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Brief communication
"The magnitude 7.2 Bohol earthquake, Philippines"

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Abstract

A devastating earthquake struck Bohol, Philippines on 15 October 2013. The earthquake originated at 12 km depth from an unmapped reverse fault, which manifested on the surface for several kilometers and with maximum vertical displacement of 3 m. The earthquake resulted in 222 fatalities with damage to infrastructure estimated at US52.06 million. Widespread landslides and sinkholes formed in the predominantly limestone region during the earthquake. These remain a significant threat to communities as destabilized hillside slopes, landslide-dammed rivers and incipient sinkholes are still vulnerable to collapse, triggered possibly by aftershocks and heavy rains in the upcoming months of November and December.

1 Introduction

Early morning at 8:12 a.m. of 15 October 2013, a Magnitude (M_w) 7.2 earthquake struck Bohol Island in the Central Philippines region of Visayas (Fig. 1). The earthquake's focus was at 12 km depth with its epicenter located at 9.86° latitude and 124.07° longitude, 6 km southwest of Sagbayan, Bohol (Phivolcs, 2013). Initial and preliminary reports by the USGS sent a few minutes after the earthquake, had the temblor pegged at Magnitude (M_w) 7.2 occurring at 8:12 a.m. (local time) with the epicenter 2 km South of Nueva Vida Sur, Bohol, Philippines. The USGS record on the earthquake was later revised to Magnitude (M_w) 7.1 with focal depth of 20 km. Based on preliminary reports on the earthquake intensity, ground shaking was highest at Intensity VII (Philippine Earthquake Intensity Scale or PEIS), felt at Tagbilaran, Bohol. In other places, ground shaking effects registered intensity VI in Hinigaran, Negros Occidental, Intensity V in Iloilo City and La Carlota, Intensity IV in Masbate City, Roxas City, San Jose, Culasi, Antique, Guihulngan, Negros Oriental and Intensity III in Davao City (Phivolcs, 2013). Later reports coming from near the epicenter of the quake show images of centuries-old churches flattened to the ground and collapsed buildings (Fig. 2)

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

giving rise to intensities measuring VIII or higher. To date (3 November 2013), the National Disaster Coordinating Council (NDRRMC) has reported 222 fatalities, 976 injured and 8 missing. A total of 73 002 houses were damaged, 14 512 of which were totally destroyed, with 58 490 houses partially affected. Out of the 41 bridges affected by the earthquake, 3 are still not passable while 2 out of the 18 roads damaged are still impassable (NDRRMC, 2013b). The total estimated cost of the damage to infrastructure is 2 257 337 182 Philippine Pesos (US$ 52.06 million dollars). Landslide occurrences were reported in 25 villages in Bohol and 13 villages in Cebu (NDRRMC, 2013b) with reports of landslides damming rivers raising fears of possible floods.

As of 4:00 p.m., 3 November 2013, 2779 aftershocks have been recorded by the Philippine Institute of Volcanology and Seismology, 75 of which were felt (NDRRMC, 2013b). The earthquake epicenters plot in a northeast-southwest trend spanning approximately 100 km from mainly inland to offshore areas southwest of Bohol Island (Fig. 1a). Focal mechanism solutions generated by the Global Centroid Moment Tensor (CMT) project (Dziewonski et al., 1981; Ekstrom et al., 2012) which depict the type of slip movement of the earthquake fault, show a reverse fault (dominant vertical motion) with a slight right lateral strike-slip component for the main shock (Fig. 3). Two significantly large aftershocks recorded at 4:36 p.m. (local time) on the day of the main shock had reverse and strike-slip focal mechanisms, respectively. The M_s 5.9 (M_w 5.7) earthquake was a reverse fault-related aftershock while the M_s 5.5 (M_w 5.6) earthquake was related to strike-slip fault movement based on their focal mechanism solutions (Fig. 3).

2 Earthquake source

When the 2013 earthquake happened, the only mapped active fault in Bohol Island is the East Bohol Fault (Phivolcs, 2000). It was originally believed to be the source of the M_w 7.2 earthquake but it would appear based on the locus of earthquake epicenters and initial field reports that an unmapped fault or faults about 20–25 km north of the East Bohol Fault were responsible for the M_w 7.2 earthquake and most of the aftershocks (Fig. 1a). Lineament analysis of digital topography show northeast-southwest-trending structures cutting across the northern portion of Bohol Island, passing through several municipalities of Bohol in the northern portion of the island. In the village of Anonang, municipality of Inabanga, where there were several aftershocks recorded, displacement of originally gently sloping to flat ground formed a northeast- to southwest-trending wall as much as 3 m high and extends more than five kilometers long (Fig. 4). The length measurement of the raised wall due to reverse faulting is currently being determined in the field and through lineament mapping using high-resolution imagery.

