

Article

Complex Shear Partitioning Involving the 6 February 2012 M_W 6.7 Negros Earthquake Ground Rupture in Central Philippines

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Abstract: A 75 km-long, generally NE-striking ground rupture associated with the 6 February 2012 M_W 6.7 (M_b 6.9) Negros earthquake was mapped on the eastern side of Negros Island, Philippines. It closely follows a previously unmapped, pre-existing fault trace along the coast which is marked mostly by terrace-forming scarps. The dominance of vertical separation (west side up) is consistent with a west-dipping reverse fault, as indicated by focal mechanism solutions. The ground rupture map eliminates the ambiguity in the focal mechanism solution regarding the orientation, sense of motion, and location of the seismogenic fault plane, which are indispensable in the assessment of seismic hazards and the nature and distribution of deformation. This study uses the ground rupture map of the 2012 Negros earthquake in sorting out the mechanism of deformation in the Visayas Islands region. The ground rupture's length is well within the aftershock area while its scarp heights are consistent with an earthquake of its magnitude and nature of movement. The 2012 Negros earthquake rupture's pattern, scarp types, and offset of man-made structures are similar to those of recent reverse/thrust ground ruptures mapped globally and are distinct from those associated with erosion, landslide, and liquefaction. The onshore coseismic reverse fault of the Negros earthquake, which contradicts a model of coseismic slip on an offshore blind thrust fault by previous workers, represents the first thoroughly mapped ground rupture of its kind in the Philippines. The ground ruptures of the 2012 Negros and 2013 Bohol earthquakes, along with the Philippine Trench and the Philippine Fault Zone (PFZ), represent a complex shear partitioning mechanism in the Visayas Islands region. This departs from the current simple shear partitioning model for the region and is distinct from those for other regions along the PFZ and adjacent subduction zones. This study shows how an appreciation of morphotectonic features can lead to a better understanding of the distribution of deformation and the nature of earthquake hazards.

Keywords: Negros Oriental Fault; ground rupture; reverse fault; shear partitioning; fold-and-thrust belt; Philippines

1. Introduction

On 6 February 2012 (03:49 UTC/11:49 AM local time), a magnitude (M_W) 6.7 earthquake struck the island of Negros in Visayas, Central Philippines (Figure 1A). The mainshock epicentral location was 23 km southwest of Guihulngan City (9.97° N, 123.14° E) and the focus was estimated to be ~5 km deep (Figure 1A). The mainshock focal mechanism solution (FMS) (strike = 180°, dip = 60°, rake = 60°)

and aftershock epicentral locations from the Philippine Institute of Volcanology and Seismology [1] are combinedly consistent with a roughly NNE-striking, steeply dipping fault that intersects the surface both along the coast and inland.

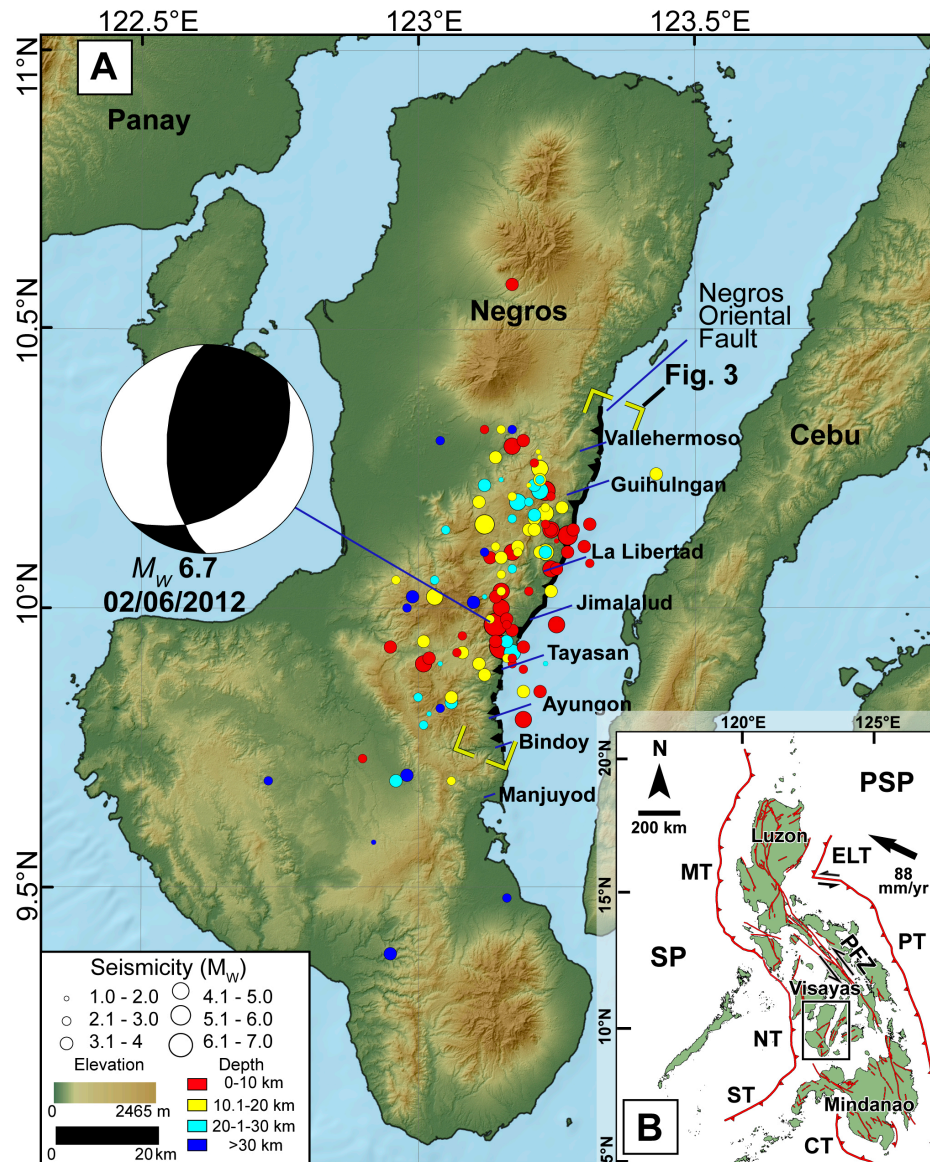


Figure 1. (A). Map of Negros Island with the focal mechanism solution (FMS) of the mainshock and plots of aftershocks (6–20 February 2012) from the regional seismic network of the Philippine Institute of Volcanology and Seismology (PHIVOLCS) [1] (color-coded and scaled circles according to focal depth and magnitude, respectively); a rough trace of the ground rupture (thick black line enclosed in yellow box corners); and names of the coastal municipalities intersected by the ground rupture. The base map is a 30-m digital elevation model Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM). For locations of PHIVOLCS' seismic stations, readers are referred to the following website: <https://www.phivolcs.dost.gov.ph/index.php/earthquake/earthquake-monitoring>. (B). Inset map showing the Philippine archipelago and its currently mapped active tectonics features according to PHIVOLCS (<http://faultfinder.phivolcs.dost.gov.ph/>). SP—Sunda Plate, PSP—Philippine Sea Plate, MT—Manila Trench, NT—Negros Trench, ST—Sulu Trench, CT—Cotabato Trench, ELT—East Luzon Trough, PT—Philippine Trench, and PFZ—Philippine Fault Zone. Black rectangle indicates the location of Negros Island.

