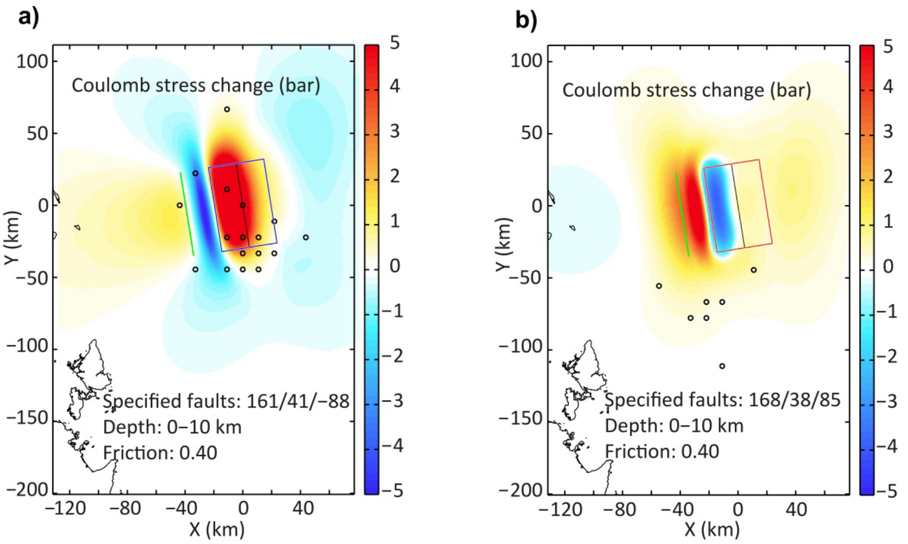

Fig. 9. (a) Maximum Coulomb stress changes (0–10 km depth) due to the Samar earthquake on target normal faults. Only aftershocks with normal mechanisms are plotted. (b) The same calculation as in (a) but on a target reverse focal mechanism. Only aftershocks with reverse mechanisms are plotted. The SWIFT solution of the mainshock dipping to the east is used for these calculations (strike, dip, rake) = (351°, 49°, 72°). Green line indicates the fault surface projection.

nificantly lower than most areas of the trench. No large historical earthquakes have been attributed to the area in the last 400 years [2, 3, 19, 23].

The focal mechanism for the mainshock, as obtained by SWIFT (**Fig. 7a**), was a reverse fault striking in a north-south direction (strike, dip, rake) = (351°, 49°, 72°) / (197°, 44°, 110°). The source centroid was located ~100 km east of the Philippine trench axis (127.0°E, 10.9°N), within the Philippine Sea Plate, and with a centroid depth of 45 km. The estimated seismic moment of this earthquake was $M_0 = 3.57 \times 10^{20}$ Nm corresponding to $M_w = 7.6$. **Fig. 7(b)** shows that there is a good waveform match between the observed and synthetic seismograms, with a normalized residual of 0.10.

We also obtained CMT solutions for 32 of the aftershocks ($M_w > 4.4$), which show (**Fig. 8**) that the aftershocks formed two distinct clusters: normal faulting events scattered close to the mainshock, and another cluster of thrust faulting events closer to the Philippine Trench axis. In order to understand this complex sequence of aftershock triggering, we carried out calculations of stress transfer in relation to our estimated mainshock mechanism. We first calculated the Coulomb stress change on target normal faults that were obtained as an average of the normal fault aftershocks related to an east dipping fault, as in the SWIFT CMT solution (strike, dip, rake)

= (351°, 49°, 72°), and a fault plane area obtained from an empirical scaling [24]. However, the fault area could not be easily inferred from the distribution of aftershocks (**Fig. 8**), which could have been affected by some events with large errors in location and poorly constrained depths due to lack of good azimuthal coverage of stations. Our results (**Fig. 9a**) show that most of the normal fault events fall within an area of positive Coulomb stress changes up to 10 bars, for depths between 0 and 10 km. The same calculations on target reverse faults, obtained as an average of the reverse fault aftershocks, also indicate that reverse fault aftershocks occurred within a region of positive Coulomb stress changes (up to 6 bars) (**Fig. 9b**). This implies that Coulomb stress changes in the region could explain the mixture of fault mechanisms triggered by the mainshock. Ye et al. (2012) [25] noted a similar stress change using a different data set composed of 9 GCMT solutions and a technique using waveform template analysis. Our results, which are based on a larger dataset of CMT solutions (32 events), do not only validate earlier observations but also provide a clearer spatial image of the triggering of reverse and normal events. These observations are thus considered to be of considerable significance, as some studies [e.g., 26] have noted that similar occurrences of large off-trench intraslab events within an oceanic plate can be correlated with the subsequent generation of megathrust earthquakes in the adjacent subduction area.

