活断層研究　39号　29～37　2013
Active Fault Research, No. 39, P. 29~37, 2013

Large-scale active fault map of the Philippine fault based on aerial photograph interpretation

Hiroyuki Tsutsumi[*1] and Jeffrey S. Perez[*2]

Abstract

The Philippine fault is a ~1250-km-long, left-lateral strike-slip fault extending NNW parallel to the Philippine archipelago. This fault has been very active in the past 200 years with several destructive earthquakes accompanied by surface rupture. However, there was no large-scale map of the Philippine fault, which is essential for mitigating seismic hazard from future earthquakes. We mapped the surface trace of the Philippine fault on 1:50000-scale topographic maps based mainly on interpretation of ~1:30000-scale aerial photographs. We then compiled these fault trace data on a Geographic Information System to produce the first digital active fault map of the Philippine fault. These 1:50000-scale active fault maps are available from the website of Philippine Institute of Volcanology and Seismology (PHIVOLCS). These maps reveal that there are notable along-strike variations in fault trace geometry and magnitudes of historical seismicity of the Philippine fault. The Philippine fault in central Luzon and Mindanao Islands are well segmented and produced large (M≥7) earthquakes. In contrast, the fault in Masbate and Leyte Islands are more continuous and produced only moderate earthquakes in the past 400 years. There are geomorphic and geodetic evidence of aseismic creeping on the Philippine fault in northern and central Leyte. These observations suggest that the Philippine fault may be comparable to the San Andreas fault in that both of the faults are composed of locked, transition and creeping segments as previously suggested.

1. Introduction

Large-scale active fault maps are one of the most fundamental data sets for active tectonics and seismic hazard mitigation studies. These maps are available in countries where active fault research is well established, such as Japan (Research Group for Active Faults of Japan, 1991; Nakata and Imaizumi eds., 2002), New Zealand (New Zealand Active Faults Database, GNS Science, data.gns.cri.nz/af/, last accessed on 22 June 2013), and the United States (Quaternary Fault and Fold Database of the United States, USGS, earthquake.usgs.gov/hazards/qfaults/, last accessed on 22 June 2013). In contrast, there are many earthquake-prone countries, especially in Asia, where detailed active fault maps do not exist due to lack of financial and human resources. In this regard, we have produced large-scale active fault maps of Asian countries or regions, such as Pakistan (Nakata et al., 1991) and Sakhalin (Tsutsumi et al., 2005).

The Philippine fault is a ~1250-km-long, arc-parallel strike-slip fault extending NNW parallel to the Philippine archipelago (Fig. 1). The fault traverses Luzon and Mindanao Islands where most economic and population centers of the country are located. The left-lateral motion on the fault is interpreted to be a result of oblique subduction of the Philippine Sea plate beneath the Sunda plate (Fitch, 1972). Campaign mode GPS surveys depicted 20-30 mm/yr left-lateral motion on the fault (Duquesnoy et al., 1994; Aurelio, 2000; Bacolcol et al., 2005). The Philippine fault is seismically active with several surface-rupturing earthquakes in the past 200 years. The most recent devastating earthquake on the fault was the 1990 M_W7.7 central Luzon earthquake that

*1 Department of Geophysics, Kyoto University, Kyoto 606-8502, Japan
*2 Philippine Institute of Volcanology and Seismology, Department of Science and Technology, Quezon City 1101, Philippines

