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Earthquakes, Volcanic Eruptions, and Other Geological Disasters During Historical Records In Yogyakarta Special Region, Indonesia

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Abstract - Yogyakarta, Indonesia, is a very fast developing area. The Yogyakarta historical time is divided into Pre-Old Mataram Era (1st - 8th century), Old Mataram Era (8th - 12th century), and Young Mataram Era (since 16th century). Geology has recorded many intermittent natural disasters within those historical time: volcanism, earthquakes, and rock movements as well. Those natural disasters have caused lots of damages, shown by buried and collapsed old buildings. Larger volcanic eruptions were known to occur once in 50 - 150 years ago, which were mostly followed by lahars as far as 32 km from the crater of Merapi Volcano, of which the last eruption was in 2010. Earthquakes were identified based on bumpy foundations that particularly occurred in the first pile of temple stones, *i.e.* at the temples of Kedulan, Plaosan, Morangan, Gampingan, and Boko Palace. Surface fractures are also present on the base of the palace floors. During 18th - 21st century, larger earthquakes with magnitude of 5 - 8 Richter scale occurred once in 20 - 70 years, of which the last earthquake was in 2006. A geological study clarified that there was a marine volcanism during the Tertiary with radial normal faults. The normal faults have been potential to reactivate since Plio-Pleistocene untill now, shown by surface deformations at Sudimoro Hills with a mass movement occurence as happened in Imogiri (March, 17th 2019), Pleret (2018), Piyungan, and Dlingo (March, 17th - 18th 2019). A stratigraphic study of volcaniclastic deposits around Gendol, Opak, Kuning, and Bedog Rivers shows potential floods around the rivers.

Keywords: volcanic, earthquake, disasters, hazards, historical time

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Introduction

The tectonic setting of Yogyakarta was influenced by an active subduction zone located in the south of Java Island as long as 200 km (Hamilton, 1979; Figure 1). It has dynamically formed geological processes, including upliftings, volcanism, and mountain buildings in a very long period, since the Early Miocene (van Bemmelen, 1949). An earthquake was noticed in the Saturday morning of 27th, May 2006. It caused serious damages and fatalities on thousands of people living in Yogyakarta and Klaten (Central Java).

For millions of years, the studied area has gradually moved from submarine to subaerial area (Hamilton, 1979; Bronto *et al.*, 2009; Mulyaningsih and Sanyoto, 2012). Those affected the geological deformations in the region that formed plain morphology of Yogyakarta graben, Southern Mountain, West Progo Mountain, and Merapi

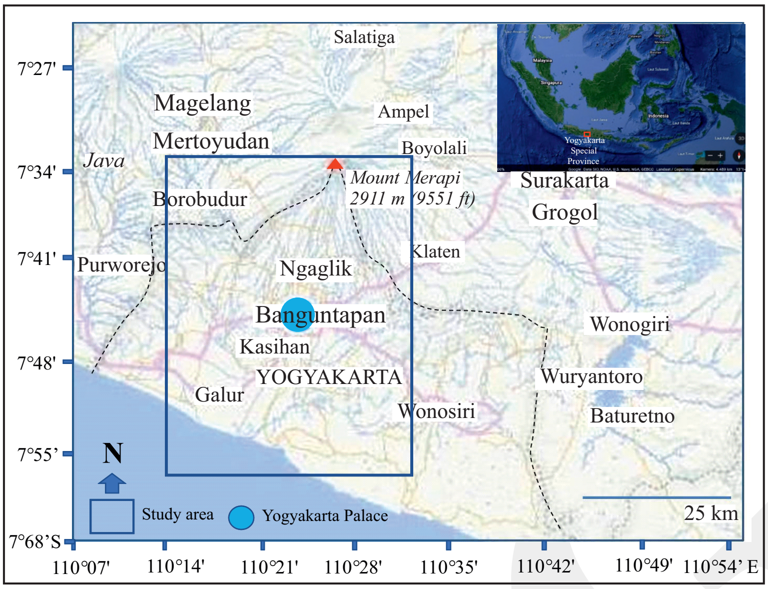

Figure 1. Map of study area, located in Yogyakarta Special Region (surrounded by dash line) (source: google.map)

Volcano. Mulyaningsih (2006), Mulyaningsih *et al.* (2006), and Mulyaningsih (2016) noted some geological disasters, such as volcanic eruptions, lahars, and earthquakes that had occured since the 1st century, in and around the studied area. Therefore, it can be assumed that the studied area has potential hazards, *i.e.* volcanic eruptions, lahars, and earthquakes. All of the geological processes have affected the development of cultures as shown by the local wisdom. The hypothesis is the dynamic geological processes occurring from time to time. They tend to be more frequent and more intense, even though they occurred periodically, unavoidably, and countably.

