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The central Philippine Fault Zone: Location of great earthquakes, slow events, and creep activity

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The central Philippine Fault Zone is found to be the locus of great earthquakes, a transition zone with slow slip and creep activity. This is based on the analysis and correlation of seismic historic data and detailed documentation of recent seismic events in the region. Based on this study the Guinyangan fault is defined to be the northern locked portion with recurrence interval of as short as 65 years. The Masbate fault is the central part with large and medium earthquakes accompanied by unusually large ground rupture. The north Central Leyte fault and the south Central Leyte fault, on the other hand, are characterized by aseismic creep and medium-sized events, usually with clusters of foreshocks, respectively. Unusual seismic activity both on the Masbate fault and Central Leyte fault somehow correlates well with the behavior of known slow events and creep activity. Further investigation of this region could lead to deeper understanding of impending major earthquakes, especially along the Guinyangan fault, which usually produces larger damaging events, and for further understanding of the impact of slow events and creep on the adjoining active structures.

Key words: Philippine Fault Zone (PFZ), historical earthquakes, slow events, creep, Masbate fault, transition zone, Guinyangan fault, Leyte fault.

1. Introduction

One of the major tectonic features in the Philippine region is the Philippine Fault Zone (PFZ). The PFZ is a left-lateral strike-slip fault that transects the whole archipelago along a general strike of N30°–40°W from northwestern Luzon to southern Mindanao (PHIVOLCS, 2000; Barrier *et al.*, 1991). It is comparable to the San Andreas fault (SAF) because of its young geomorphic features (Willis, 1937; Allen, 1962). From southeastern Luzon, the PFZ traverses offshore into the Ragay Gulf area and continues southeastward east of Burias Island, along which at least ten major historical events occurred with associated ground rupture (Rowlett and Kelleher, 1976). From Quezon Province, the PFZ transects west offshore of Ticao Island before entering southeastern Masbate Island. The continuation of the PFZ is found on the island of Leyte along the same trend (Fig. 1). In this region, the active fault map of PHIVOLCS (2000) is based mainly on satellite images and topographic interpretations and shows at least two parallel structures defining the PFZ, the Masbate Fault and Uson Fault. The Uson Fault is the shorter western trace on Masbate Island while the Masbate Fault refers mainly to the trace onshore Masbate Island to the trace east of Burias Island (Fig. 2).

Based on GPS data, the mean displacement rate of the PFZ in southern Luzon to northern Mindanao, is at least 2–3 cm/yr (Aurelio, 2000). Recent work further indicated that the Masbate Fault is a transition zone (Bacolcol, 2003) while the northern Central Leyte fault is creeping aseismically at a rate of at least 2.6 cm/year (Catane *et al.*, 2000; Duquesnoy *et al.*, 1994). In terms of seismicity, the Guinyangan fault had a recent large event (Morante and Allen, 1973; Morante, 1974), the Masbate fault has moderate background seismicity and the Leyte fault has a much less activity (PHIVOLCS, 1999).

Lastly, the occurrence of the Ms 6.2 earthquake on the island of Masbate in east central Philippines on 15 February 2003 lead to closer analysis of the earthquakes occurring in the central portion of the PFZ. The 2003 Masbate earthquake was located at a depth of 22 km west of Magcaraguit Island along the PFZ, and accompanied by significant surface ground rupture (Besana *et al.*, 2003; Besana *et al.*, under review). Besana *et al.* (2003) also noted that the ground rupture was larger and longer than expected while its southern portion had an apparent post-seismic deformation. Considering the limited earthquake information available for the region, this paper attempts to give an overview of the possible trend and characteristics of the earthquakes along this part of the central PFZ.

2. Data and Method

Historical earthquakes were compiled for the central PFZ, particularly for the Guinyangan, Masbate, and central Leyte faults. Most of the recent data for central PFZ came from the PHIVOLCS (1999) while the historical data are culled from the Southeast Asia Association of Seismology