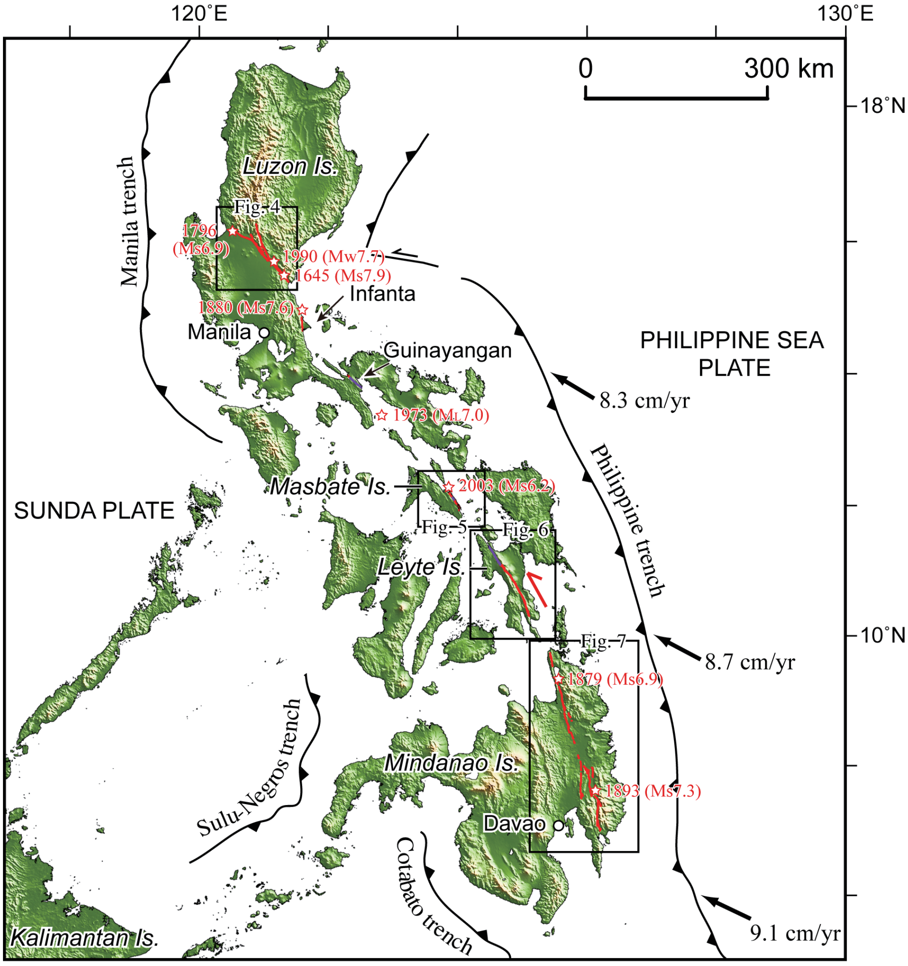

Fig. 1. Tectonic framework of the Philippine archipelago. Red lines denote traces of the Philippine fault based on interpretation of aerial photographs whereas purple lines denote those based on interpretation of shaded relief and topographic maps. Red arrow indicates the left-lateral motion on the Philippine fault. Red open stars show large historical earthquakes along the Philippine fault from Bautista and Oike (2000). Black lines with triangles denote subduction boundaries with arrows showing relative motion between the Philippine Sea plate and Sunda (Eurasia) plate from Seno et al. (1993). Shaded relief map was drawn from SRTM 3 arc-seconds elevation data. Locations of detailed maps (Figs. 4-7) are also shown.

produced 125-km-long surface rupture (Nakata et al., 1990; Nakata et al., 1996; Velasco et al., 1996). More than half of large historical crustal earthquakes in the Philippines are related to the Philippine fault (Bautista and Oike, 2000).

The gross structural and geomorphic features of the Philippine fault have long been known since the middle of the last century (Willis, 1944; Allen, 1962). Detailed tectonic geomorphic studies have been conducted at local scales, such as Nakata et al. (1977, 1996) and Daligdig (1997), all of which identified evidence for repeated late Quaternary faulting in central Luzon. Despite its high activity and seismic risk, there was no large-scale active fault map of the entire Philippine fault. The Philippine Institute of Volcanology and Seismology (PHIVOLCS) published a 1:500000-scale active fault map of the Philippine islands based on analysis of satellite images (Philippine Institute of Volcanology and Seismology, 2000). Although this map has been widely used for seismic hazard evaluation in the country, the unavailability of large-scale stereographic satellite images limited the reliability of the map. Many faults shown on Philippine Institute of Volcanology and Seismology (2000) follow topographic lineaments lacking geomorphic evidence of late Quaternary activity, while some faults with small-scale late Quaternary tectonic landforms were not recognized as active. The scale of the map is also too small to be used as a base map for any further studies. The lack of detailed map of the Philippine fault seriously hampers attempts to mitigate seismic hazards in the country and understand active tectonics of the oblique convergence zone.

Since 2003, we mapped the surface trace of the Philippine fault from Luzon to Mindanao Islands based mainly on interpretation of large-scale aerial photographs. We were able to map ~90 % of the on land stretch of the fault from central Luzon to Mindanao using aerial photographs (Fig. 1). The rest of the fault zone, for which aerial photographs were unavailable, was mapped based on analysis of shaded relief and topographic maps. We compiled the fault data on a Geographic Information

System and made the data available to the public on the PHIVOLCS website.

In this paper, we introduce the new digital map of the Philippine fault. We then briefly describe the geometry, tectonic geomorphology, and historical earthquakes of the Philippine fault from central Luzon Island southward to Mindanao Island.