The 2012 Negros earthquake, the historically strongest earthquake to strike Negros Island, provides a valuable opportunity to document a previously unmapped reverse fault. Globally, such information is important, since there is a dearth of information on ground ruptures associated with reverse fault-related earthquakes [2]. Locally, its recognition allows for a better assessment of seismic hazards within the island. Lastly, recognition of the ground rupture of the 2012 Negros earthquake (which we propose to call the ‘Negros Oriental Fault’), along with other recently recognized active structures in the Visayas region [3], allows us to explore the role that these structures possibly play in the accommodation of deformation in the complex tectonic setting of the Philippines. Previous models of shear partitioning in or near the area suggest distribution of relative plate motion of the Philippine Sea Plate (PSP) only on the Philippine Trench and the Philippine Fault Zone (PFZ) [4–6], or mainly on the Philippine Trench, the PFZ, and other strike-slip faults [7]. While the importance of documenting the recent occurrence of events with reverse/thrust faulting mechanisms from the standpoint of hazard assessment is widely recognized [8], the ground ruptures should be mapped accurately through the appreciation of the physical evidence, the foremost of which is geomorphological in nature. This study resolves the uncertainty regarding the location and manifestation of the 2012 Negros earthquake rupture, which previous workers [8] hypothesized to have occurred along an offshore blind thrust fault. With the occurrence and precise mapping of the ground rupture of the 2012 Negros earthquake and ground ruptures of the other recent reverse/thrust events, a more complex model of shear partitioning can be drawn with greater confidence.

2. Tectonic Setting

Negros Island is situated in western Visayas, Central Philippines (Figure 1A,B). The Philippine Archipelago is predominantly an island arc flanked to its west and to its east by two major trench systems. The Sunda plate subducts southeastward along the Manila-Negros-Sulu-Cotabato Trench System, while the PSP subducts northwestward along the Philippine Trench System (Figure 1B) [9–14]. The Philippine Sea Plate-Sunda Plate oblique convergence is supposedly currently being accommodated by shear partitioning, with the lateral and perpendicular components of plate motion being translated along the ~1400-km-long, left-lateral strike-slip Philippine Fault Zone (PFZ) and the East Luzon Trough-Philippine Trench System, respectively (Figure 1B) [4,5,7,9,15]. Whether the East Luzon Trough truly plays an active role in this in northern Luzon shall be discussed in this paper. The northernmost extent of the PFZ can be traced from Luzon in the north [16–19], through the central Philippines (Figure 1B) [5,15], and southward to Mindanao (Figure 1B) [20–22].

Negros Island is bound to its west by an east-dipping subduction zone defined by the active Negros Trench and to its east by the southern-central segment of the PFZ (Figure 1B). The region, in which Negros and the adjoining seas and islands of Panay, Cebu, and Bohol belong, is composed of Pre-Late Middle Oligocene volcanic plutonic basement of the Visayan block, Middle Miocene Valderrama volcanic arc terrane, Late Oligocene-Middle Miocene sediments, and the Pliocene-Quaternary Negros volcanic arc (Figure 2) [23]. The four volcanoes and their deposits in Negros are associated with the Negros Trench. These are preceded by Oligocene to Pliocene intrusions and their equivalent extrusives in the island [24]. The Visayan Sea Basin, from the eastern coast of Negros to Bohol and through Cebu, represents the back-arc region of the Negros arc system and is underlain by ~4-km-thick carbonate and volcanoclastic deposits. NNE-SSW folds and thrusts and other structures were generated during deformation periods associated with collisions/subductions during the Miocene [23,25] and from Late Miocene to the present, which is associated with the collision of the Visayan Block with the North Palawan Block [23]. Younger NNE-SSW-trending horst and graben structures, that are probably related to the slowing down of convergence along the Panay-Negros boundary, are thought to be present as well (Figure 2) [23]. In the Late Miocene-earliest Pliocene, convergence along the Negros Trench was more important than movement along the PFZ [23]. The slowing down of convergence between colliding blocks along the Panay-Negros boundary resulted in decoupling along the PFZ as the high convergence rate between the Eurasian Plate and the PSP can no longer be absorbed wholly along the

Panay–Negros boundary [23]. At present, motion along the PFZ is more important and has slowed down along the Negros Trench [23]. The PFZ formed 4 Mya after the plate convergence changed from north to NNW with respect to Eurasia [6]. Estimates suggest that about one third (2 to 4 cm/y) [5,26] of the NW motion of the PSP is currently being accommodated by the PFZ. It was believed that the rest of the plate motion was absorbed only along the Philippine Trench and the PFZ [4,5,7] before the 2012 Negros and 2013 Bohol earthquakes occurred.

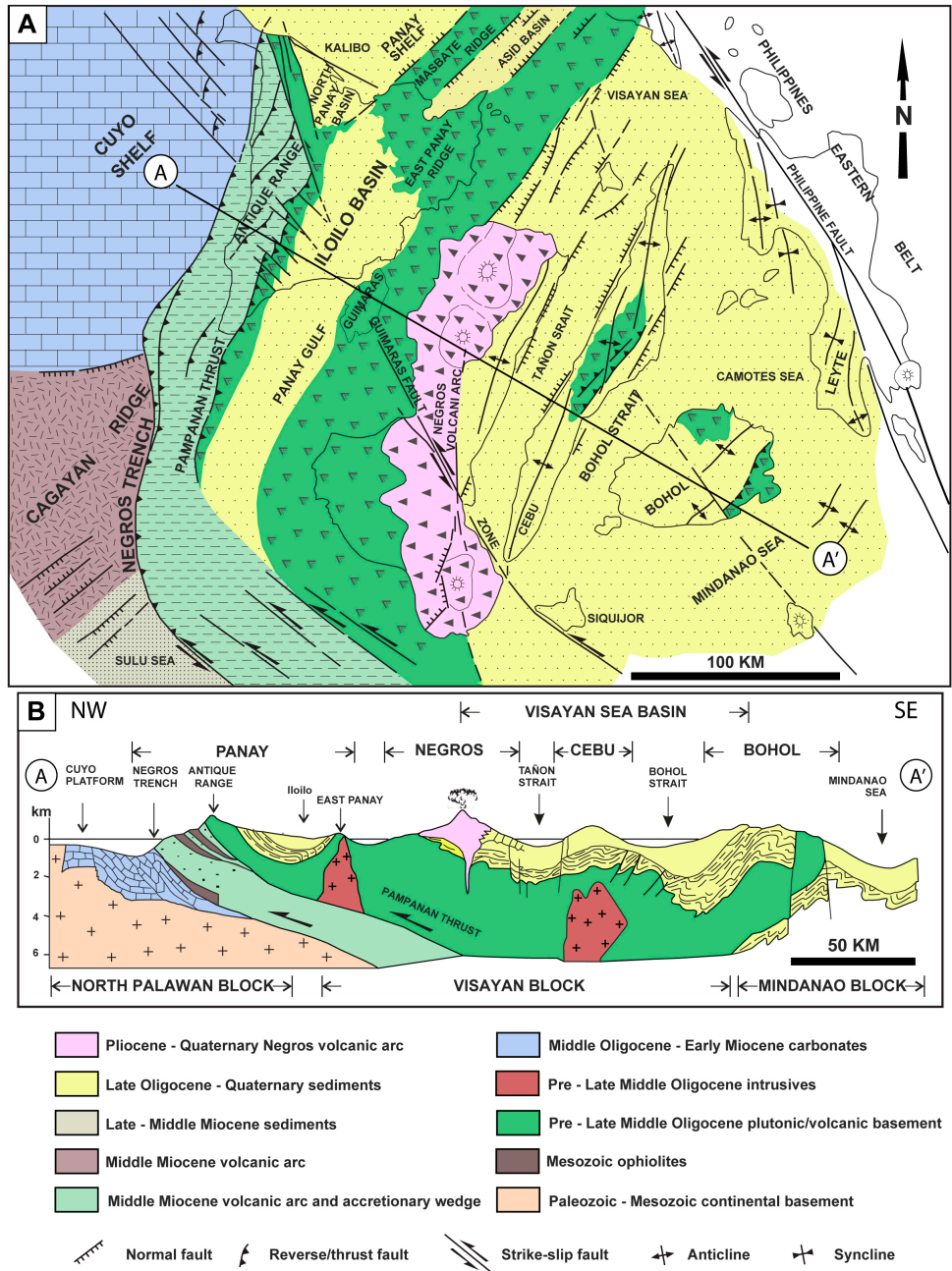


Figure 2. (A). Geologic map of the Panay–Negros–Cebu–Bohol region, west of the Philippine Trench and the Philippine Fault as modified from Rangin et al. (1989) [23]. The map shows an active Trench (Negros Trench) west of the region and a complex of broad fold-and-thrust structures, interrupted in places by normal and strike-slip faulting. **(B).** Schematic cross-section taken from A–A' more clearly shows the relationships and distribution of the structures as modelled by Rangin et al. (1989) [23].