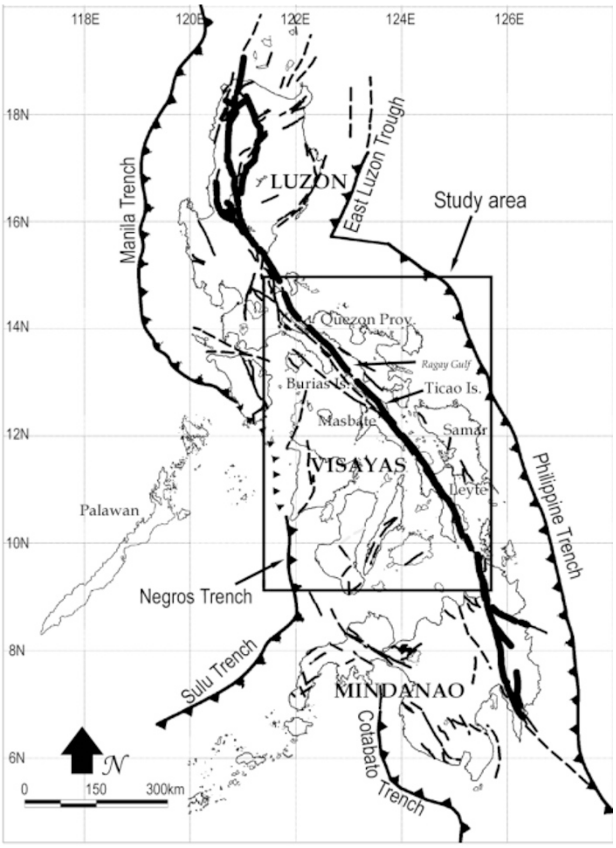

Fig. 1. Map showing the extent of the PFZ (bold solid line) transecting the Philippine archipelago from northeastern Luzon to southeastern Mindanao. Also shown are the major tectonic features of the region. Solid hachured lines are trenches while dashed lines are other active faults in adjoining islands. The rectangular area defines the study area.

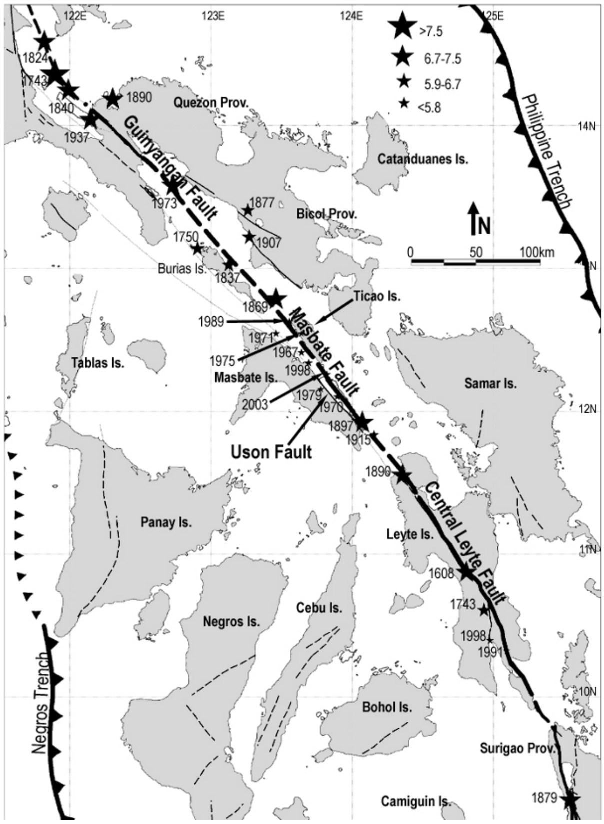

Fig. 2. Map showing the historical earthquakes along the central portion of the PFZ (modified from PHIVOLCS, 2000). Star indicates the epicenter of the historical events. Offshore location of the PFZ and trenches are indicated by dashed line and hachured lines, respectively.

and Earthquake Engineering (SEASEE, 1985). Due to the limited historical data in the Philippines, note that most of these events are documented for only the last four centuries. Dates older than this period can be only acquired from radiocarbon dating results. Even though trenching excavations had been undertaken in the Guinyangan and Masbate areas, results from radiocarbon dating is not yet available (Daligdig, per. comm.).

For the magnitudes, the determinations for historical earthquakes in this region depended mainly on the estimate of seismic intensity. Thus, the magnitude estimate depends on the number of affected areas, and the epicentral location of old events may have varied as much as 30 km (PHIVOLCS, 1999; SEASEE, 1985). On the other hand, the recent additional data set for the Masbate region came from information gathered during the investigations undertaken for the 2003 Masbate event (Besana *et al.*, 2003; Besana *et al.*, in prep.). Additional moderate-sized (∼M5.5–6.2) quakes were recognized during that field survey, which were deemed important in the analysis of recurrence intervals in this area. In the case of the 2003 aftershock sequence, 232 aftershock events were analyzed with magnitudes ranging from M3.5∼6.1. It should be noted that due to the configuration and limited number of stations comprising the existing PHIVOLCS seismic network, the aftershock plots for the 2003 Masbate earthquake have location errors of about ±5 km (Punongbayan, per. comm.). Furthermore, small (<M3.5) aftershocks were obviously incomplete and not included in the analysis, considering the distance and location of the existing seismic stations, most of which are located west of the Masbate fault region.

