Historical and Paleoseismic Evidence of the 1879 M_w 7.4 Surigao Earthquake, Philippines

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Abstract

The 1879 *Mw* 7.4 Surigao earthquake was considered as one of the largest and damaging earthquakes in the southern part of the Philippines. It occurred along the Surigao segment of the Philippine fault, a major strike-slip fault that has relatively few surface rupturing earthquakes. Based on written historical records, this earthquake generated strong ground shaking that caused significant damages to infrastructures such as churches and buildings near the epicentral area. Widespread liquefaction and landslides were also described. A significant account of this earthquake is a detailed description of the surface rupture. Through aerial photograph interpretation, geologic mapping and paleoseismic investigation, we identified the 100-km-long surface rupture during the 1879 Surigao earthquake. The surface rupture was manifested by continuous tectonic scarps and offset creeks. In two paleoseismic trenches, we also identified evidence of at least two and probably four surface-rupturing earthquakes including the 1879 event during the past 1300 years. If we assume that the coseismic lateral displacement of the 1879 Surigao earthquake is at least 5 m, the slip rate along this segment is calculated to be 5-17 mm/yr, which is comparable with the GPS measured slip rate and with recurrence interval of about 300-1000 years.

Keywords: Philippine fault, active tectonic, paleoseismology, surface rupture

1. INTRODUCTION

The Philippine fault is one of the most important active tectonic structures in the western Pacific region. This 1,250-km-long sinistral strike-slip fault traverses the Philippine archipelago from Luzon Island in the north to eastern Mindanao Island in the south (Allen, 1962; Aurelio, 2000; Barrier et al., 1991; Tsutsumi and Perez, 2013) (Fig. 1a). This NNW-trending, arc-parallel fault is a result of the oblique subduction of the northwest-moving oceanic Philippine Sea plate beneath the Philippine archipelago (Aurelio, 2000; Fitch, 1972).

The Philippine fault has been the source of more than 10 earthquakes with magnitudes greater than 7 for the past 200 years (Bautista and Oike, 2000) (Fig. 1a). For the past 50 years, 3 surface-rupturing earthquakes occurred along the different segments of the Philippine fault including the 1973 M_L 7.0 Ragay Gulf earthquake (Guinayangan segment) (Morante, 1974; Tsutsumi et al., 2015), the 1990 M_s 7.8 Luzon earthquake (Digdig segment) (Nakata et al., 1996) and the 2003 M_s 6.2 Masbate earthquake (Masbate segment) (PHIVOLCS Quick Response Team, 2003). The largest and most destructive earthquake was the 1990 Luzon earthquake that ruptured the 120-km-long Digdig segment of the Philippine fault with 6 m maximum left-lateral horizontal displacement (Nakata et al., 1996) (Fig. 1a). GPS observations showed slip rates ranging from 20 to 30 mm/yr along the different segments of the fault (Aurelio, 2000; Barrier et al., 1991; Galgana et al., 2007).

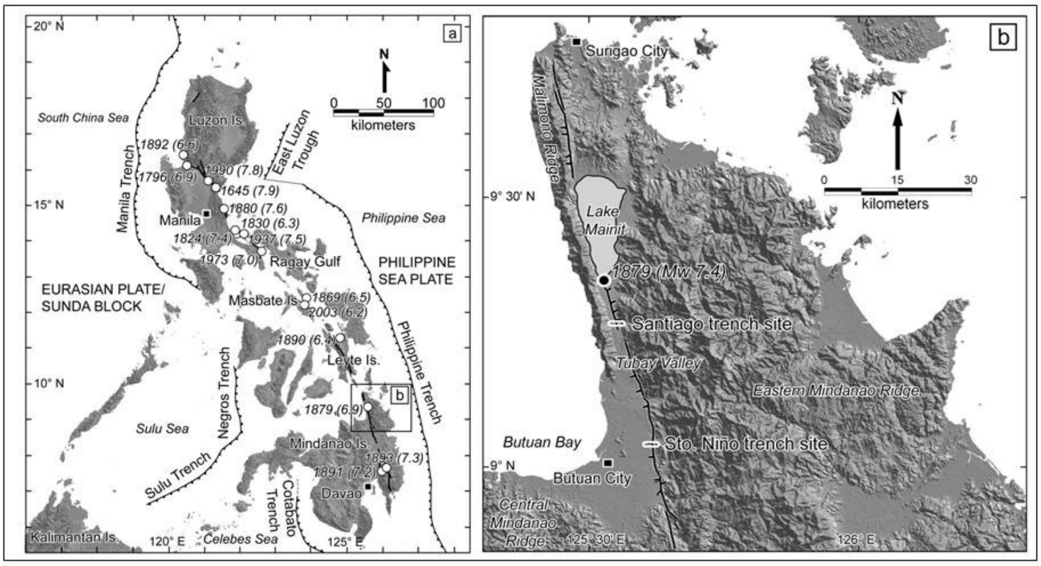

Figure 1. (a) Map showing the tectonic structure of the Philippine archipelago, the Philippine fault and epicenters (circles) of earthquakes with M> 6 along the Philippine fault. Other active faults are not shown for simplicity. (b) Map showing the Surigao segment of the Philippine fault and location of trench sites. The trace of the Philippine fault is from Tsutsumi and Perez (2013), the Surigao segment and location of trench sites is from Perez and Tsutsumi (2016) while the epicenters are from Bautista and Oike (2000).