3.3. The 2013 M_w7.2 Bohol Earthquake

On October 15, 2013 at 00:12 UTC, a shallow large earthquake (generated by a previously unmapped fault) occurred on the island of Bohol (in the Philippines), devastating many towns in the northern and western part of the island. Bohol Island is famous both for its churches (that are centuries old) and the Chocolate Hills, which are a natural formation of hundreds of conical Karst mounds. Bohol had not experienced a large inland earthquake in 400 years, as attested by its many churches that had been standing since the 1600s. Unfortunately, the Bohol event damaged 25 churches, reducing some of the biggest and oldest ones to rubble. Recent seismic hazards mapping in Bohol [27] showed that the earthquake sources in the area were the East Bohol Fault (no associated earthquake of $M > 6.0$), and the offshore fault along the southern coast of the island that generated a series of events in 1990 (M_w6.6) and caused a small tsunami of < 1 m (**Fig. 10a**). However, prior to the 2013 event, the only indicators of the existence of another active fault in the area were the 1981 M_w6.6, 1982 M_w5.7 event, and the 1996 M_w5.6 event (**Fig. 10a**) (the latter event occurred close to the 2013 hypocenter and caused slight damage to a number of poorly built structures). PHIVOLCS reported an M_s5.2 event in 2004, but located its epicenter and aftershocks offshore to the north of the 2013 epicenter. It is of considerable interest that although these events had occurred, there was no clear indication of a major thrust fault in the area capable of generating the 2013 event. The deterministic ground-shaking hazards assessment of Narag et al. (2007) [28] attempted to consider the 1996 and 2004 events, but lacked detailed fault parameters, and thus the generator was modeled as a point source offshore with a maximum seismic potential of M_w6.5. The results therefore underestimated the hazards, predicting a maximum intensity of VII (PHIVOLCS Earthquake Intensity Scale or PEIS) [29], while accounts of the 2013 earthquake imply that it reached at least PEIS VIII in towns along the fault zone [30].

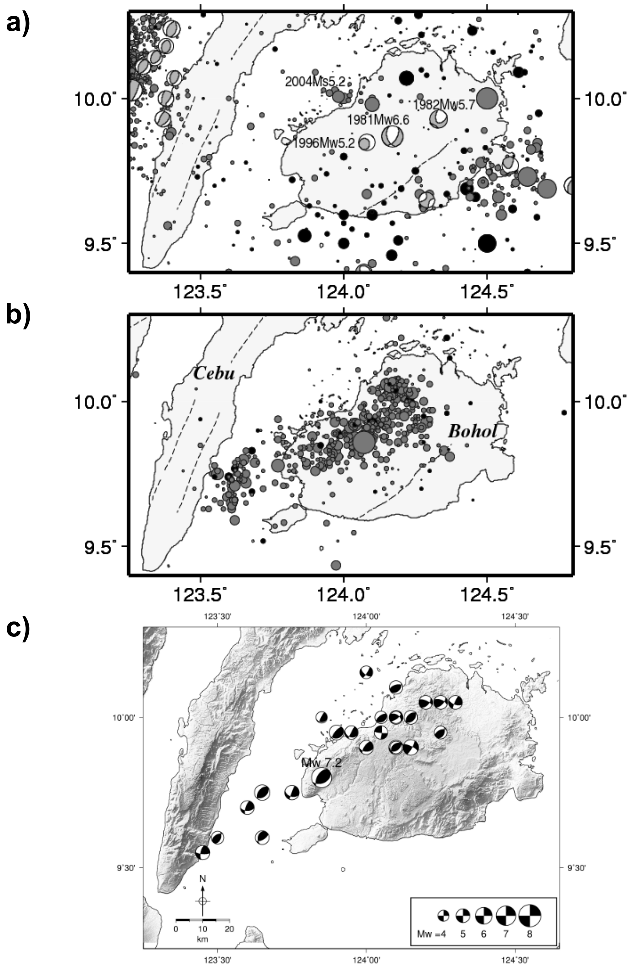

Fig. 10. Seismicity of Negros, Philippines. a) Hypocenters from 1900 – October 14, 2013 and b) October 15, 2013 to March 31, 2014. Data source: PHIVOLCS. c) Focal mechanisms obtained by SWIFT for events within the period of October 15 to November 2013.