In the worldwide database of earthquakes, a 3 m displacement of a fault approximately corresponds to a magnitude 7.2 earthquake (Wells and Coppersmith, 1994). Based on this, the fault seen very well exposed in Barangay Anonang, Inabanga is most likely to have been responsible for the M_w 7.2 earthquake in Bohol. This earthquake triggered more than 3198 aftershocks, 94 of which were felt. But the trend of the epicenters of these earthquakes which span more than 100 km and reach nearly the southern part of Cebu island, do not follow exactly the orientation of the fault trace found in Inabanga municipality (see Fig. 1). The reverse fault in Inabanga also does not account for the strike-slip focal mechanism solution of an earthquake recorded in the afternoon of the devastating Bohol event (see Fig. 3a). There are other lineament structures found in the northern part of Bohol and they could correspond to a fault system defined by the large number of earthquakes triggered by the main shock. These too must be mapped out in detail when possible.

The nomenclature of newly discovered faults or geological formations for that matter, are normally based on where they are best exposed and described. Because Inabanga municipality is where the reverse fault was first seen and archetypal for the fault that generated the fatal M_w 7.2 earthquake of Bohol, we propose to name the fault, the Inabanga Fault. This also would prevent complications in the future should there be any other active faults that will be discovered and mapped in the large area affected by the temblor, north of Bohol.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

3 Past earthquakes

The East Bohol Fault was responsible for generating the M6.8 Bohol earthquake on 8 February 1990, which generated tsunamis as high as 2 m and significant inundation in the southeastern coast of the island. The epicenter of the 1990 Bohol earthquake was located 17 km east of Tagbilaran City with intensities reaching VIII on the Rossi-Forrel scale in the town of Jagna, Duero and Guindulman in Bohol (Umbal et al., 1990). The temblor exacted six fatalities with more than 200 injured. Approximately 46 000 people were displaced with at least 7000 rendered homeless. Damage to property for the 1990 Bohol earthquake was estimated at 154 million pesos (Phivolcs, 1996b). Another Magnitude 5.6 earthquake struck on 27 May 1996 and was centered in the municipality of Clarin, Bohol. Damage brought by the 1996 earthquake was confined to poorly built structures and/or old wooden, masonry, limestone walls of houses and buildings, generally due to ground shaking. There were no reports and observations attributed to other earthquake hazards such as liquefaction, ground subsidence, landslide and any other geologic ground disturbances during the 1996 Bohol earthquake (Phivolcs, 1996b).

4 Tectonic framework of the Philippines

The Philippine archipelago is a mature island arc that is at present being accreted to the eastern margin of the Eurasian Plate. It is composed of a complex mixture of terranes (Encarnación, 2004) formed through plate interaction of the Philippine Sea Plate, Eurasian Plate and the Indo-Australian Plate (Fig. 5).

The entire archipelago is characterized by a system of subduction zones, collision zones, and wrench faults. The actively deforming region of the Philippines is a zone known as the Philippine Mobile Belt or PMB (Fig. 5; Gervasio, 1967), bound on both sides by subduction zones. West-dipping subduction zones are the East Luzon Trough and the Philippine Trench. Generally east-dipping subduction zones are the Negros

Trench, Sulu Trench, and Cotabato Trench. In between these west- and east-dipping subduction zones is the left-lateral Philippine Fault (Allen, 1962), which straddles the entire length of the PMB. There are many active faults in the archipelago but the closest active faults in the Bohol region, are the Cebu lineaments, Central Negros Fault, Panay Fault and the West Mindanao fault. The tectonic structures in the Philippines accommodate the stress imparted by the ongoing northwest movement of the Philippine Sea Plate towards Eurasia (Huchon, 1986). Southwest of the PMB is the Palawan-Mindoro block, an aseismic region of the Philippines of continental affinity (Holloway, 1982).

The trenches in the east and west of the archipelago are major sites of seismicity and where marginal basins surrounding the Philippines are consumed. The South China Sea, Sulu Sea and the Celebes Sea Basins subduct along the east-dipping Manila, Negros and Cotabato trenches, respectively. The Sulu Trench is the locus where the Sulu Sea is consumed while the Philippine trench is the site where the Philippine Sea Plate subducts (Lagmay et al., 2009).