2. Resources and methods

We interpreted stereographic pairs of ~1:30000-scale aerial photographs of central Luzon and Mindanao Islands that are archived at PHIVOLCS. For Masbate and Leyte Islands, we purchased ~1:30000-scale aerial photographs from the National Mapping and Resource Information Agency (NAMRIA) of the Philippine government and private companies. Most of the aerial photographs were taken in the late 1970s and early 1980s, except for the aerial photographs in central Luzon that were taken immediately after the 1990 earthquake. These aerial photographs cover ~90 % of the on land stretch of the Philippine fault south of latitude 17° N (Fig. 1). The rest of the fault zone was mapped based on shaded relief maps drawn from SRTM (Shuttle Radar Topography Mission) 3 arc-seconds elevation data and topographic maps. Although Pinet and Stephan (1990) and Ringenbach et al. (1990) mapped the possible northern extension of the Philippine fault in northern Luzon, we have not yet systematically mapped it due to lack of aerial photographs and exclude the area from the scope of this paper.

Representative stereographic pairs of the ~1:30000-scale aerial photographs are shown in Fig. 2; these photographs clearly show fault scarps and stream offsets. We identified active faults on the basis of geomorphic criteria commonly used for active fault mapping in Japan (Research Group for Active Faults of Japan, 1991; Nakata and Imaizumi eds., 2002). We employed two categories of active faults: active faults and presumed active faults. Active faults offset geomorphic surfaces or strata of late Quaternary time. Presumed active faults lack clear evidence of late Quaternary displacement. For example, a fault traversing bedrock terrain with no late Quaternary geomorphic surfaces or strata is classified as a presumed active fault. Fault scarps, linear depressions, systematic deflection of streams, and fault saddles are the most commonly observed geomorphic expressions of strike-slip faults (Research Group for Active Faults of Japan, 1991) and also develop along the Philippine fault.

Tectonic geomorphic features identified from interpretation

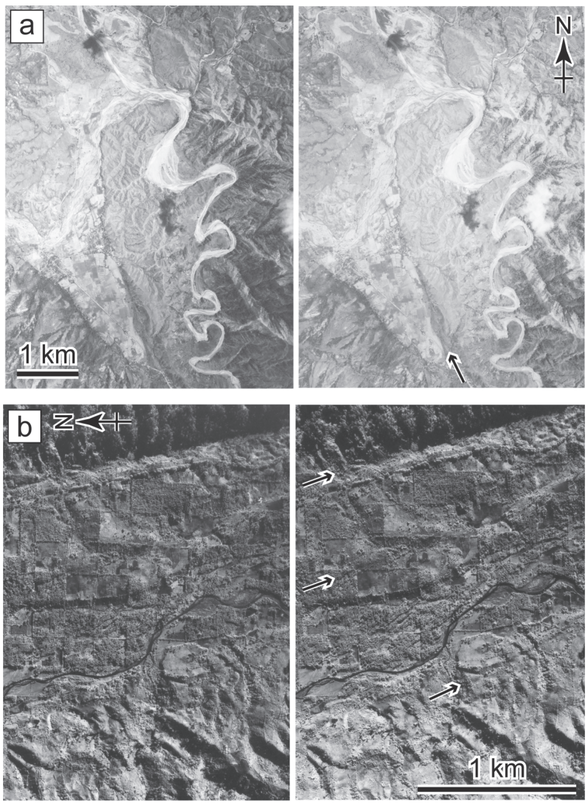

Fig. 2. Examples of stereo-paired aerial photographs we used to map the Philippine fault. Arrows denote active fault traces. (a) The Digdig fault south of Digdig, Nueva Ecija Province, Luzon Island. (b) Three parallel fault traces north of Mati City, Davao Oriental Province, Mindanao Island.