In this paper, we will describe the historical, tectonic geomorphology and paleoseismic evidence of the 1879 M_w 7.4 Surigao earthquake using historical documents (Bautista and Oike, 2000; PHIVOLCS, 2012; Repetti, 1946; SEASEE, 1985), tectonic geomorphic mapping and paleoseismic studies conducted by Perez and Tsutsumi (2016). This earthquake is considered as the largest earthquake that hit northeastern Mindanao that caused significant damage. It also provided important geologic information to characterize the 100-km-long Surigao segment of the Philippine fault. This information is very important in terms of medium to long-term earthquake risk assessment because this segment of the Philippine fault passes through major population centers.

2. HISTORICAL ACCOUNTS OF THE 1879 SURIGAO EARTHQUAKE

Before instrumental seismic monitoring in 1880, earthquake records in the Philippines started in 1589 and were based on historical documents that include church chronicles and government documents written by Spanish priests and government officials assigned in the country (Bautista and Oike, 2000; Repetti, 1946). The 01 July 1879 earthquake was documented by Dr. Jose Centeno, a Spanish geologist assigned by the Governor General (Spanish Head in the Philippines) to observe the effects of the earthquake (Repetti, 1946). Based on his account, we will summarize the effects and identify occurrence of geologic processes during the 1879 Surigao earthquake.

2.1 EFFECTS OF GROUND SHAKING ON STRUCTURES

The earthquake occurred at 2:55 am (local time) and was felt in the entire northeastern Mindanao Island and was followed by strong aftershocks for several days. Description of damages due to strong ground shaking was documented by Dr. Centeno:

> *'The effects caused in the capital were not so disastrous as was at first feared. The only three stone buildings with tile roofs in the town had withstood the shocks, although two of them, the Governor's house and Administration building, had suffered numerous vertical cracks in the walls of the ground and upper floors… The town church, which has sufficiently thick walls, of coral limestone, known in Visayas Island as tablilla, and reinforced with timbers has suffered considerable damage…. The rest of the buildings in the town, all wood, nipa, and bamboo have suffered damage of little importance… The town of Anaoaon must have felt very violent shocks; of its forty houses of wood and nipa, twenty-six collapsed and the rest were so greatly tilted that most of them had to be reconstructed. Two wooden bridges of the town were rendered useless…'* (Repetti, 1946).

There were very few documented damages on built structures because of the materials used. During that time, most of the structures are made up of light construction materials such as wood, nipa and bamboo.

2.2 SURFACE RUPTURE

A significant account by Dr. Centeno is the surface rupture of the 1879 Surigao earthquake:

> *'About 12 minute walk south of the town there is an open plain about 1500-m-long and 500-m-wide. It is very level and on it are some houses surrounded with betel and coconut palms. This plain suffered a drop of about 50 cm over its whole area without noteworthy damage to the houses and trees. The surface of the break or slip can still be seen in the slopes of the valley and at one place a new spring of portable water has appeared…'* (Repetti, 1946).

Perez and Tsutsumi (2016) suggested that this account is a description of the surface rupture of the 1879 Surigao earthquake (Fig. 1b and 2). They identified that Anaoaon (now San Francisco) as the town mentioned by Dr. Centeno and the open plain south of this town is the alluvial plain of the Anaoaon River. Using aerial photographs, Allen (1962) identified tectonic scarps between Anaoaon and Lake Mainit related to the 1879 Surigao earthquake. Perez and Tsutsumi (2016) also conducted aerial photograph interpretation, field survey and paleoseismic trenching and revealed that the tectonic scarps along the Tubay Valley south of Lake Mainit were also associated with the surface fault rupture of the 1879 Surigao earthquake.

2.3 LIQUEFACTION

Another significant geologic process (liquefaction) was documented as lateral spreads and sand boils during the 1879 Surigao earthquake:

> *'The most striking effect observed in Surigao, as a consequence of the frequent repetition of the earthquake, is the sinking of the shore of Bilan-Bilan, the port of the town. The drop is said to be one foot. It must be noted, however, that the whole of that place is mangrove area… In the streets of the town and in the adjoining fields there are signs of fissures which opened during the earthquake and according to the people, vomited white mud which I could still see marking the direction of the fissures (N20° W – S20° E). It is nothing but very white sand, coming, no doubt, from a soft layer near the surface…'* (Repetti, 1946).