Note that there is no permanent Global Positioning System (GPS) network in the region, thus most of the available information regarding crustal deformation in the area is from regional and temporary networks. Discussion of results is in three parts, concentrating particularly on the Guinyangan fault in Quezon province, the Masbate fault in Masbate island, and the Central Leyte fault in Leyte island, where the corresponding names of the faults were taken.

In the last section of the paper, we made an initial attempt to compare the PFZ to the SAF. However, considering that much of the PFZ is offshore and studies on the PFZ are quite limited, the comparisons were made simply in general terms, using the seismicity and regional trends of the structure.

3. Results

A plot of historical earthquakes along the central PFZ is shown in Fig. 2 including the moderate events that were found during the 2003 field investigations in the Masbate region. Based from this plot, it could be perceived that there is some clustering of large events along the Guinyangan Fault. There were at least one large event and three records of earthquake-related damage in the 17th and 18th

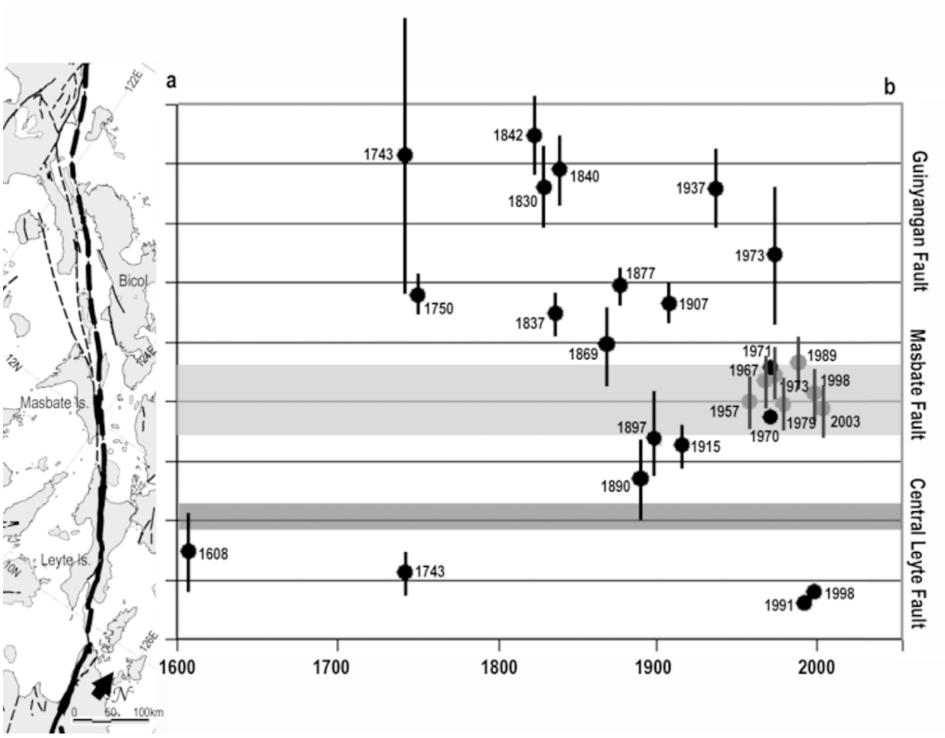

Fig. 3. (a) The central portion of the PFZ corresponding to the earthquake activity on the right (b) on temporal plot. The fault portion with reported creep (Catane *et al.*, 2000; Duquesnoy *et al.*, 1994) and the location of the 2003 eventon Masbate (Besana *et al.*, 2003) are indicated by light grey and dark grey, respectively. Vertical lines indicate the possible extent of ground rupture using the magnitude estimate from the Wells and Coppersmith (1994) empirical relations. Solid gray circle indicates the moderate-sized (>M5–6) events along the MF, mostly with significant ground rupture.

century along this portion of the PFZ. Most of these events are M7 or larger, occurring mostly along and north of the Guinyangan fault. In contrast, another cluster can be seen in Masbate, which is characterized by moderate earthquakes with unusually large ground ruptures. North of the central Leyte fault, on the other hand, activity is noticeably quiet while the southern extension has very few earthquakes.