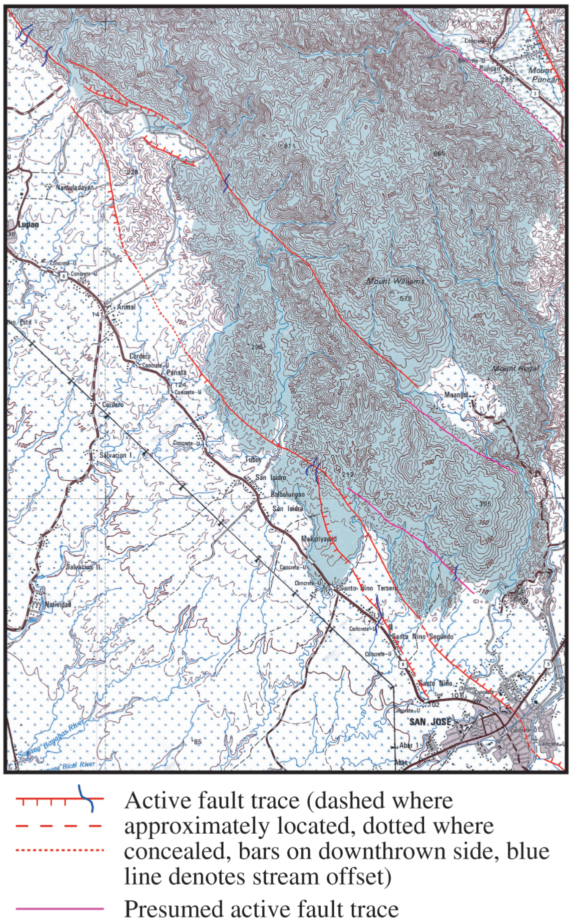

Fig. 3. An example of digital active fault map of the Philippine fault (around San Jose City, Nueva Ecija Province, Luzon Island) in PDF format available at the PHIVOLCS website. Location of the map is shown in Fig. 4.

of aerial photographs and shaded relief maps were then traced over the base maps that were scanned and rectified 1:50000-scale topographic maps published by NAMRIA. These are the largest-scale topographic maps covering the whole Philippines with contour interval of 20 m.

Fault traces and tectonic geomorphic features compiled on 50 sheets of the base maps were digitized and attributed using the MapInfo Professional (Pitney Bowes Inc.). These digital fault maps are now available to the public as PDF files at the PHIVOLCS website (http://www.phivolcs.dost.gov.ph/). An example of the PDF map sheets is shown in Fig. 3. The fault data in shapefile (.shp) format, a common geospatial vector data format for various GIS platforms, are available on request to PFZmap@gmail.com.

3. Distribution and characteristics of active faults

The Philippine fault from central Luzon to Mindanao is ~1250 km long, however, only ~700 km long stretch is subaerially exposed. The overall shape of the Philippine fault is convex to the ENE (Fig. 1). The general strike of the fault south of Leyte Island is N20° W whereas it is N40° W north of the island. The distance between the Philippine fault and the axis of the Philippine trench increases to the north from ~100 km in southeastern Mindanao to ~300 km in southern Luzon (Fig. 1). The Philippine fault crosses the volcanic front related to the Philippine Sea plate subduction at the latitude of Leyte Island.

The fault trace is marked by well-defined geomorphic features characteristic of strike-slip faults. The fault trace includes numerous discontinuities, such as steps with dimensions as large as several kilometers, which may have strong influence on coseismic behavior of the fault.

In the following sections, we briefly describe the geometry, geomorphology, and historical earthquakes of the Philippine fault from Luzon Island southward to Mindanao Island. More detailed regional description of tectonic geomorphic features, slip rates, and historical- and paleo-seismic activities will be given in separate papers.

3. 1 Luzon Island

The Philippine fault is subaerially exposed in Luzon Island at three localities: central Luzon, Infanta and Guinayangan areas of southern Luzon (Fig. 1). The Philippine fault in central Luzon consists of four left-stepping fault segments with a total length of ~150 km: the San Manuel, San Jose, Digdig, and Gabaldon faults from northwest to southeast (Fig. 4). Surface traces of these faults were previously mapped by Nakata et al. (1977) and Daligdig (1997) based on aerial photograph interpretation and field survey. We built upon their work and newly identified fresh fault scarps less than 1 m high across alluvial lowland on the eastern extension of the San Manuel fault east of San Manuel and the southern extension of the San Jose fault south of San Jose City. Although the left (dilatational) steps separating the faults are small scale (≤2.5 km wide), they acted as segment boundaries during large historical earthquakes. The 1990 central Luzon earthquake ruptured the entire length of the 125-km-long