The 2013 event left ENE-WSW trending surface ruptures with a length of approximately 6 km in the northern towns of Bohol [30], and the fault has now officially been labeled the "North Bohol Fault" [30]. In addition to this geological feature, the large number of aftershocks plotted by the Philippine national network showed a distribution of events that extended for ~100 km (**Fig. 10b**). Therefore, with only 6 km of observable surface rupture, the implication is that the North Bohol Fault is practically a blind fault for most of its length, and as the island has a limestone foundation there is clearly a challenge in relation to mapping the faults of the area. However, using the fully operational moment tensor analysis system in the Philippines, we determined the CMT source parameters for the Bohol mainshock and 27 of its aftershocks recorded from October 15 to November 11, 2013. For the mainshock, the best fitting double couple solution (**Fig. 11a**) indicated a thrust faulting source oriented ENE–WSW, which is consistent with those obtained by global networks [31, 32]. It also indicated that the centroid was located at a depth of 10 km at 123.8°E and 9.8°N, and that the two nodal planes were oriented at (strike, dip, rake) = (212°, 53°, 68°) / (66°, 42°, 116°). **Fig. 11(b)** shows the waveform match between the observed and synthetic seismograms. We obtained an estimated seismic moment of $M_0 = 7.12 \times 10^{19}$ Nm, corresponding to $M_w = 7.2$.

We also obtained SWIFT CMT solutions for 27 aftershocks ($4.1 \le M_w \le 5.7$). The spatial distribution of their centroid locations shows that the events occurred offshore between Bohol and the southern tip of Cebu. The spatial distribution of the aftershock centroids formed a band of about ∼100 km long, which was oriented ENE–WSW (**Fig. 10c**), probably indicating the extent of the fault zone. This observation is coherent with the aftershocks reported by PHIVOLCS. It should also be noted that the centroid of our mainshock is near the center of the aftershocks band, and that the area corresponds very well to the area of the largest ground displacement (exceeding 1 m) in the northwest part of Bohol Island, as detected from SAR pixel offset analysis [33]. Our analysis also showed that the majority (21/27) of the aftershocks had reverse focal mechanisms, with the principal compressional axes consistent with that of the mainshock, while some aftershocks near both termini of the inferred fault zone showed strike-slip mechanisms. Interestingly, most of the strike-slip aftershocks were concentrated on the northern terminus of the aftershocks, directly near the area where the fault was documented to have broken surface for ∼6 km, and where vertical displacements of ∼2 m were evident [30, 31].

Based on the above observations, we can infer that the fault zone for the M_w7.2 2012 Bohol earthquake was ∼100 km long and oriented ENE–WSW. In addition, it was established that the fault transects a large part of Bohol and extends offshore towards Cebu. This case represents another example of how the new component of Philippine earthquake monitoring, which allows regional moment tensor analysis, can contribute to the understanding of earthquake generation in the Philippines.