3. Ground Rupture Mapping

Field mapping of the ground rupture was conducted in May 2013, guided by information that was gathered from earlier investigations which described the various coseismic ground deformation features associated with the 2012 Negros earthquake. Several teams that set out to map the geologic impacts of the 2012 Negros earthquake were able to identify and characterize the earthquake's secondary effects, such as landslides, liquefaction-related features (e.g., lateral spreading, fissuring, and sand boils), subsidence, coastal uplift, and tsunami-related inundation markers—all except for the trace of the earthquake generator's ground rupture [8,27–29]. In the following subsections, we present the details of our mapping and the characteristics of the ground rupture that we documented.

3.1. Rupture Trace

A ~75-km-long ground rupture was traced on the eastern coast of Negros Island from Vallehermoso to the north and Bindoy to the south (Figures 1, 3 and 4). The locations of the rupture traces were documented by taking waypoints and by plotting these on Google Earth imagery. Where available, 1-m-resolution (0.5-m vertical and horizontal accuracy) light detection and ranging (LiDAR) digital elevation models (DEMs) from the Philippine-Light Detection and Ranging (Phil-LiDAR) program [30], were used to accurately plot the rupture trace. LiDAR strip maps of select sites show the bases of traces determined in the field (Figure 5A–F). The ground rupture follows the orientation of the coastline: NNE-striking (~N5E) for the most part of the Vallehermoso; NE-striking (~N25–30E) from Guihulngan to Tayasan; and NNW (~N5W) from south of the municipalities of Tayasan to Bindoy (Figure 3). The traces of the rupture are longer (Figures 3 and 4A–C; up to ~6 km in Guihulngan) and separated by shorter gaps from Vallehermoso to Tayasan. South of Tayasan to Bindoy, however, the traces of the rupture become shorter and more discontinuous (Figures 3 and 4D,E; as short as ~300 m in Bindoy).

The Negros Oriental Fault's trace complexity and scarp morphologies resemble the ground rupture characteristics of large magnitude reverse/thrust fault-generated earthquakes in the past few decades, such as the 2013 M_W 7.2 Bohol earthquake, also in the Visayas region, Philippines [3], and the M_W 7.9 2008 Wenchuan (Sichuan) earthquake in China [31–37], M_W 7.6 2005 Kashmir earthquake in Pakistan [38], and the M_W 7.6 1999 Chi-Chi earthquake in Taiwan [39,40].

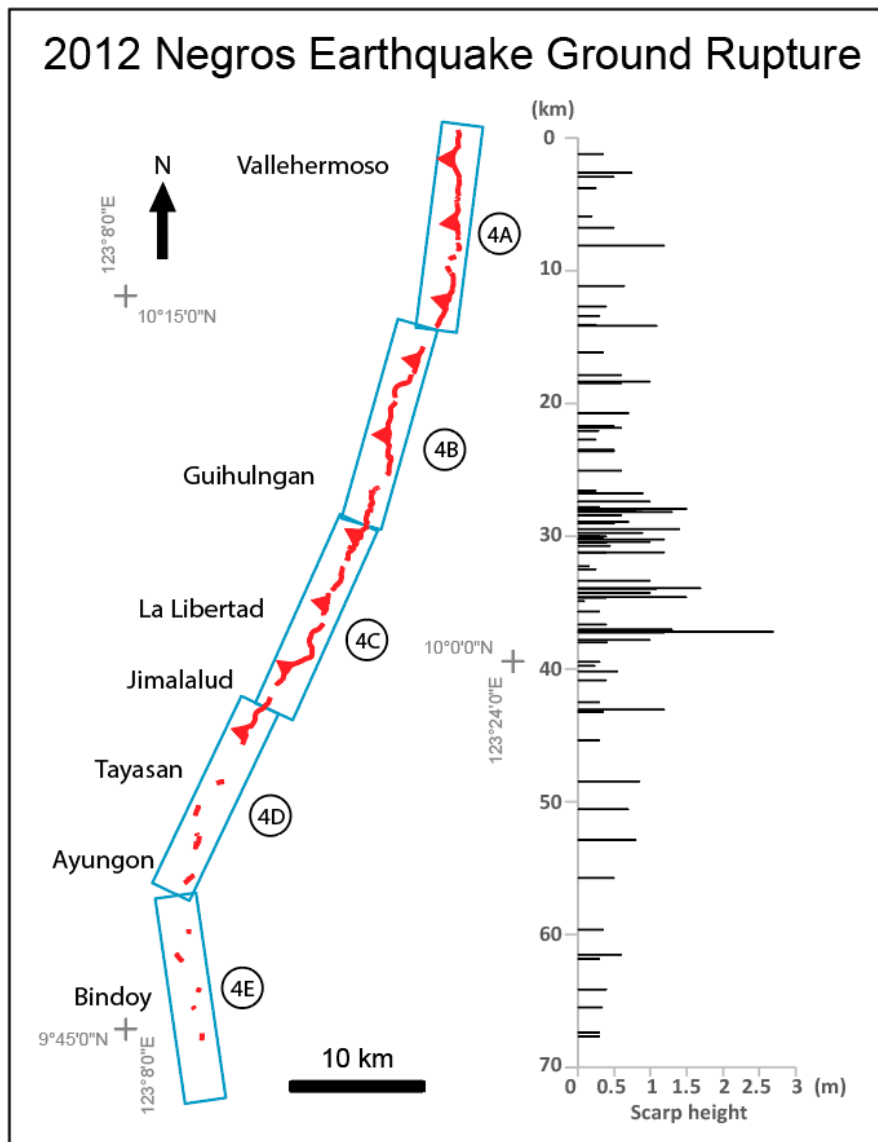


Figure 3. Large-scale trace of the coseismic ground rupture associated with the 6 February 2012 Negros earthquake (the Negros Oriental Fault) juxtaposed with a bar graph of field-measured scarp heights. Blue rectangular boxes indicate the boundaries of the more-detailed strip maps of the ruptures. Letter-number combinations in circles indicate the figure labels that correspond to each strip map.