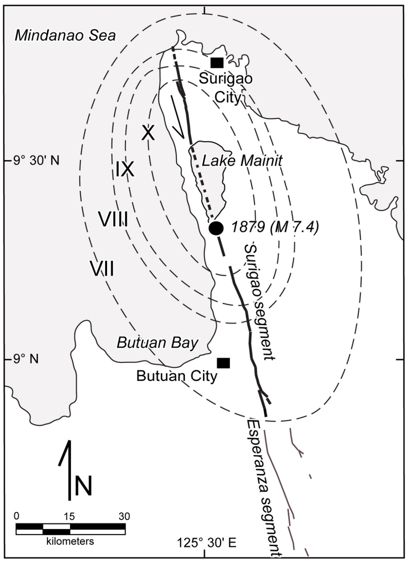

Figure 2: Modified Mercalli Intensity (MMI) scale isoseismal and epicenter (black circle) of the 1879 Surigao earthquake. Solid black lines (with dashed line in Lake Mainit) is the trace of the Surigao segment and the surface rupture of the 1879 Surigao earthquake while thin gray line are the trace of other segments of the Philippine fault (e.g. Esperanza segment). The isoseismal map is from Bautista and Oike (2000) and the magnitude of this earthquake (M_w 7.4) was determined by Perez and Tsutsumi (2016).

2.4 EARTHQUAKE-INDUCED LANDSLIDE

Earthquake-induced landslides were also documented during the 1879 Surigao earthquake. The following are excerpts from the report of Dr. Centeno:

> *'Going northwest from Surigao by sea, the point of Bilaa is about six miles distant... I saw conspicuous and recent landslides at the steep point of the coast and some large fissures. At point Bilaa, the landslides measured several hundred cubic meters and one fissure practically divided the promontory of the point in two… I was told, although I could not verify it, that in the mountain range separating Lake Saponan form the Pacific, fissures of greater dimensions had opened and landslides of greater volume had occurred that at Point Bilaa…'* (Repetti, 1946).

Bautista and Oike (2000) assessed the seismic intensities (maximum of MMI X around the epicentral area) for each reported site based on written historical accounts and proposed an isoseismal map for the 1879 Surigao earthquake (Fig 2). They estimated that the magnitude of this event is M_s 6.9 and the epicenter is located south of Lake Mainit. They also proposed that the source of this earthquake was the Surigao segment of the Philippine fault.

3. EVIDENCE OF THE 1879 SURIGAO EARTHQUAKE SURFACE RUPTURES

Using aerial photograph interpretation, tectonic geopmorphic mapping and paleoseismic investigation, Perez and Tsutsumi (2016) have mapped the Surigao segment of the Philippine fault that ruptured during the 1879 Surigao earthquake.

3.1 TECTONIC GEOMORPHOLOGY

Surigao segment is the northernmost segment of the Philippine fault in Mindanao Island. This 100-km-long fault is fairly continuous and traverses the eastern margin of Malimono Ridge, Lake Mainit, Tubay Valley and the western edge of Eastern Mindanao Ridge. The general strike of the fault is N15°-20°W.

Pronounced tectonic geomorphic features were identified along the Surigao segment such as scarp, offset streams, sag ponds and pressure ridges. A continuous 10-km-long, east facing, 0.5 to 1.0 m high tectonic scarp was identified south of Lake Mainit using aerial photograph and field survey. Along this continuous scarp, Perez and Tsutsumi (2016) identified systematic left-lateral deflection of streams. They have also measured a left-laterally displaced west-flowing stream channel (5.7±1 m for the northern bank and 5.3±1 m for the southern bank). Combining the results from the review of historical documents, aerial photograph interpretation, geomorphic mapping and paleoseismic investigation, they have concluded the continuous scarp observed south of Lake Mainit and the displaced stream channel is part of the surface rupture of the 1879 Surigao earthquake.

South of Tubay Valley, the fault traverses the recent alluvial fans at the edge of the Eastern Mindanao Ridge. At the southern end of the Surigao segment, the fault trace changes its strike significantly from N15°-20°W to N20°-30°W and the fault branches as it enters the ridge. The branching of the fault to the south and the changes in the strike led Perez and Tsutsumi (2016) to identify the southern end of the Surigao segment near the western edge of Eastern Mindanao Ridge.

Using the relationship of surface length and moment magnitude suggested by Wells and Coppersmith (1994), the maximum credible earthquake for the Surigao segment is M_w 7.4 and most probably ruptured its entire length (100 km) during the Surigao earthquake.