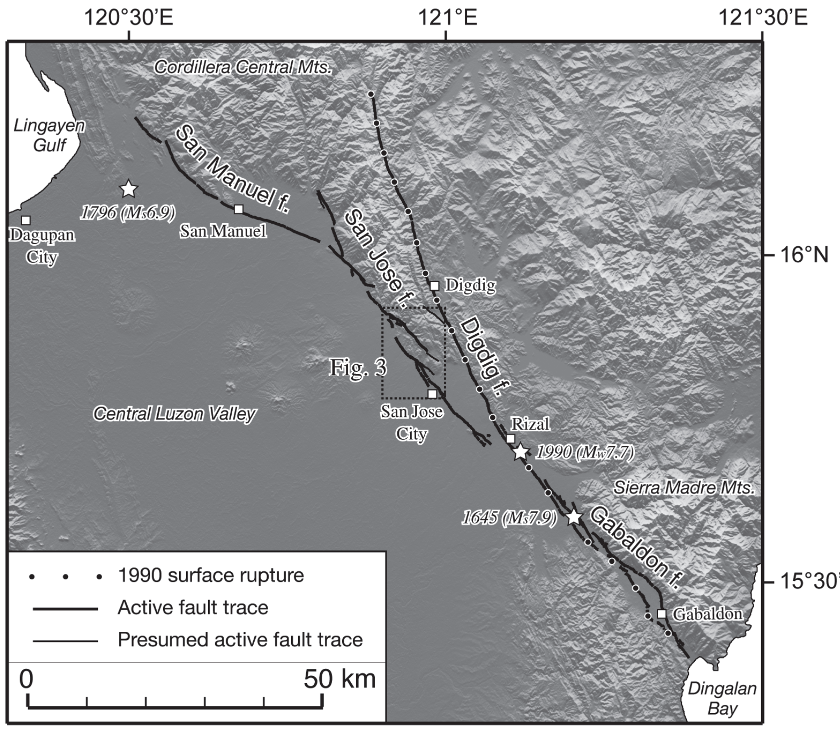

Fig. 4. The Philippine fault in central Luzon Island. Open stars denote historical earthquakes along the Philippine fault; the epicenter and magnitude are from Bautista and Oike (2000). Surface rupture of the 1990 earthquake is from Nakata et al. (1996).

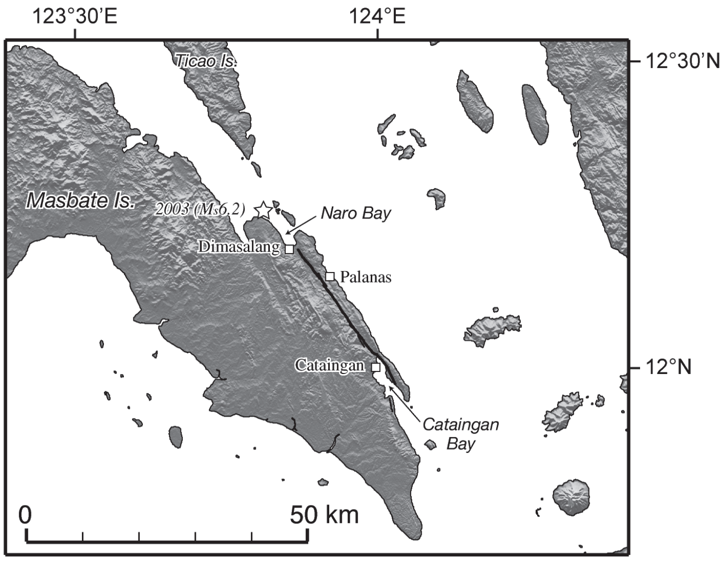

Fig. 5. The Philippine fault in Masbate Island. The legend is the same as in Fig. 4. The epicenter and magnitude of the 2003 Masbate earthquake is from PHIVOLCS Quick Response Team (2003).

Digdig fault with a maximum left slip of ~6 m (Nakata et al., 1990; 1996) but the coseismic rupture did not propagate into the Gabaldon fault or the San Jose fault. Paleoseismic trenching suggests that only the Gabaldon fault ruptured during the 1645 M_S 7.9 earthquake (Tsutsumi et al., 2006).

The Philippine fault is observed again on land in Infanta area for a distance of ~25 km (Fig. 1). The fault trace is fairly straight separating the mountains to the west and coastal lowland to the east. The last large earthquake in this area was the 1880 M_S7.6 earthquake (Bautista and Oike, 2000). In the field, we can identify uplifted wave-cut bench ~1 m above the mean sea level on the up-thrown side (west) of the fault that may be related to the 1880 earthquake.

To the southeast, the Philippine fault traverses the Guinayangan area for a distance of ~30 km. Because aerial photographs were available only for the northern portion of the fault, we mapped the rest of the fault trace using topographic maps and later conducted reconnaissance field surveys (Fig. 1). The fault trace is remarkably straight. The Philippine fault here ruptured during the 1973 M_L 7.0 Ragay Gulf earthquake. The predominant coseismic motion was left lateral and the amount of displacement ranged from 1 to 3.5 m (Morante, 1974). Offsets of coconut tree lines are identified at several localities in the field, suggesting 1.5-2 m left-lateral coseismic displacement. The epicenter was located at about 50 km southeast of the southern end of the on land fault trace in Guinayangan area (Fig. 1).