The studied area was located in Yogyakarta Special Region, *i.e.* southern−southeastern Sleman and northeastern−eastern Bantul (Figure 2). Administratively, it includes Bantul, Sleman, and Gunungkidul Regencies. Geographically, its coordinate is from 7°34'S and 110°14'E to 7°55'S and

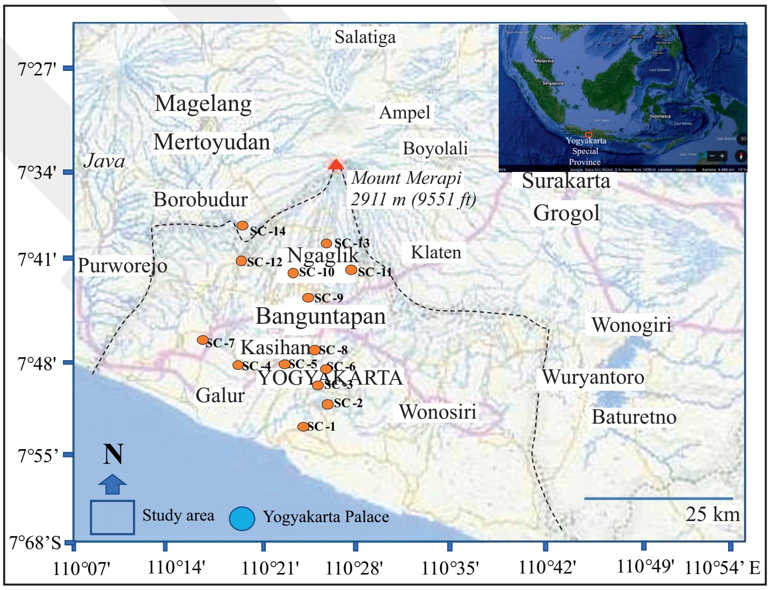

Figure 2. Location map of observations and measurements of geological data, as well as areas with data collection questionnaires (source of base map: google.map).

110°30'E. Yogyakarta is an area occupied with volcaniclastic deposits coming from Merapi Volcano bordered with scarps trending southwest–northeast of the Southern Moutain. The main purpose of this study is to describe natural disasters that have taken place in the researched area through geological approaches and the knowledge of the local people on the history. Hopefully, the results of this study can be used as the basis for determining policies in handling geological hazards in Yogyakarta Special Region, especially by volcanic eruptions, lahars (floods), and earthquakes.

Sampling and Analytical Method

The research performed geological and statistical data. More than ~70% of data were collected as primary data in the field through geological mapping, while ~30% of data were as secondary data which are direct infomation from the local people and questionnaires, literatures, journal, and reports.

The geomorphology of the studied area was described in the basis of morphostructures, morphometries, and morphoarrangements. It is comprehensively analyzed to interprete the deformations (active faults), distribution of historical community, historical disasters caused by pyroclastic and lahars/floods, palaeovalleys, and palaeoslides. Those are directly done in the field, supported by imagery analyses. Stratigraphic profiles are obtained by measuring surface outcrops for both exposed Quaternary and Tertiary volcanic deposits, as well as through several mass movements and anthropogenic processes. Geological structures (faults and joints) were studied in the field that showed lots of cracks in the temple walls and floors, river terraces, cliffs with ancient lakes, ancient mass movements, surface deformations, and also studied by carrying out questionnaires. The questionnaires include information from the local people about the disasters and the victims of earthquakes on May 27th, 2006 and on Merapi Volcano eruption on October 2010. The identification was intended to reveal the main geological processes causing the damages of public facilities and houses. It was also supported by the resistivity method using dipole-dipole configuration to describe the ripple fields and the thickness of the avalanches. The observation was carried out in six ranges of three stopsites before the landslide on March 17, 2019, and identified several buried faults that had potential to move in the future.