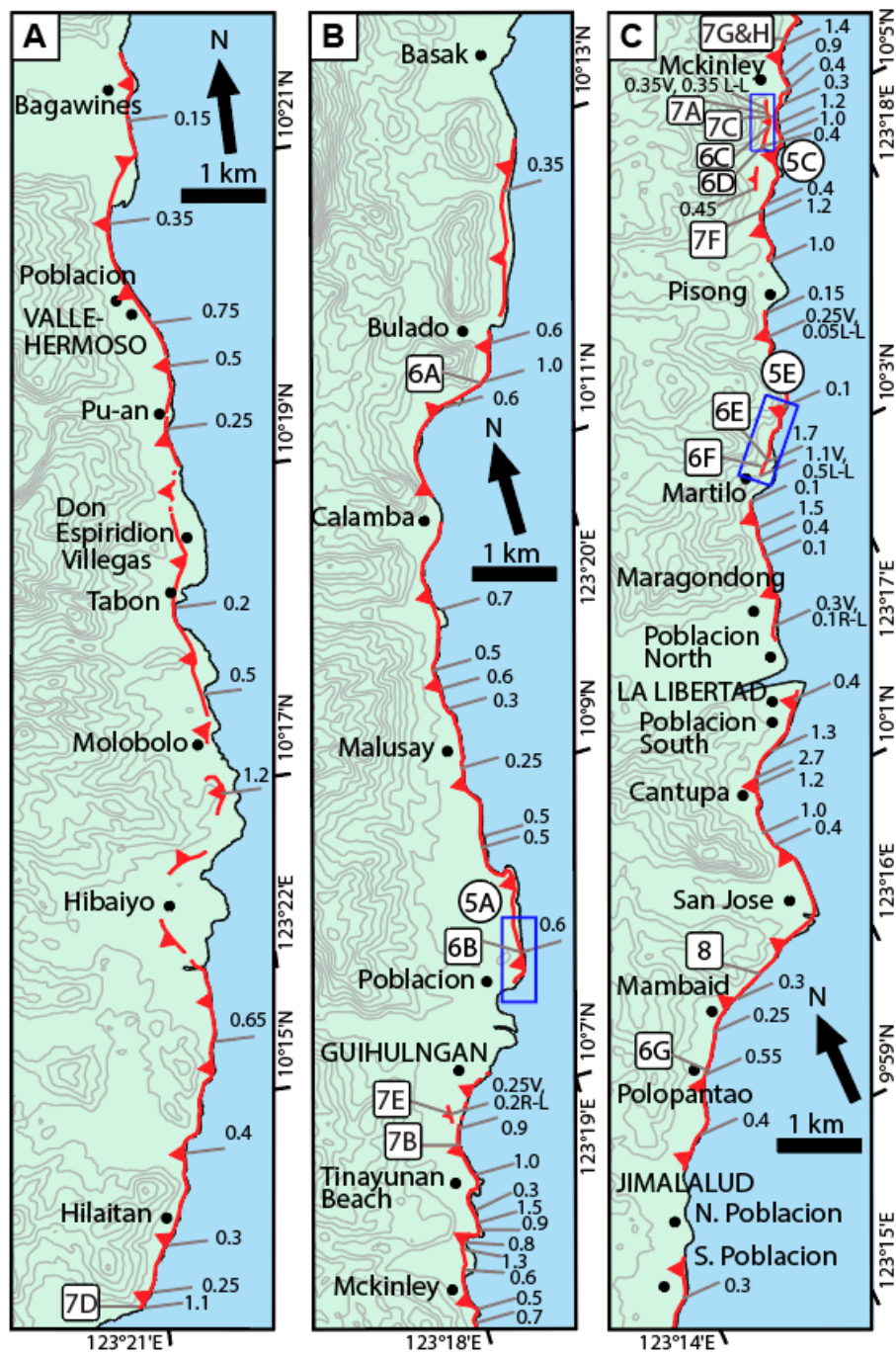


Figure 4. Cont.

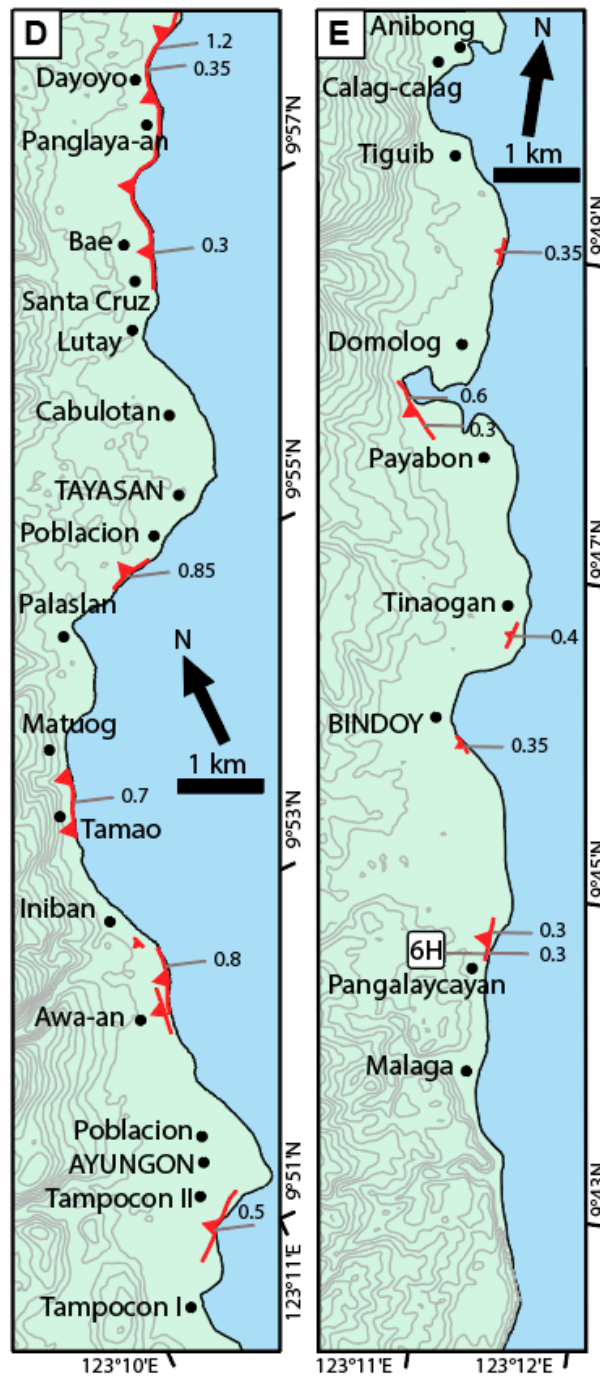


Figure 4. (A–E) Detailed strip maps of the coseismic ground rupture of the 6 February 2012 Negros earthquake (the Negros Oriental Fault). Field measured scarp heights are indicated in meters; any horizontal component of slip is indicated and distinguished from vertical measurements or scarp heights by appending the notations ‘L-L’ for left-lateral and ‘R-L’ for right-lateral. Capitalized place names are municipalities; all others are names of *barangays* (‘village’, which is the country’s smallest government unit). Letter–number combinations in circles indicate the figure numbers of selected LiDAR strip maps (enclosed in blue rectangles), while letter–number combinations in squares indicate locations of photos. Contours are spaced at 20-m intervals, starting at 0 m along the coast.