3. 2 Masbate Island

The Philippine fault traverses the eastern edge of Masbate Island almost parallel to the coastline for a length of ~30 km (Fig. 5). The surface trace lies along a linear trough that trends N40° W and is fairly straight except for steps less than 300 m in width west of Palanas. Bacolcol et al. (2005) calculated 22 ± 2 mm/yr slip rate for the Philippine fault on this island based on campaign mode GPS surveys. The Philippine fault here is seismically active with several moderate earthquakes in historic time. The 2003 M_S 6.2 Masbate earthquake whose epicenter was located offshore in Naro Bay was a moderate earthquake, however, ~18-km-long surface rupture appeared on land along the Philippine fault. The surface rupture was characterized by en echelon fractures and mole tracks. The slip was predominantly left lateral and the maximum displacement was 47 cm (PHIVOLCS Quick Response Team, 2003). Paleoseismic trenching of the surface rupture by Papiona and Kinugasa (2008) identified stratigraphic evidence for four surface-rupturing earthquakes in the past ~680 years.

3. 3 Leyte Island

The Philippine fault extends along the backbone range of Leyte Island for a distance of ~140 km (Fig. 6). The surface trace is characterized by linear valleys, stream offsets, hillside ridges, and wind gaps.

From the Biliran Strait, the fault extends southeastward onto Leyte Island and forms a narrow linear depression as far south to Lemon for a distance of ~20 km as described by Allen (1962). Perez et al. (2008) reported creeping of the Philippine fault in Leyte town based on offsets of concrete structures and asphalt roads. South of Lemon, the fault trace is marked by a series of hillside ridges along the western flank of the backbone range. Lake Danao is located at a ~1-km-wide releasing step of the fault trace. There is another ~1-km-wide left step in fault trace ~10 km to the south (Fig. 6).

South of Lake Danao, the fault extends along the western flank of Mt. Lobi. Between Burauen and Abuyog, the fault

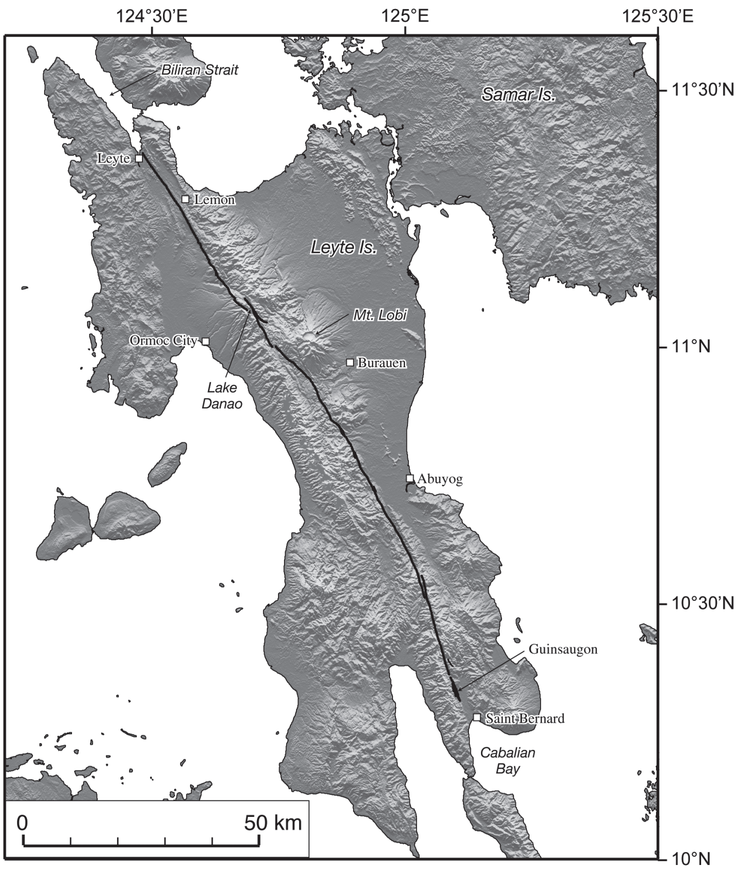

Fig. 6. The Philippine fault in Leyte Island. The legend is the same as in Fig. 4.

trace is located mostly along the eastern margin of the backbone range, however, in many localities the fault trace is marked by west-facing fault scarps. South of Abuyog, the fault trace traverses mountainous terrain forming narrow linear valleys with systematic left-lateral offset of stream channels. Near the southern end of the Philippine fault on Leyte Island, three parallel fault traces transect Guinsaugon where catastrophic landslide occurred in 2006 claiming more than 1000 lives. South of Guinsaugon, we could not identify clear fault trace across the alluvial lowland on which Saint Bernard is located.