To check for seismicity patterns, the earthquakes were plotted in time and space as shown in Fig. 3. In this graph, the events are also shown with their possible length of rupture, based on aftershock distributions, observed ground rupture, and calculated length of ground rupture from an empirical relation by Wells and Coppersmith (1994). In Fig. 3, it is noticeable that the recent major earthquakes had occurred along the Guinyangan fault. The region had at least seven major earthquakes in the last two centuries with an average recurrence interval of about 50 years, and even as short as 30 years. Although most reports were about damage on man-made structures, clear information regarding surface rupture was reported during the 1973 event (Morante and Allen, 1973; Morante, 1974).

In the Masbate region, the northern portion has had several moderate earthquakes between 1800 and 1900. This location is partly covered by the extent of the aftershock distribution of the 1973 event (PHIVOLCS, 1999). However, in its southern portion where the Masbate 2003 event occurred, a cluster of magnitude 5∼6 earthquakes are noticeable. These events are accompanied by large ground ruptures, usually comparable to a M7.0 earthquake (Besana *et al.*, 2003). Although such a cluster was not previously known, field accounts show a recurrence interval of as short as 5 years for these moderate earthquakes. Most of the earthquakes were also preceded by moderate foreshocks (Tordesillas, per. comm.)

Another interesting aspect of the Masbate fault system is the observed post-seismic deformations after the 2003 Masbate earthquake. After the 2003 Masbate event, a 23-km onshore ground rupture was mapped (Fig. 4). Fig. 4(b) and 4(c) show typical manifestations of the ground rupture as gashes and fissures. However, along the southern terminus of this ground rupture in Cataingan, Masbate additional rupture occurred about 2 months after the mainshock. The faulting was first found transecting the asphalt-paved highway as hairline cracks. After two weeks, further field observations showed these hairline cracks had became larger and caused damage to the highway. After two months, additional mapping results also showed that the same area experienced additional horizontal displacements, wherein the measured left-lateral displacement is about 8 mm from the original hairline cracks.

The 2003 Masbate aftershock sequence (Fig. 5) also demonstrated an interesting pattern of seismicity. Assuming that the plots of aftershocks from 1-day aftershock to one month can indicate the extent of the ground rupture (Nanjo and Nagahama, 2000; Rybicki, 1973), plots of the Masbate 2003 aftershocks (Figs. 5(a) and (b)) indicate about a 90 km-long ground rupture. The one-day and one-month aftershock plot indicates an almost symmetrical rupture relative to the epicenter (Figs. 5(a) and (b)). The preceding months show almost the same pattern as the seis-