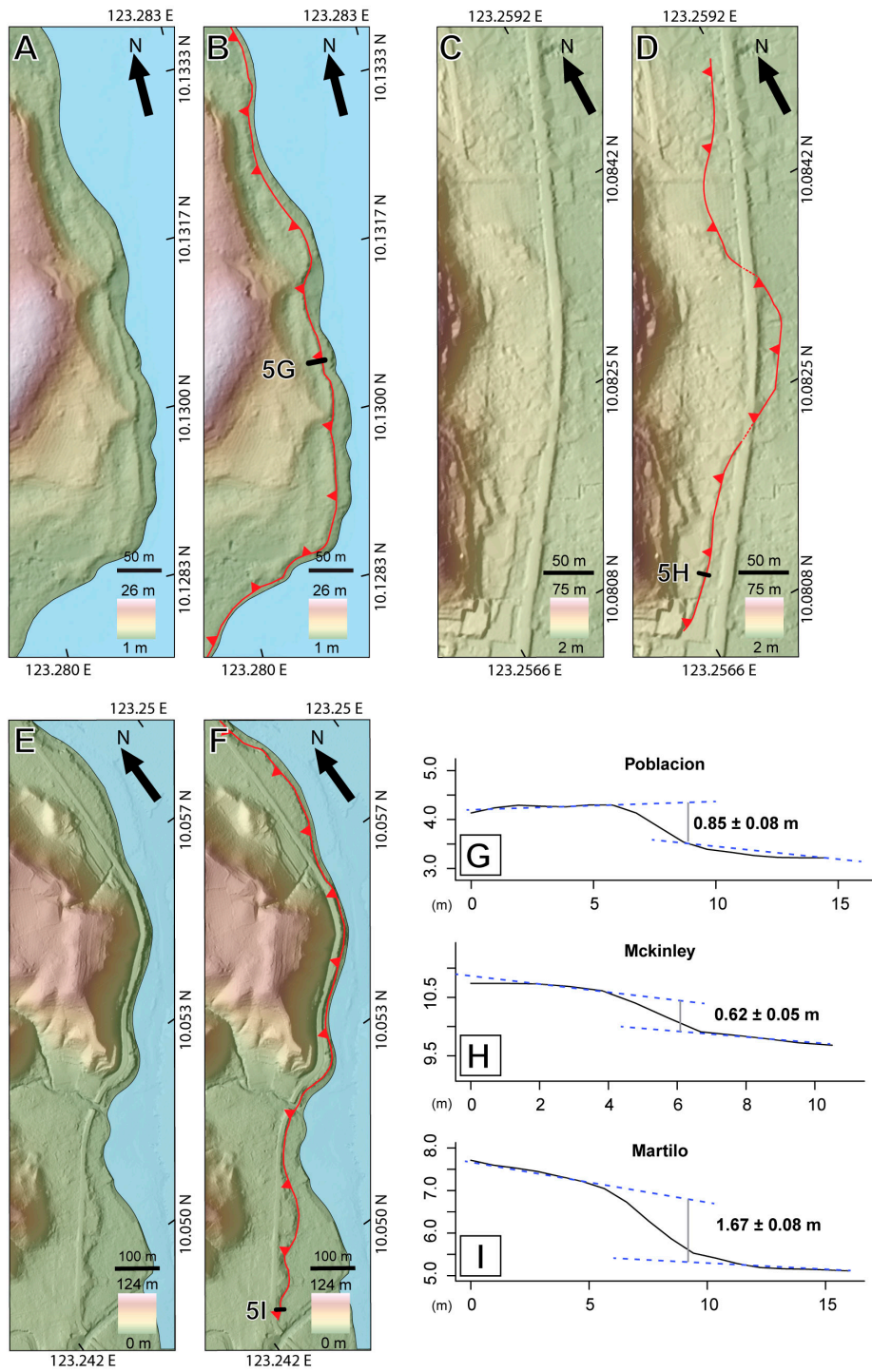


Figure 5. LiDAR rupture strip maps of the Negros Oriental Fault. (A,C,E). Bare, digital elevation model-hillshade overlay strip maps showing the bases of the rupture trace. (B,D,F). Rupture trace strip maps with location of scarp topographic profiles (thick black lines labelled with letter-number combinations). Figure 6B,D,F shows the sites of scarp profiles shown in Figure 5G–I, respectively.

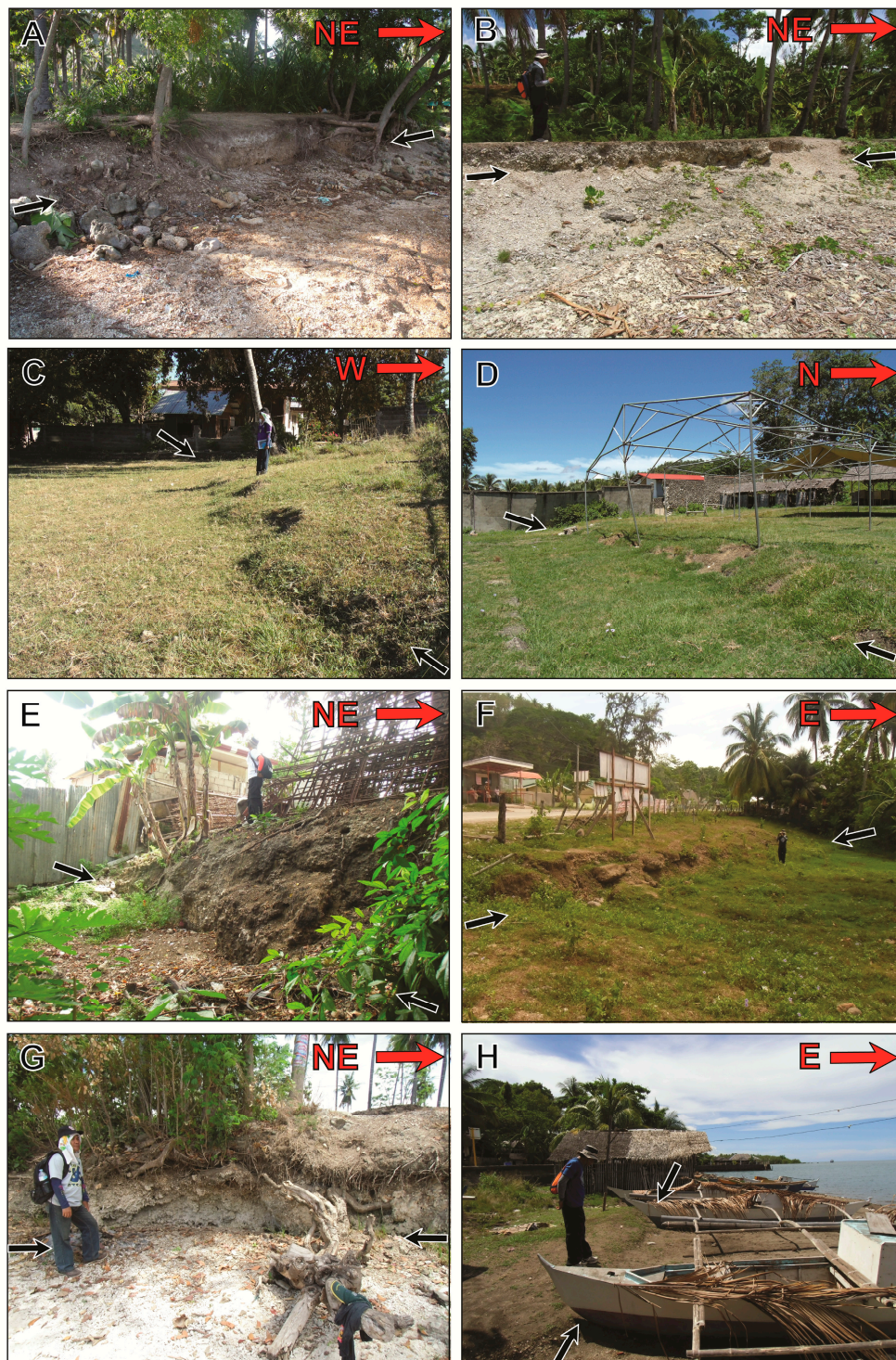


Figure 6. Scarps of the 2012 Negros earthquake ground rupture. (A). Eroded collapsed scarp (Kinayan, Calamba, Guihulngan). (B). Eroded simple scarp (Poblacion, Guihulngan). (C). Protruded fault scarp (McKinley, Guihulngan; vertical displacement is evident from tilting and bending of post of tent frame; horizontal shortening is shown by deformation of fence on downthrown side). (D). Flexural type of scarp (McKinley, Guihulngan). (E). Eroded collapsed scarp (Martilo, La Libertad). (F). Fault scarp with combined features of simple and flexural fold scarps (Martilo, La Libertad). (G). Fault scarp with combined features of simple and flexural fold scarps (Mambaid, Jimalalud). (H). Flexural type of scarp (Pangalaycayan, Bindoy).

3.2. Scarp Heights

Scarp heights (Figure 3) were measured manually using a stadia rod with 5-cm precision. Scarp height measurements are higher towards the center of the fault between Guihulngan and La Libertad, reaching a maximum of ~2.7 m. Towards the northern and southern ends of the fault in Vallehermoso and Bindoy, respectively, scarp height measurements taper (Figure 3; Supplementary Materials Table S1). Scarp heights, on average, were ~0.6 m. Coverage of the LiDAR DEM for Negros Island from the Phil-LiDAR program was incomplete and did not cover the entire length of the fault. In some areas where LiDAR data were available, the displacement from the 2012 earthquake was either too small (<0.25 m) to confidently measure displacement by constructing scarp profiles or indistinguishable from previous displacement on pre-existing scarps. However, a study of the ground rupture associated with the 2013 M_W 7.2 Bohol earthquake by Rimando et al. (2019) [3], which also utilized Phil-LiDAR data, demonstrates that a good correspondence exists between scarp heights measured in the field using a tape measure and those measured from scarp topographic profiles derived from LiDAR DEM. Indeed, field-measured scarp heights from Poblacion, Mckinley, and Martilo of ~0.6, ~0.4, and ~1.7 m (observation points 25, 44, and 52 in Table S1, respectively), are very similar to the scarp heights of ~0.85, ~0.62, and ~1.67 m calculated from select LiDAR-derived scarp topographic profiles (Figure 5G–I).