Evidences of disasters were collected based on geological mapping and questionnaires to people who lived in the areas of the recorded disasters. The mapping had been done on the deformed areas of 2006 earthquake, located in Imogiri, Piyungan, Dlingo, Pleret, and at some buried temples located along Opak and Gendol Rivers. Conversations were carried out with the victims' family of 2010 Merapi Volcanic eruption, located in Cangkringan, Pakem, and Ngemplak. About a hundred people responded to the questionnaires on disaster in Merapi Volcano eruption on October 2010, and about a hundred and fifty people responded to the questionnaires on disasters of 2006 earthquake and 2018 - 2019 landslides in Imogiri, Pleret, and Dlingo areas.

Lahars and floods caused by the ancient volcanic eruptions were interpreted from measured stratigraphic sections on the observation areas with volcanic deposits that hoard the temples. Hot ash clouds (by co-PDC) were identified from their antidune depositional structures (by turbulent mechanisms: high pressure and low percent particles), the availability (residential areas: temples/artifacts), the thickness, and their physical properties. Disasters caused by lahars were identified by using the thickness of flows. It is assumed that debris lahars contain 60–80% of particles and 20 - 40% of water. While uncohesive lahars contain 40 - 60% of water and 40–60% of particles, and cohesive lahars or fluvio-volcanic (distal lahar) that are usually called as floods contain 60 - 80% of water and 20 - 40% of material (Mulyaningsih, 2015). If there is 40 cm of lava in one layer, then the flow amount that forms 40% of particles + 60% of water is 100 cm - 160 cm.

All data were compiled, then analyzed by overlapping each other, and synthesized so that the evidence of recurring disasters was obtained in the studied area. Disasters occurred alternately from time to time, but people reacted wisely. Conclusions were obtained after all qualitative and quantitative data were discussed.

Geological Setting

Yogyakarta had been a deep sea volcanism area since the Late Oligocene, then it had gradually been becoming shallower until the Middle Miocene, forming volcanic rock units composed of Kebo-Butak, Semilir, and Nglanggeran Formations (Rahardjo *et al*., 1995). Since the Middle Miocene, the volcanic activity had declined, deposited epiclastic rocks of Sambipitu Formation. In the Late Miocene, the volcanism stopped completely, depositing sedimentary rocks of Oyo and Wonosari Formations. Figure 3 presents the regional stratigraphy of the studied area.

Pillow basaltic lava composing lower Kebo/Butak Formation indicates as a result of deep sea volcanism, spotly found in Watuadeg (Berbah-Sleman), Tegalrejo, and Kalinampu (Surono, 2009; Mulyaningsih, 2016), and Bawuran (Mulyaningsih and Sanyoto, 2012). Those were interpreted as the oldest volcanism in Yogyakarta and Central Java Province (Bronto *et al*., 2008; Faisal *et al*., 2018). However, Harijoko *et al.* (2014) found the presence of smectite, cristobalite, and heulandite (zeolite) minerals in the calcareous sediments trapped within the pillow lavas of Watuadeg outcrops. The paleontological analysis recognized foraminifera fossils (*Globoquadrina altispira* and *Globorotalia peripheroronda*) indicating the Middle Miocene age, and the benthic fossils (*Amphistegina lessonii*) showing neritic condition.

The next larger volcanism widely occurred in Giriloyo-Wonolelo (Mulyaningsih *et al.,* 2018), Candisari, Piyungan, Gedangsari, and Tegalrejo (Rahardjo *et al*., 1977; Mulyaningsih and Sanyoto, 2012; and Bronto, 2013). The recorded volcanic rocks were dark colour crystal tuff that