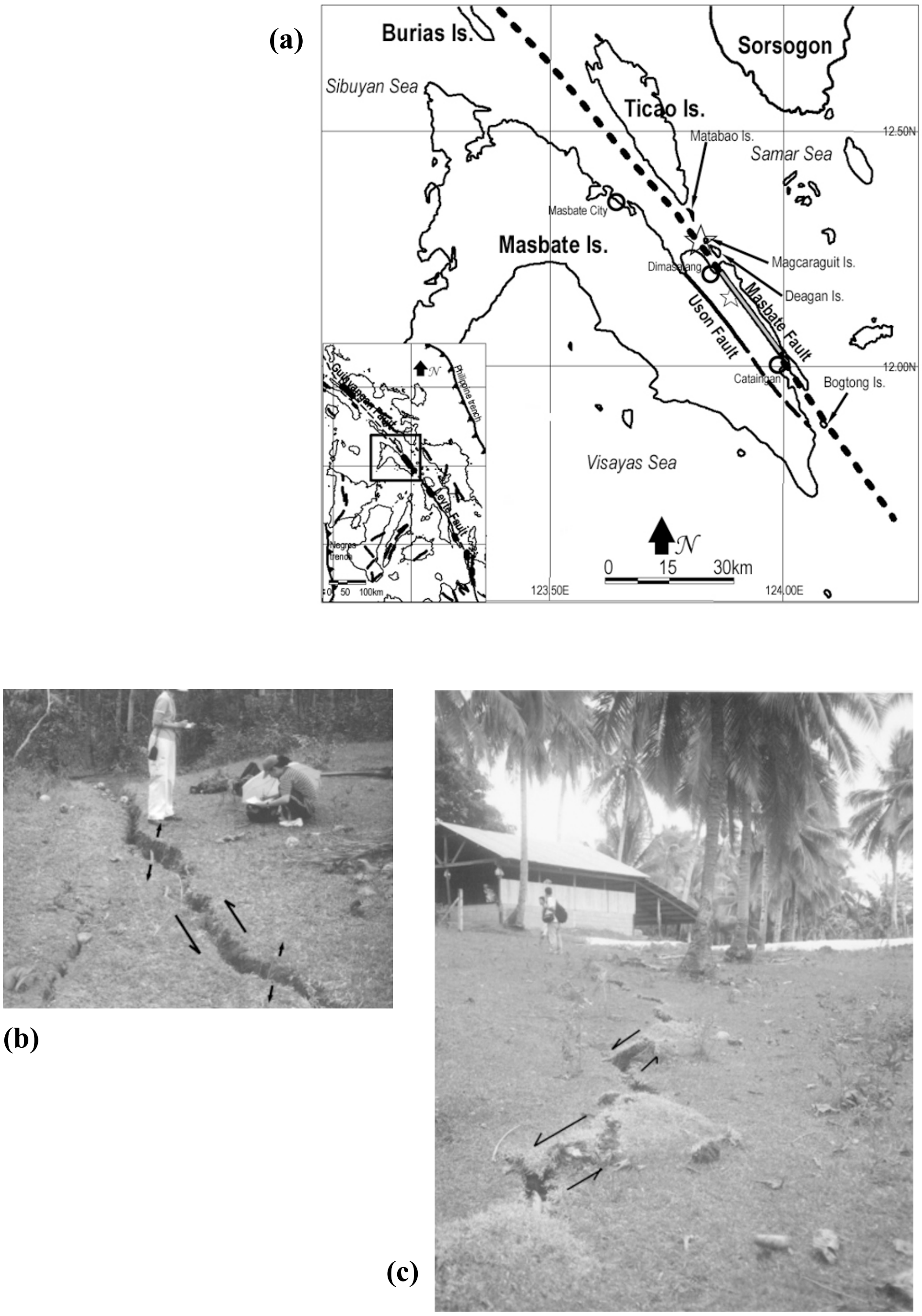

Fig. 4. (a) Map showing the location and extent of the mapped surface rupture (solid gray line) associated with the 2003 Masbate quake. Long dashed line is the possible extension of the Uson fault while the short dashed line indicates the offshore location of the PFZ. Large and small stars indicate the locations of the 2003 mainshock and foreshock epicenter, respectively (Besana *et al*., 2003). Open circles are major cities and towns on eastern Masbate island. Photos showing the left-lateral left-stepping fissures (b) and alternating mole tracks and tensional gashes (c) observed for the 2003 quake.

micity in Fig. 5(a). However, after three and four months, the seismicity showed some clustering in the southern and northern portions, relative to the previous aftershock plots. After six months, the seismicity became more dispersed and approached the background seismicity, with still a few perceptible events (Figs. 4(e) and (f)). Considering the locations of the observed post-seismic displacement and the clusters of aftershocks in southern Masbate, even after several months after the mainshock, it is quite possible that the moderate 2003 earthquake displayed post-seismic deformation or even a post-seismic slow event. However, since such post-seismic deformation and the presence of a slow slip component can only be detected and confirmed by crustal deformation measurements, we can only presume such occurrence at this time.

For the Leyte region, noticeably the area had very few major earthquakes. The largest ever recorded was about four centuries ago in the central Leyte area (Figs. 2 and 3). The northern part of the Central Leyte fault has no record of any major destructive events. The rest of the events