Historical and instrumental seismicity of the Philippine fault on Leyte Island is quite different from that in the other areas; no large destructive earthquakes occurred in the past 400 years (Bautista and Oike, 2000). Tsutsumi et al. (2013) documented that large portion of slip on the Philippine fault in Leyte Island is accommodated by creeping based on InSAR analysis and field observations.

3. 4 Mindanao Island

The location and geometry of the Philippine fault in Mindanao Island were poorly known prior to this study because the fault mostly traverses alluvial lowlands and low-lying hills with thick vegetation cover. The Philippine fault enters onshore west of Surigao City and traverses the eastern portion of the island southward to Mati City for a distance of ~320 km (Fig. 7). North of the Agusan marsh, the fault trace is fairly continuous with a strike of N20° W. The overall strike of the fault south of the marsh is also N20° W, however, the fault zone is composed of several north-trending strands that are arranged in en echelon manner. We also identified scarps less than a few meters high on alluvial lowlands that appear to be associated with historical earthquakes.

From Surigao City southward to Lake Mainit, the Philippine fault cuts across the Malimono Ridge. Immediately south of Lake Mainit, less than 50-cm-high scarp cuts across alluvial lowland for a distance of ~7 km. Historical documents (Repetti, 1946; Bautista and Oike, 2000) suggest that this scarp is related to the 1879 Surigao earthquake (M_S 6.9). Paleoseismic trenching across this scarp revealed that at least three surface-rupturing earthquakes occurred during the past ~1000 years including the 1879 earthquake (Perez and Tsutsumi, 2011).

Immediately south of Esperanza, an east-facing scarp less than a few meters high and 7 km long is identified across the alluvial plain of the Agusan River. For a distance of ~50 km between 8° N and 8° 30' N, it is difficult to trace the fault continuously across the flat and heavily vegetated Agusan marsh. South of Veruela, several fault strands accommodate left-lateral movement on the Philippine fault. The westernmost strand extends due south to Mawab across low hills west of the Compostela Valley, although tectonic geomorphic features along

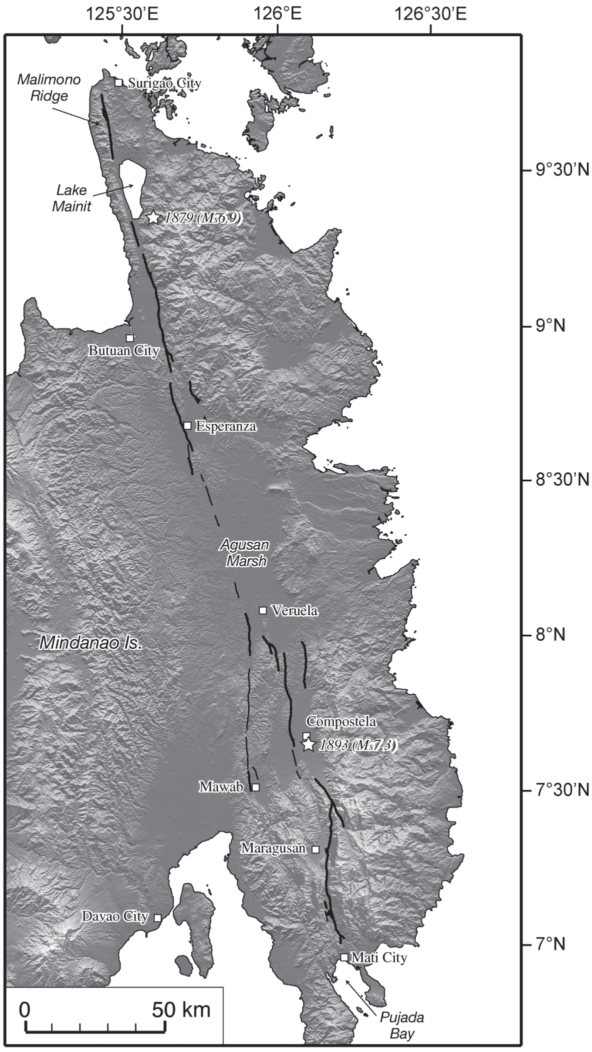

Fig. 7. The Philippine fault in Mindanao Island. The legend is the same as in Fig. 4. Open stars denote historical earthquakes along the Philippine fault; the epicenter and magnitude are from Bautista and Oike (2000).

this fault are not as pronounced as those along the faults to the east. The main component of motion is probably taken up by the left-stepping strands to the east that cut across the Compostela Valley. West of Compostela, we identified less than 5-m-high east-facing scarps across alluvial lowland that may be associated with the 1893 M_S 7.3 earthquake. Paleoseismic trenching across this scarp exposed near vertical faults that show geologic evidence for multiple faulting events during the past ~1000 years (Perez and Tsutsumi, 2011). Southeast of Compostela, the fault steps to the left for ~5 km and extends south to Mati City across mountainous terrain. The fault here bounds inter-mountain valleys such as Maragusan Valley that is interpreted as a fault-angle depression. The Philippine fault probably extends south to Pujada Bay although we could not identify clear fault trace across the coastal lowland on which Mati City is located. Aurelio (2000) obtained a slip rate of 21 mm/yr for the Philippine fault in Mindanao Island based on campaign mode GPS surveys.