5 Conclusions

The Bohol earthquake is a devastating event that emanates from one of the many faults that straddle the Philippine islands. There are many active faults that have been mapped and are potential sites for devastating earthquakes. Many active faults listed by Phivolcs are near urban centers, populated by millions of people. Metro Cebu, which is the second most populous Metropolitan area in the Philippines after Metro Manila, came out relatively unscathed with only 12 deaths compared to the 209 fatalities in Bohol Island where the earthquake emanated. A year and a half earlier, on 6 February 2012, a shallow focus M_b 6.9 earthquake generated by an unmapped thrust fault and referred to as a hidden fault, struck Negros Island immediately west of Cebu. That earthquake caused considerable damage killing 51 people with 62 missing and presumed dead (NDRRMC, 2013a). The most recent fatal temblor is the 2013 Bohol earthquake, which released underground, tremendous amount of energy equivalent to more than 30 Hiroshima atomic bombs. That amount of energy, which can trigger an earthquake, can only be built up again on the same fault system over a long period of time, perhaps a hundred years or more. In the meantime, the reverse fault found and best seen in Inabanga, Bohol, in most probability, will be quiet and will not pose imminent danger from earthquake hazards sans landslides triggered by aftershocks and further destabilization of already weakened ground and infrastructure. These recent events are a wake up call for all residents of the Philippines to brace for possible earthquakes that may strike the country elsewhere, anytime.

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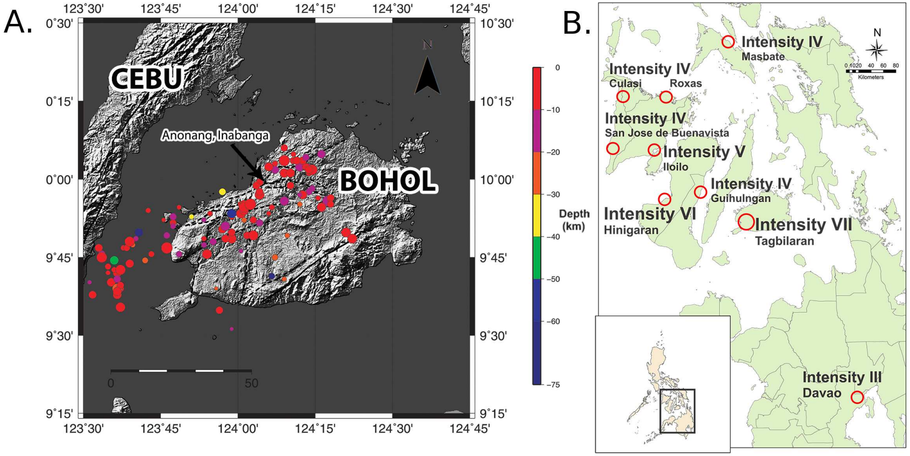
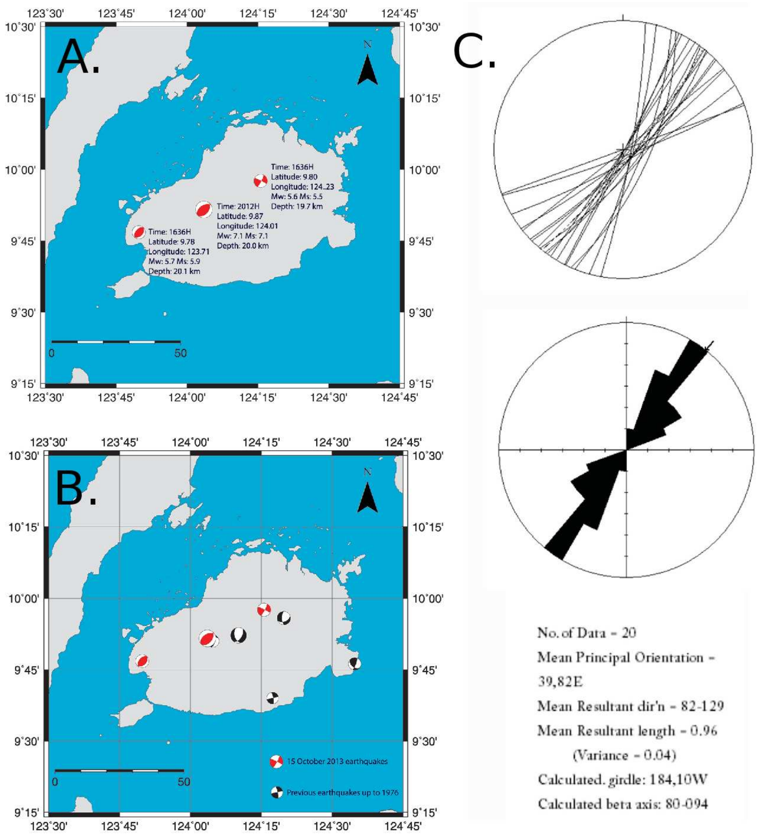