3.3. Scarp Morphologies

The ground rupture of the 2012 Negros Oriental earthquake is quite similar to the scarp morphologies of several historical reverse/thrust ground ruptures mapped elsewhere (e.g., Taiwan, China, and Pakistan) (Figure 6) [31–40]. The most-common types of scarps encountered were simple (Figure 6B), collapse (Figure 6A), and flexural-fold fault scarps (Figure 6D). The pressure that accompany thrusting generates monoclin scarps or flexures, and rollovers. Both monoclin and simple scarps oftentimes go together (Figure 6F,G). Most of the near-shore scarps encountered display a simple scarp morphology (Figure 6B). Some display a complex profile due to collapse of the simple scarps. The deformation along the rupture zone had also caused tilting of many trees.

4. Discussion

In the initial absence of reports of a ground rupture trace both on Negros Island and offshore in between the islands of Negros and Cebu immediately after the earthquake (Figure 1) [27–29], Aurelio et al. (2017) [8] suggested an offshore blind thrust nature for the 2012 earthquake. Their model was based both on focal mechanism solutions obtained from other seismic networks that suggest an offshore mainshock location [41,42], and on interpretation of fold-fault structures from pre-2012 industry seismic profiles. While Aurelio et al. (2017) [8] present important evidence for the existence of shortening structures in a region which was previously characterized by extension, direct proof of movement of a pre-existing offshore, blind thrust fault during the 2012 Negros earthquake has yet to be established. However, SONAR surveys conducted by PHIVOLCS [28] across the Tañon strait's seabed show no evidence of hanging wall deformation (e.g., warping or broad uplift) that would correspond to an offshore blind thrust fault that is consistent with an M_W 6.7 earthquake. The fact that practically all the damage was very close to or along the coast and very little damage was documented offshore clearly contradicts the offshore blind thrust model by Aurelio et al. (2017) [8]. Furthermore, the fact that previous workers did not recognize the ground rupture [8] does not preclude its presence onshore. Unfortunately, Aurelio et al.'s (2017) [8] surveys during the "critical first 72 h following the earthquake" mostly involved helicopter rides and mere cursory field inspection of randomly selected sites that show the different types of earthquake secondary effects, thereby preventing them from focusing on the more specialized and demanding task of mapping the ground rupture. Closer examination of the deformation along and/or very close to the eastern coast of Negros Island (the surface projection of the fault plane suggested by seismicity), including revisiting and establishing the length and continuity of

‘probable ground ruptures’ partly described by Abigania et al. (2012) [27], led to the identification of the elusive ground rupture of the 2012 Negros earthquake. The findings were first presented in the annual geological congress held in 2013 in Manila [43].

Our interviews with residents of areas adjacent to the ground rupture revealed a number of theories by the locals about the nature of the suspected scarps/ground rupture that have appeared after the February 2012 earthquake in Negros Oriental. Not surprisingly, teams from several agencies dispatched to the scene are as uncertain about the nature of the scarps along the ground rupture that they have encountered. Among the mechanisms mentioned include erosion, coseismic uplift due to movement of an offshore ground rupture, subsidence, and liquefaction. Notwithstanding all the theories that have been made, the ground rupture of the 2012 Negros earthquake was mapped along the eastern coast of Negros Island. A focal mechanism solution indicating mainly reverse faulting with minor strike-slip component is consistent with field observations (i.e., displaced features with mostly vertical displacement and lateral component as well; Figure 7). The location of ground rupture is consistent with the geometry of the subsurface rupture inferred from the mainshock focal mechanism and distribution of aftershocks (Figure 1).

There are several reasons why an onland coseismic ground rupture cannot be missed during field mapping. Indicators such as ground rupture length, scarp height distribution, scarp morphologies (Figure 6), ground rupture patterns (Figures 3 and 4), nature of materials cut by the surface trace (Figures 6 and 7), relation to pre-existing fault scarps (Figure 8), and damage to structures and vegetation (Figure 7) are helpful tools in recognizing the ground rupture.

The length and along-strike scarp height distribution of the fault mapped along the eastern coast of Negros Island are consistent with the configuration of the fault suggested by the seismicity data (Figure 1A). The length of the ground rupture (75 km) hovers beyond but near the upper limit of the range for a M_W 6.7 event, as determined by the empirical relationship between moment magnitude and surface rupture length [2]. However, this is based on a limited number of coseismic reverse/thrust fault earthquakes (only 19). Since it is difficult to rule out a data bias with a sample size that is so small, it is possible that calculations from the scaling relationships could be biased towards shorter rupture lengths. More data from events with a reverse faulting mechanism such as the 2012 Negros earthquake should help refine the model [2]. Nevertheless, the surface trace of the 2012 Negros earthquake is well within the aftershock area. Based on the same model, scarp heights are within the range for M_W 6.7 earthquakes with reverse faulting mechanism. Equally likely is a scenario in which significant aftershocks ($\sim M_W$ 5–6), which occurred within a few days of the mainshock, may have also ruptured and overlapped with the ground rupture associated with the main event. Another possibility is that the frictional resistance along the fault may have allowed a longer than usual ground rupture length. If it is not a ground rupture related to the 6 February 2012 M_W 6.7 Negros earthquake, it must be the longest continuous earthquake-related liquefaction, erosional, or landslide feature, to be mapped. As in Negros Oriental, the coseismic liquefaction features documented along the shores of Haiti [44] are not thoroughgoing features (e.g., no more than a few hundred meters long).

The scarp morphologies and the rupture trace are characteristic of primary reverse/thrust fault ruptures recognized in recent and historic times [45–48]. The scarps are distinct from the surface expression of phenomena other than primary surface faulting such as landslide-toe scarps or sackungen associated, for instance, with an east-directed, deep-seated landslide; secondary faulting resulting from backthrusting of a hypothetical east-dipping primary fault; secondary faulting such as a fault splay branching off from a hypothetical primary offshore blind thrust fault; liquefaction-related lateral spreading; ground subsidence due to differential settlement; or crown scarps of offshore, large-scale landslides. Fissures are tensional in nature, but those observed along the ground rupture are clearly closed features. Many of the clearly coseismic liquefaction features encountered are associated with (but not limited to) roads and bridge approaches.



Figure 7. Damage caused by the ground rupture to structures and vegetation. (A). The unrepaired fence in McKinley, Guihulngan shows left-lateral offset due to the ground rupture. (B). Breaking and tilting of a concrete structure south of Guihulngan town proper due to vertical displacement and horizontal shortening caused by the ground rupture with simple-flexural-fold scarp. (C). Breakage of concrete fence in McKinley, Guihulngan. The ground rupture which consists of a simple scarp followed a pre-existing terrace scarp and caused ~ 1m vertical separation. (D). A similar but smaller ground rupture scarp in Basak, Guihulngan also damaged a fence. (E). Concrete structure was deformed and offset by the ground rupture in Bgy. Padre Zamora, Guihulngan. A 0.7 m scarp face is exposed but the larger part of vertical separation is caused by warping, which in turn caused the tilting of trees. (F). The scarp in McKinley, Guihulngan also caused the tilting and collapse of a tree. (G). 1–2 m of scarp along the ground rupture in McKinley, Guihulngan. The scarp cut unconsolidated calcareous sediments overlying a gray sandstone layer. (H). The development of a pressure ridge on the upthrown side of the scarp located directly to the south of (G) caused the tilting of structures.