4. Along-strike variations in fault trace geometry and historical seismicity of the Philippine fault

The Philippine fault in central Luzon and Mindanao Islands is highly segmented and produced M≥7 earthquakes. In central Luzon, four left-stepping distinct segments comprise the Philippine fault (Fig. 4). The dilatational steps separating these segments are only 0.5 - 2.5 km wide but appear to have arrested coseismic ruptures through multiple seismic cycles (Tsutsumi et al., 2006). Worldwide compilation of historical strike-slip earthquake ruptures revealed that more than half of the ruptures broke through steps less than a few km wide (Wesnousky, 2006). The Philippine fault in central Luzon produced large destructive earthquakes including the largest historical earthquake on the fault, the 1990 M_W7.7 earthquake. The Philippine fault in Infanta and Guinayangan areas in southern Luzon also ruptured during historical earthquakes greater than M7. The Philippine fault in Mindanao Island is also composed of several distinct fault strands separated by geometric discontinuities such as dilatational steps and branching (Fig. 7). Two historical M7-class earthquakes are known to have ruptured the Philippine fault in Mindanao Island (Perez and Tsutsumi, 2011).

In contrast, the surface trace of the Philippine fault in Masbate and Leyte Islands are much smoother and more continuous (Figs. 5, 6). The only notable discontinuities are two ~1-km-wide releasing steps near Lake Danao in Leyte Island. Historical seismicity on the two islands is quite different from that on Luzon and Mindanao Islands as noted by Besana and Ando (2005). There was no earthquake greater than M7 in the past 400 years in Masbate and Leyte Islands (Bautista and Oike, 2000). In Masbate Island, the 2003 M_S6.2 earthquake ruptured the surface, producing ~18-km-long surface rupture. In Leyte, there is no historical surface-rupturing earthquake, while the largest historical earthquake along the Philippine fault was M_S 6.1 (Bautista and Oike, 2000). There are geomorphic and geodetic evidence of aseismic creeping on the northern and central island (Tsutsumi et al., 2013). These observations are in agreement with Besana and Ando (2005) who suggested that the along strike variation of seismic behavior of the Philippine fault is comparable to that of the San Andreas fault in that the fault zone is composed of locked, transition and creeping segments.

5. Conclusions

We introduced the first digital active fault map of the Philippine fault which is available through the internet. We also briefly described its surface trace geometry and geomorphic features together with geodetic slip rates and historical seismicity. We believe the map provides fundamental information for seismic hazard mitigation from local to national levels as well as serves as a base map for future geological and geophysical studies of the Philippine fault. We plan to update the map based on additional aerial photograph interpretation and field observations. Although we mapped most of the subaerially exposed stretch of the Philippine fault, ~550-km-long stretch of the fault is under water. Mapping of the offshore segments is important to better assess seismic hazard from the fault and understand active tectonics of the archipelago.

Acknowledgements

This work was mainly supported by Grant-in-Aid for Scientific Research from Japan Society for the Promotion of Science (grant nos. 15403002 and 20403001) and by a grant from Fukutake Science and Culture Foundation to Hiroyuki Tsutsumi. This work was also partially funded by JICA-JST project "Enhancement of earthquake and volcano monitoring and effective utilization of disaster mitigation information in the Philippines". We thank Jessie A. Daligdig, Takashi Nakata and Hideaki Goto for collaborative mapping of the Philippine fault in central Luzon Island. We are also grateful to Renato U. Solidum, Jr. and Perla J. Delos Reyes of PHIVOLCS for their support and encouragement during the course of this project, Lucille Rose del Monte for assistance in posting our maps on the PHIVOLCS website and Shigeru Sueoka for help in GIS data compilation. Shaded relief maps were drawn on GMT (Wessel and Smith, 1998) using SRTM 3 arc-seconds elevation data. This manuscript benefited from constructive reviews by Yasuhiro Kumahara and an anonymous reviewer.

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（July 9, 2013 received）
（August 23, 2013 accepted）

キーワード

Key words : Philippine fault, active fault map, tectonic geomorphology, seismic hazard mitigation, Geographic Information System