Fig. 1. Earthquake **(A)** epicenters in Bohol and their corresponding depth according to Phivolcs as of 20 October 2013 (Online list of recent earthquakes). The largest circle is the M_w 7.2 earthquake with a depth 12 km **(B)** intensities in Bohol and adjacent cities and municipalities. Dashed black lines are lineaments in the shaded relief image of Bohol island, while the solid black line in the south is the East Bohol Fault.

Fig. 2. Images of the disaster: **(A)** collapsed house in Sagbayan municipality, Bohol. **(B)** Inabanga church in Bohol. Photos: AMF Lagmay.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion



No. of Data - 20

Mean Principal Orientation - 39,82E

Mean Resultant dir'n - 82-129

Mean Resultant length - 0.96

(Variance - 0.04)

Calculated. girdle: 184,10W

Calculated beta axis: 80-094

Fig. 3. Focal mechanism solution of earthquakes recorded on **(A)** 15 October 2013 in Bohol and **(B)** prior to the M_w 7.2 Bohol earthquake (black beachballs). **(C)** Stereo plot and rose diagram of the fault that generated the M_w 7.2 as measured in Bohol. The mean principal orientation of the fault based on 20 measurements of its plane is N39° E dipping 82° SE.

Fig. 4. Formerly gently sloping ground split through reverse faulting into an upthrown block and lower block forming a 3 m high wall that extends for several kilometers. Photo: AMF Lagmay.

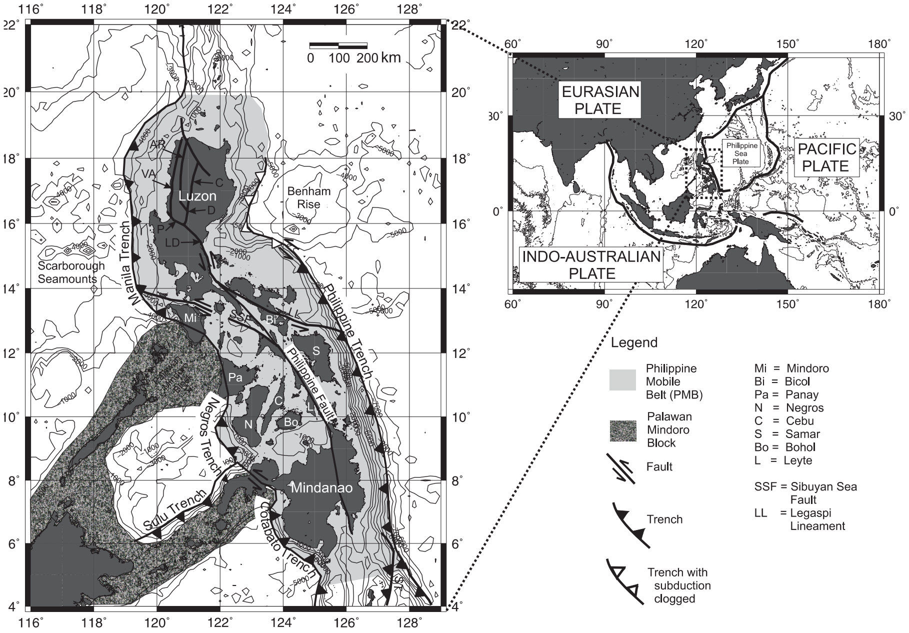


Fig. 5. Map showing the main plates surrounding and major tectonic features of the Philippines. The gray shaded area is the Philippine Mobile Belt (PMB) of Gervasio (1967). The stippled gray area is the Palawan-Mindoro continental block. AR = Abra River Fault; VA = Vigan Argao Fault; C = Cordilleran Fault; P = Pugo Fault; D = Digdig Fault; LD = Laur Dingalan Fault (Lagmay et al., 2009).