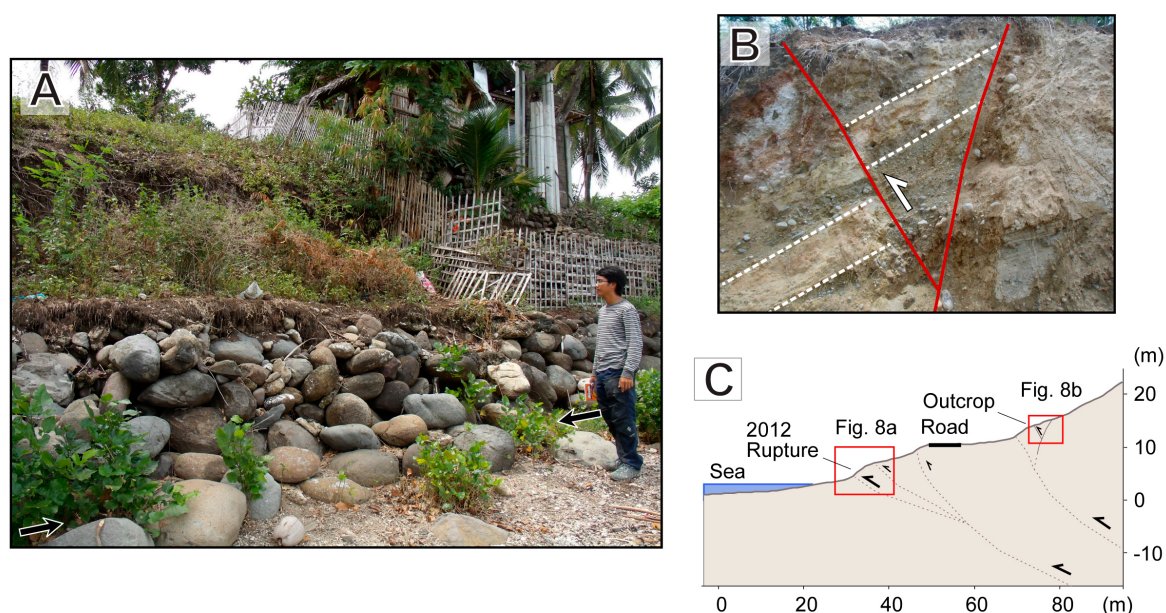


Figure 8. Proof of older, onshore late Quaternary faulting on the eastern coast of Negros Island. (A). Scarp of the 2012 Negros earthquake rupture (covered with riprap) in the foreground with older scarps of the Negros Oriental Fault in the background. (B). Outcrop of reverse/thrust faults associated with an older parallel scarp found in Mambaid, Jimalalud. (C). Schematic cross-section of faulting in the eastern Negros Island showing the possible relationship of the most recent 2012 rupture with older faulting. Location indicated by ‘8’ on Figure 4C.

Because the ground rupture mostly involves vertical displacement, some of the scarps could be confused with subsidence features. However, the sense of displacement of references with substantial lateral displacement indicate otherwise (Figure 7A). Considering the angular relationship between the ground rupture and offset references, the sense of displacement of these features by the lateral component of slip is not consistent with subsidence (Figure 7A). The scarps are also unlike the arcuate breakaway scarps and open fissures of limited extent associated with the landslides caused by the Negros earthquake.

It is also unlikely that the ground rupture we documented is a splay fault branching off from a supposedly offshore blind thrust fault, since there has not been any evidence of coseismic displacement along such a structure [8]. More importantly, the length and scarp heights of the 2012 ground rupture onshore highly suggest primary faulting.

The near-shore location of a number of the mapped scarps makes these seemingly related to erosion and/or liquefaction. However, the cutting and/or tilting of man-made structures and vegetation (Figure 7B–G) by the ground rupture do not support erosion as a cause. The observation that highly linear scarps cut coastal sedimentary units, which are either consolidated or coarse-grained (e.g., Figure 7G), makes it unlikely that these are erosional or liquefaction features. Except in a few locations, many of the sediments exposed in scarps and road cuts are either consolidated or coarse fluvio-marine sediments that are often coralline or calcareous in nature. The exposure of freshly stretched roots of trees (Figure 6A,G) by scarps indicates sudden uplift, associated with either rupturing or settlement/liquefaction, but not due to the slower process of erosion. Some of the scarps (Figure 6C–F and Figure 7A,E) are too far away from the shore (> 100 m) to be attributed to coastal erosion. Other scarp sites had been protected by seawall (e.g., Figure 7D), so attributing their formation to erosion does not seem appropriate. We disagree with the interpretation of these scarps as berms. We have revisited the exposures described as berms by Abigania et al. (2012) only to find out that these are part of the ground rupture. We have established that these are clear morphotectonic features from displacement of geological and man-made features and established the continuity of similar characteristics along the length of the ground rupture.

The fact that Abigania et al., (2012) had interpreted these same scarps immediately after the earthquake as ‘probable ground rupture,’ reinforces rather than weakens our findings.

The overwhelming majority of the scarps we encountered were on brittle sedimentary cover, cutting mostly well-cemented, fine-grained and coarse-grained sedimentary rocks. While exposure of the fault cutting through basement (in its geological and/or geophysical sense) would have formed valuable additional evidence of the ground rupture being a primary throughgoing fault, it is just not possible to have exposure of the crystalline basement in the locations transected by the fault. The entire area is covered by an up to 3-km-thick Pliocene–Pleistocene sedimentary sequence, as shown by offshore seismic profiles and onshore geologic cross-sections across the Tañon strait and Negros Island, respectively [8]. However, our experience from mapping the 1990 M_W 7.7 Luzon [18], 1994 M_W 7.1 Mindoro [49], and 2013 M_W 7.2 Bohol [3] earthquake ruptures has exposed us to different examples of scarps which cut through both exposed bedrock and soft materials. Surveying these ruptures and many other active faults in the Philippines has shown us that the key to determining if scarps are fault-related is to recognize their morphotectonic nature, regardless of the type of surface materials. Even if the scarps were the upward extension/propagation of basement-rooted faults to the brittle sedimentary cover, this fact does not disqualify the fault from being the coseismic ground rupture. It is important to note that the type of materials that the ground rupture cuts is purely circumstantial. Much of the ground rupture of the 2002 Denali earthquake in Alaska cut through glacier material [50], yet this did not raise concerns about its primary faulting nature. Considering the foregoing arguments, these scarps are unlikely merely part of the ‘deformation zone’ which represents peripheral, surface manifestations of faulting in the basement.

In some places, the ground rupture occurs at the base of a coralline terrace scarp which bears strong similarities to monoclinical scarps associated with reverse faulting. The fact that many of these scarps occur along pre-existing scarps has aided in mapping the ground rupture (Figure 8). The ground rupture did not only follow pre-existing coseismic scarps, but it also created new ones. In Jimalalud, for example, vertical separation of up to ~1.2 m has created a terrace that is parallel to and along the shore. The tectonic nature of the scarps is also borne out by location along reverse fault zones bearing strands that vertically displace sedimentary units (Figure 8). Paleoseismic trenching across the scarps of the 2012 Negros Earthquake, which should provide detailed evidence of the longer-term history of surface rupturing earthquakes onshore, was not part of the scope of this study. However, now that the ground rupture has been recognized and properly mapped, our mapping will guide the site selection for future paleoseismic trenching investigations.

The 2012 Negros earthquake and the subsequent mapping of the surface projection of the seismogenic reverse fault revealed a more complete picture of the nature and distribution of deformation in the region. Shear partitioning has been proposed as a mechanism for accommodating deformation in the region due to the west-northwest motion of the PSP [4–6]. Fitch (1972) [4] first described slip partitioning as the partial decoupling between parallel strike-slip faults and subduction zones of plate motion that is oblique to the plate margin. As an example of a large-scale shear partitioning, he cited the accommodation by subduction and strike-slip faulting of the oblique motion of the PSP. Slip partitioning is the result of upward propagation of oblique shear at depth or, on a larger scale, by deeper oblique driving motion in viscous lower crust [51].