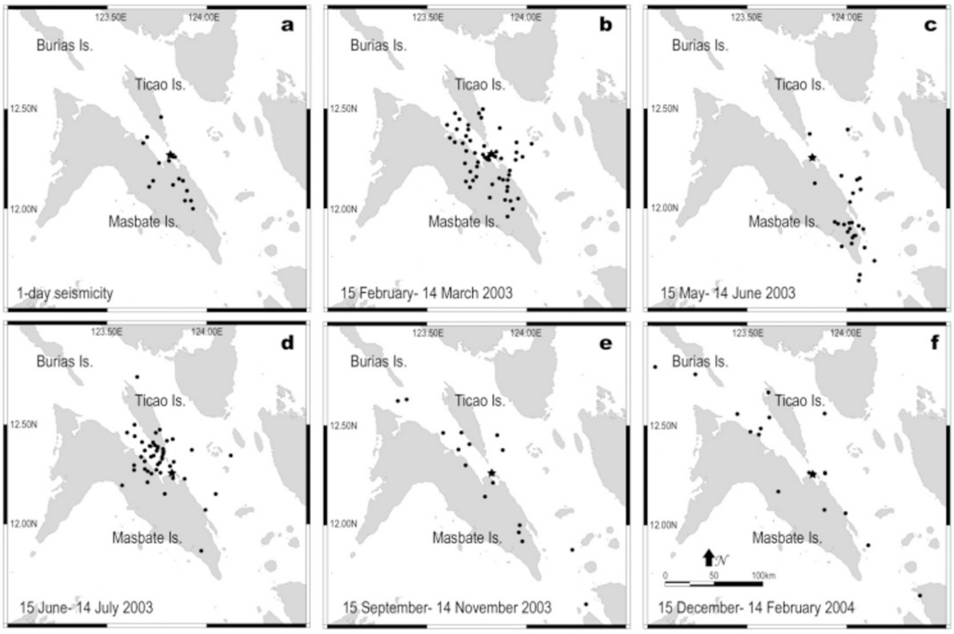

Fig. 5. The aftershocks of the 2003 Masbate event. (a) one-day aftershocks, (b) 15 February–14 March 2003 seismicity, (c) 15 May–14 June 2003 seismicity, (d) 15 June–14 July 2003 seismicity, (e) 14 September–14 November 2003 seismicity, and (f) 15 December–14 February 2004. Plots were analyzed using 232 aftershock events with magnitudes ranging from M3.5∼6.1. Solid star indicates the location of the 2003 mainshock.

Table 1. The observed characteristic activity along the three major segments of the central PFZ. GPS measurements were based on Aurelio (2000), Duquesnoy *et al*. (1994), Catane *et al*. (2000), and Bacolcol (2003), historic slip rates were based on Morante (1974), Besana *et al*. (2003), and Daligdig and Besana (1991), and geologic slip rates were calculated using the regional geologic map of the Philippines (BMG, 1981).

	Guinyangan Fault	Masbate Fault	Central Leyte Fault (CLF)*	
			NCLF	SCLF
Foreshock activity		perceptible foreshock	—	1–2 weeks clusters
Mainshock	>M7.0	>M5.0 ∼ M7.0	—	< or = M6.0
Aftershock zone	∼120 km-long zone	∼70 km-long zone	—	∼50 km-long zone
Historical activity	Major quakes	Moderate events with surface rupture	—	Moderate events w/o surface rupture
Geologic slip rate	33 mm/yr	5–35 mm/yr	25 mm/yr	8 mm/yr
GPS Slip Rate	20–33 m/yr	10–30 mm/yr	26 mm/yr (creep)	22–30 mm/yr
Historic slip rate	22–33 mm/yr	∼100 mm/yr	—	No observable ground rupture
Recurrence interval	∼30–100 years	∼5–10 years	—	∼5–10 years

recorded on Leyte island are two moderate earthquakes on the southern Central Leyte fault. Interestingly, both of these moderate events occurred with a cluster of foreshocks for at least one week, many of which were perceptible. Although there was no observed surface ground rupture associated to these events, the extent of the rupture can be deduced to be around 50 km, based on the 1-month aftershock distributions (Daligdig and Besana, 1991). Again, such possible extent of the rupture is relatively large for a M5.5 earthquake when plotted on empirical magnitude-surface rupture relations (Acharya, 1979; Wells and Coppersmith, 1994). We also noted that north of the 1608 event, no significant events have occurred. This northern portion is where the central Leyte Fault transects a volcanic region with active geothermal activity. Since the whole stretch of the Central Leyte fault displays contrasting seismic activity, we hereby separate the northern portion from the southern portion and name these structures as, the north Central Leyte fault (NCLF) and the south Central Leyte fault (SCLF).

To understand the regional characteristics of the central PFZ in terms of the seismicity and slip rates, a summary of observed values in each region were compiled in Table 1. Geologic slip rates are conservative estimates of slip rates, considering that these are based on the regional geologic map of the Philippines (BMG, 1981). Slip rates along the Guinyangan fault are more or less consistent geologically, with GPS observations and historical records. The Masbate fault, on the other hand, has large variations in slip rate, and has a lower bound on the slip rate from historical data. Only relative slip rates can be determined for the CLF since there have been no earthquake on the NCLF and no observable ground rupture on the SCLF during the moderate seismic activity.