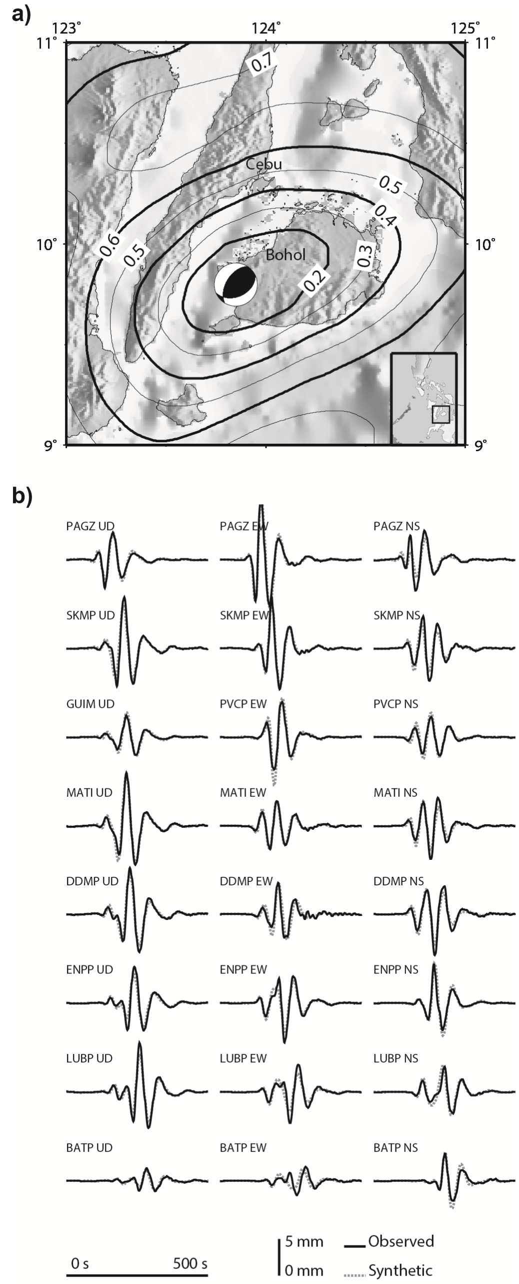

Fig. 11. Waveform matches obtained from the waveform inversion of the M_w7.2 Bohol earthquake of October 15, 2013. a) Contour plot of the horizontal residual distribution around the best-fitting source centroid. b) Solid black and dashed gray traces represent the observed and synthesized seismograms, respectively. The station code and component of motion are indicated at the upper left-hand side of each seismogram.

4. Conclusions

This paper shows how the development of a regional moment tensor analysis in the Philippines can contribute to earthquake monitoring, and to gaining an understanding of the seismotectonics of the region. During the initial implementation of the system (2011–2013), we obtained source parameters for three recent damaging earthquakes in the Philippines: the M_w6.7 February 6, 2012 Negros; the M_w7.6 August 31, 2012 Samar; and the M_w7.2 October 15, 2013 in Bohol. In our first case, we determined that the Negros mainshock could be explained by a source with a centroid located slightly offshore from the eastern coast of Negros, and characterized by a shallow NE–SW trending reverse fault with a small strike-slip component. The CMT solution agreed well with the aftershocks reported by the national network, indicating a fault zone close to, or underneath, the eastern coast of Negros, and thus explaining the devastation of many of the island's coastal towns. For the second case, we showed that the new system detected the Samar earthquake, and determined it as an outer-trench slope thrust event within the Philippine Sea Plate. The earthquake triggered a large number of normal aftershocks near its vicinity, and fewer thrust events closer to the trench axis. This work shows, through a Coulomb stress analysis using the SWIFT CMT solutions of 32 aftershocks, that the clustering can be explained by a Coulomb stress change in the region. These observations are important, as some studies [e.g., 26] have noted that similar occurrences of large off-trench intraslab events within an oceanic plate can be correlated with the subsequent generation of megathrust earthquakes in the adjacent subduction area. The Samar 2012 earthquake series could have an implication for the level of readiness of nearby towns in relation to tsunamis, especially as the Samar outer-trench slope thrust event is found adjacent to an area of the Philippine Trench (which is an apparent seismic gap). For the case of the Bohol earthquake, we used SWIFT CMT solutions for the mainshock and 27 aftershocks, and inferred that the fault zone was ∼100 km long, oriented ENE–WSW, with the fault transecting a large part of Bohol and extending offshore towards Cebu. This result agrees well with the distribution of aftershocks reported by PHIVOLCS. However, only ∼6 km of surface ruptures have been found associated with the Bohol earthquake, which implies that the North Bohol Fault is practically a blind fault for most of its length. This nature, aggravated by the limestone foundation of the island, clearly poses challenges to fault mapping in the area, which again highlights the usefulness of obtaining seismic data.

Our recent descriptions of the three most recent damaging earthquakes in the Philippines shows that the newly developed regional moment tensor analysis system could be very useful in the advancement of an understanding of the seismotectonics in the area, and in the better assessment of the seismic potential of both known and unknown earthquake sources in the country. When further developed, the new system (which allows for a quick and automated source determination using regional data) will be useful in providing a scientific basis for appropriate tsunami warnings, or for the adjustments of initial warnings.

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