Shear partitioning in the region has been thought to be mainly through subduction along the Philippine Trench and strike-slip faulting along the Philippine fault [4–6]. Shear partitioning or slip partitioning, however, is a mechanism of accommodating deformation that may involve multiple parallel faults with different mechanisms, instead of a single fault with oblique slip [4,52–54]. On a larger scale, it could involve oblique plate convergence associated with subduction zones or collision zones. There has been no specific mention in previous models of the participation and magnitude of involvement of reverse/thrust faults in Central Philippines and the Negros Trench in accommodating deformation in the region through shear partitioning. The recognition of the ground rupture affirms the critical role of reverse/thrust faults that previous studies on the 2013 and 1990 Bohol earthquakes [3],

which occurred along the NBF and EBF(?), respectively (Figures 9 and 10), should have revealed earlier. These ground ruptures more likely occurred along pre-existing structures belonging to the set of structures generated since the Miocene that had been reactivated under the current stress regime (Figures 9 and 10).

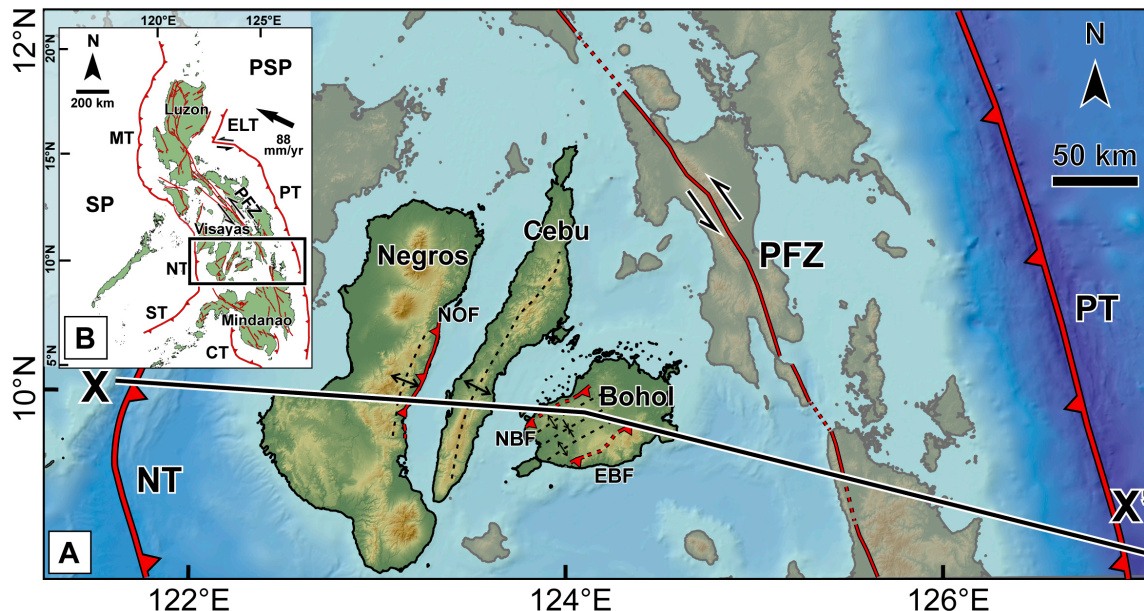


Figure 9. Currently known, Quaternary-active shortening structures in west-central Philippines. (A). Map highlighting the known late Quaternary-active folds and faults on the islands of Bohol, Cebu, and Negros. X—X' indicates the location of the sectional-view schematic block diagram in Figure 8. NT—Negros Trench, PT—Philippine Trench, and PFZ—Philippine Fault Zone. (B). Inset map showing the location (black rectangle) of Figure 7A in the Philippine archipelago and its tectonic context.

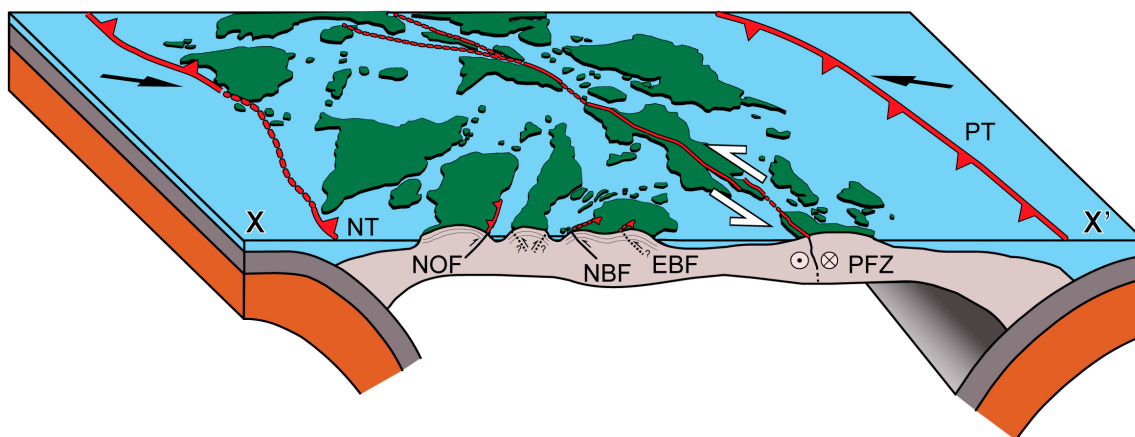


Figure 10. Schematic block diagram showing the structural and kinematic relationships of the Philippine Trench (PT), Negros Trench (NT), Philippine Fault Zone (PFZ), and some of the active shortening structures (i.e., faults and folds) in central Philippines (Bohol, Cebu, and Negros islands) along transect X—X' in Figure 9. NOF—Negros Oriental Fault; NBF—North Bohol Fault; EBF—East Bohol Fault.

Shear partitioning in the central Visayas region is distinct from the style of shear partitioning in other parts of the archipelago. For example, shear partitioning in northern Luzon mainly involves subduction and strike-slip faulting along a broader portion of the PFZ, which is composed of multiple segments [6]. If shear partitioning indeed occurs in northern Luzon, it is more likely that the Manila Trench, and not the East Luzon Trough, is the subduction zone that is currently the active participant

in accommodating the WNW relative motion of the PSP. Bautista (1996) [55], Rimando (2002) [56], Rimando and Knuepfer (2006) [57] argued that northern Luzon moves en masse northwestward along with the PSP rather than subducting along the seismically inactive East Luzon Trough. While shear partitioning mainly involves subduction along the Manila Trench and strike-slip faulting along the PFZ, it could also involve other types of faulting or structures.

5. Conclusions

The 6 February 2012 Negros earthquake is associated with a ~75-km ground rupture which closely follows the eastern shores of northern Negros Island. The ground rupture can be followed along the eastern coast of Negros Island from Bindoy in the south to Vallehermoso in the north. The location of the ground rupture is consistent with the mainshock focal mechanism and aftershock distribution. The length of the ground rupture is well within the aftershock distribution, while the scarp heights measured are within the expected range for a M_W 6.7 earthquake with reverse faulting mechanism. The scarps are distinct from those resulting from coseismic uplift associated with an offshore ground rupture, liquefaction/settlement, erosion, or landslides. The nature of rupturing, including variations in scarp morphology and aerial pattern, is consistent with an almost pure reverse faulting mechanism.

The occurrence of a reverse fault ground rupture can no longer be considered a rare phenomenon in this part of central Philippines. The earthquake precedes another event that occurred along the NBF in 2013 and follows an event which occurred along the EBF(?) in 1990. Both of these are of the same mechanism and both occurred in Bohol. The Negros earthquake ground rupture probably occurred along a pre-existing structure belonging to the set of structures generated since the Miocene. The earthquake and its ground rupture reveal that deformation by shear partitioning in the study area is not limited to subduction (on the east) and strike-slip faulting. Shear partitioning involves not only the Philippine Trench and the Philippine Fault but also the Negros Trench and the reverse/thrust faults in the Visayan Sea Basin, Central Philippines. That other structures aside from trenches and strike-slip faults are also involved in other parts of the archipelago where shear partitioning is important should not be discounted. This has implications for determining the slip budget and the nature and magnitude of earthquake hazards of these regions. The development of multiple faults within oblique convergent margins increases the potential extent of the area affected by earthquake hazards. The presence of more seismogenic structures presents more constraints for hazard forecasting.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2076-3263/10/11/460/s1>, Table S1: Scarp height measurements.

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