4. Discussion

Taking a closer look into the seismicity along the central PFZ, it is defined by interesting clusters of large and moderate earthquakes. Based on the limited available seismic data in the region, it is apparent that the Guinyangan fault usually generates larger and more destructive events compared to the Masbate fault and the CLF. It has a recurrence interval that ranges from about 30 to 100 years. The southern part of the Guinyangan fault likewise has moderate-sized earthquakes that preceded the event of 1937. Small and moderate events also clustered in the Masbate area prior to the 1973 event in the Guinyangan area (Fig. 3). Thus, observations and analyses of the pattern of such moderate-sized quakes along the Masbate fault and the southern portion of the Guinyangan fault might give some indication of the large events that could occur along the Guinyangan fault. Such information is important considering the magnitude of events that occur along this fault and the presence of cities and towns in the nearby Guinyangan area.

For the Masbate area, it is quite interesting to consider the aftershock distribution of the 2003 event to gauge the possible total length of the ground rupture in this region considering that the epicenter and the rest of the aftershocks are located offshore. Aftershock distributions have been suggested to define the extent of faulting for large earthquakes (Wilson, 1936; Benioff, 1955), as well as small events (Buwalda and St. Amand, 1955; Brown and Vedder; 1967; McEvilly *et al*., 1967) and even the geometry of the mainshock (Iida, 1965; Matsuda, 1977; Nakamura and Ando, 1996; Nanjo and Nagahama, 2000). If this is the case, using the aftershocks for the 2003 Masbate event, the distribution roughly delineates a rupture of approximately 90 km (Fig. 5). However, we do not discount the possibility that aftershocks could be off-fault events (Das and Scholz, 1981; Stein and Lisowski, 1983), or active seismicity near the edges of the fault zone, as described by Rybicki (1973). Thus, considering the extent of the aftershock distribution and keeping in mind the limitations and error in aftershocks determination, the possible length of the ground rupture could be around 70 km. Assuming this ground rupture length, the value for the 2003 event, using the empirical relations established by Acharya (1979) for the Philippine region and by Wells and Coppersmith (1994) for the worldwide data, corresponds to a magnitude of at least M7.

On the other hand, the observed widening and elongation of the hairline fissures near the southern terminus of the 2003 ground rupture apparently indicate post-seismic deformation. Post-seismic response may reflect either a continuing afterslip following the earthquake or equilibration of a fluid regime or a combination of both processes as shown by Johnston *et al*. (1987). It was noted that afterslip is common in regions where aseismic fault slip occurs, such as on the San Andreas fault following the 1966 Parkfield earthquake (Smith and Wyss, 1968; Scholz *et al*., 1969) and on the Imperial fault following the 1979 Imperial Valley earthquake (Langbein *et al*., 1983). The occurrence of post-seismic deformation is also noted during aftershocks (Hough *et al*., 1993) or could be aseismic slip along a transition zone after a moderate event (Gladwin *et al*., 1994; Rubin *et al*., 1999). Taking into account the lack of waveform analysis and continuous GPS observations in the area, we can only surmise that probably afterslip after the Masbate 2003 event continued for at least 2 months after the earthquake based on the observed continued displacement near the southern terminus followed by a cluster of aftershocks. If we suppose that the 2003 event had post-earthquake deformation and/or aseismic slip this could account for the small moment magnitude for the 2003 event. The measured magnitude is M6.2 (Besana *et al*., 2003), however, considering the post-seismic deformation observed and aftershock distribution, the 2003 event could have after-slip or a slow event component with a total magnitude of at least 7.0. The presence of a small asperity along this area may explain the combination of large rupture and small magnitude for this earthquake. Thus, the Masbate fault of the central PFZ can generally be characterized as a zone where large and moderate earthquakes occur accompanied by large ground rupture and most probably with post-seismic deformation or a slow-event component. This type of observation is the first along the PFZ and has not yet been seen in other active faults in the archipelago.