3.2 PALEOSEISMIC INVESTIGATION

To determine the recurrence interval of surface-rupturing earthquakes along the Surigao segment and to verify the extent of the surface rupture, Perez and Tsutsumi (2016) conducted paleoseismic investigation in two sites (Santiago and Sto. Niño trenches that is 30 km apart). The Santiago trench was excavated across the identified continuous tectonic scarp, South of Lake Mainit (Fig 1b and 3). Perez and Tsutumi (2016) identified from this trench site evidence for at least four surface-rupturing events that occurred within the last 1,300 years including the 1879 Surigao earthquake.

Sto. Niño trench was located along a young alluvial fan, west of Eastern Mindanao Ridge (Fig. 1b and 4)). This trench exposed fault strands that showed evidence of at least two surface-rupturing events for the past 1,100, that also include the 1879 Surigao earthquake. Combining the results of the two paleoseismic trenches, we suggested that the recurrence interval along the Surigao segment is about 300-1000 years.

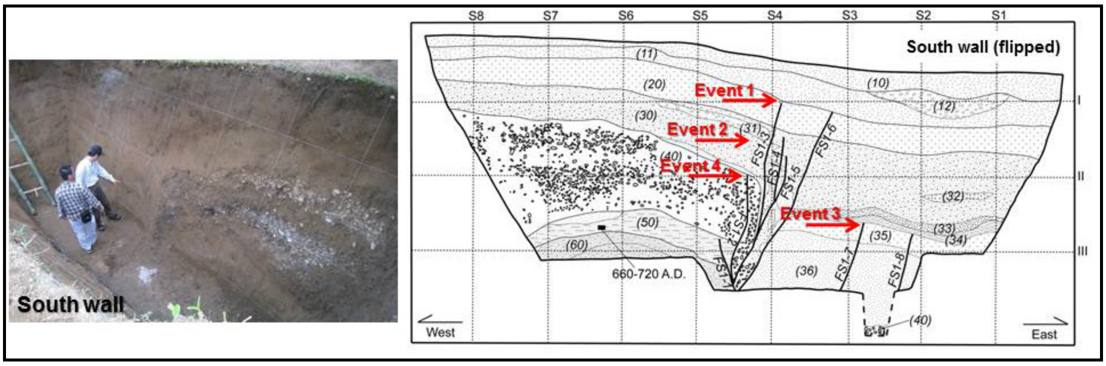

Figure 3: Santiago trench stratigraphic log (south wall). This trench exposed at least four surface-rupturing earthquakes for the past 1,300 years that includes the 1879 Surigao earthquake (Event 1).

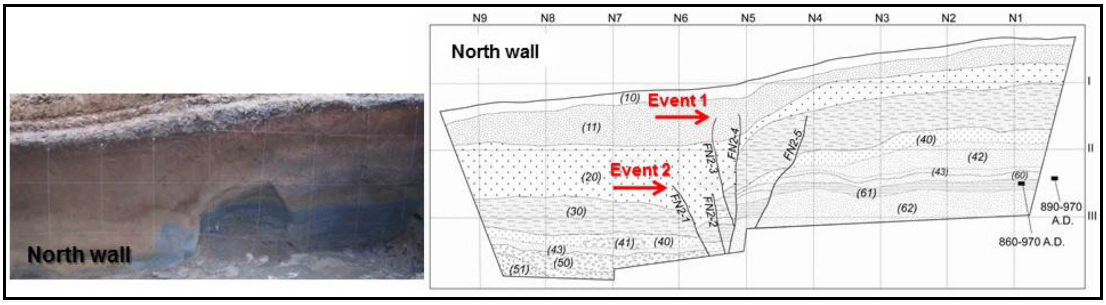

Figure 4: Sto. Niño trench stratigraphic log (north wall). This trench showed evidence of at least two surface rupturing earthquakes for the past 1,100 years that includes the 1879 Surigao earthquake (Event 1).

4. SUMMARY

We have reconstructed the 1879 Surigao earthquake based on historical documents, aerial photograph interpretation, tectonic geomorphic mapping and paleoseismic investigation. We have mapped geomorphic tectonic features, identified the surface rupture of the 1879 Surigao earthquake and propose a magnitude 7.4 for this historical earthquake that is much larger than the previous estimate. The two paleoseismic trenches excavated across the Surigao segment revealed evidence of at least two and probably four surface-rupturing events for the past 1300 years that include the 1879 Surigao earthquake. If we assume that the coseismic lateral displacement of this earthquake is at least 5 m, as measured from offset stream, the slip rate of this segment is 5-17 mm/yr and the recurrence interval of surface-rupturing earthquake is about 300-1000 years.

5. Acknowledgement

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