The CLF, on the other hand, is composed of a creeping NCLF and locked SCLF with moderate earthquakes. The creep activity associated with the NCLF has been observed in a very limited area along the CLF. Geomorphological features along this region indicates active faulting, however, there is no observable displacement of any cultural markers that can be associated with the large creep measured through GPS observations. On the other hand, the SCLF has been the usual locations of moderate earthquakes preceded by several days of perceptible foreshocks. Such occurrence of foreshocks, many of which were perceptible, make the main shock relatively predictable and even anticipated by the local inhabitants. In between the NCLF and SCLF was a large earthquake that occurred about 4 centuries ago. Note that from Surigao of northeastern Mindanao, the central portion of the PFZ is almost straight on Leyte and Masbate islands. However, there is some change in the fault trend on central Leyte island. Such a bend could represent a fault jog that hinders the rupture propagation along this region. Also note that the large quake of 1608 occurred just south of this bend. We can surmise that the differences in the characteristic behavior between the NCLF and SCLF could probably be due to differences in geology which could have caused a jog and changed its geometry, and hence, the presence of a fault bend located in central part of Leyte island.

In general terms, the central portion of the PFZ, a left-lateral fault, comprising of the Guinyangan fault, the Masbate fault and the CLF is comparable to the SAF not only in terms of geomorphological features but also in its faulting and seismic characteristics as shown in this paper. This portion of the PFZ trends N30–40W and is almost straight in the Visayas region with a change in trend of the PFZ in Surigao and northern Quezon province (Fig. 1). On the other hand, the SAF is a right-lateral fault in California, whose northern region is composed of the San Juan Bautista, Parkfield, Cholame and the Carrizo Plain sections. This length along the SAF is also quite straight, changing its regional trend in the Carrizo Plain, with locations of locked, transition zones and creep activity (Scholz *et al*., 1969; Eaton *et al*., 1970; Rogers and Nason, 1971; Schulz *et al*., 1982; Lienkaemper and Prescott, 1989). Both structures have locked portions at both ends where the fault trend changes and major large earthquakes have occurred in the past. Interestingly, the transition zone in the PFZ, particularly the Masbate area, has aseismic slip and the locus of moderate quakes, similar to the Parkfield area on the SAF. However, in contrast to the SAF, the transition zone along the central PFZ is not only slipping aseismically but also the location of large earthquakes, usually with significant ground rupture. Both moderate and large earthquakes in this portion are accompanied by large surface displacements. Furthermore, aseismic slip along the central PFZ is faster compared to the SAF and has a much shorter recurrence interval (5–10 years). The creeping section on the central PFZ has no observable left-lateral displacement on cultural markers compared to the evident right-lateral displacements along the SAF.

In terms of disaster mitigation, closer and continued studies should be undertaken along the whole stretch of the central PFZ. The short recurrence interval along the Guinyangan fault indicates that the next future earthquake has a high probability of occurring soon. However, the recurrence time could vary greatly considering the very limited data that was analyzed. Thus, farther observations and paleoseismological studies for the Guinyangan fault are necessary to more accurately resolve the recurrence interval. Closer analysis of the clusters of moderate earthquakes in the southern part of Guinyangan fault is also needed to understand the possible relation of these events with the large events on the Guinyangan fault and northern Quezon province. Likewise, the Leyte and Masbate faults of the PFZ are interesting area for research specifically for detailed seismic and crustal deformation analysis. Such analyses could define in details the extent of aseismic and creeping sections along the Masbate fault and CLF, for both along the fault and in depth, and its possible effect(s) on the locked Guinyangan fault. A continuous GPS network could also help verify the occurrence and define the magnitude of the slow slip along this portion of the PFZ.

5. Conclusions

The central Philippine Fault Zone (PFZ) is comprised of the Guinyangan fault, Masbate fault, and CLF. This part of the PFZ is found to be the locus of great earthquakes, fault creep activity and most probably a slow-slip event. We found that the Guinyangan fault is the location of large major events that have recurrence intervals as short as 65 years. The Masbate fault is a transition zone characterized by large and medium earthquakes accompanied by unusually large ground rupture with post-seismic deformation and possibly slow-slip components. Recurrence intervals along this zone range from 5 to 10 years. Lastly, the NCLF and SCLF are characterized by creep and by medium-sized events, respectively, usually with clusters of foreshocks that serve as warning to the impending mainshocks. No recent observable surface displacements are known to be associated with the NCLF and SCLF aside from the geomorphic features despite the large left-lateral displacements measured using GPS. Further investigations of this region are needed for deeper understanding of the central PFZ in terms of better resolution of recurrence intervals, clearer delineation of the extent of locked portion, transition zone, creeping segments, and the occurrence of slow slip that could give important information for disaster mitigation efforts.

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