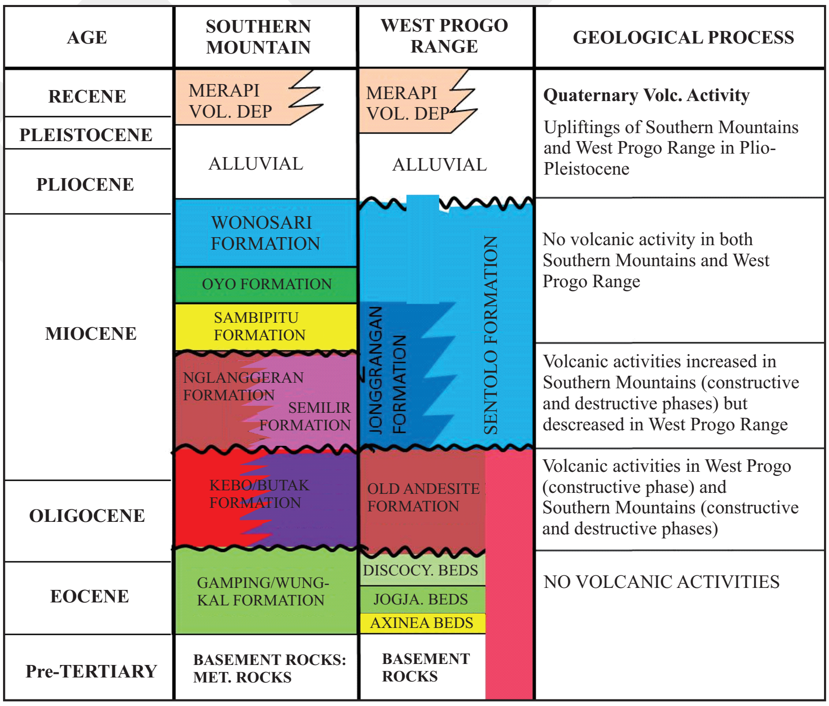

Figure 3. Stratigraphic regional of Southern Mountains and West Progo Range based on previous study (compiled from: Rahardjo *et al*., 1977; van Bemmelen, 1949; Bronto, 2009; and Mulyaningsih, 2016) and its interpretation of geological and volcanic activities during geological records of Yogyakarta Special Region.

were gradually lighter in the top, dyke, lava, breccia, and agglomerate in basaltic-andesitic composition. Mulyaningsih *et al*. (2018) grouped those volcanic rocks as Kebo/Butak Formation, but Surono *et al.* (1992) and Rahardjo *et al.* (1995) grouped them into Nglanggeran Formation. Mulyaningsih *et al.* (2009) analyzed that the planktonic foraminifera fossils contained within the calcareous sandstones above this group, has age of N5-9 (Early Miocene).

Semilir Formation is also a volcanic rock unit overlying Kebo/Butak Formation. The formation is composed of very thick beds of pumice breccia and tuff, originated from very explosive eruptions that caused more than 1/3 of the volcano body collapsed. The volcanic rocks of Semilir Formation are widely exposed from the east to the west in Wonogiri (Parangjoho), Baturagung Range, Imogiri-Siluk, and Parangtritis-Dlingo (Surono *et al*., 1992; Rahardjo *et al.,* 1995; Bronto *et al*., 2009; Hartono, 2010; Smyth *et al*., 2011; Mulyaningsih *et al*., 2011; Mulyaningsih and Sanyoto, 2012; Yusliandi *et al*., 2013; and Hartono, 2014). According to Rahardjo *et al.* (1995), based on nanno and foraminifera fossils contained in the calcareous claystone of the lower beds of Semilir Formation, this neritic marine formation is of the Early Miocene age (N3). At the top of the formation, as exposed at Ngalang River (Gedangsari) that borders Nglanggeran Formation, several thin lenses of lignite and wood fossil that might be as terrestrial deposits (Mulyaningsih and Sanyoto, 2012) occur. Based on the age determination using zircon fission track (within pumice breccia), Surono (2009) determined the age is 17.0 ± 0 - 16.0 ± 1.0 Ma (late Early Miocene).

After the Mega-Plinian explosive eruptions of Semilir Formation, the volcanic activities took place which yielded andesitic breccia, agglomerate, dike, and brown tuff of Nglanggeran Formation. Inflasions and diflations during the volcanism (since the formations of Kebo/Butak until Semilir) allegedlly that they have formed many open fractures, which were then traversed by magma to form new neritic−subaerial volcanoes in the Middle−Late Miocene. Those volcanic rocks, forming Nglanggeran Formation, outcrops well at Baturagung Range, Wonolelo (Pleret), Imogiri, and Parangtritis, of which in some places they alternate with dacitic pumices and tuffs of Semilir Formation (Smyth *et al*., 2005; Mulyaningsih and Sanyoto, 2012).

Based on the volcanostratigraphic study, two kinds of volcanic activities affected the occurrence of deformations at the Southern Mountain. There was a constructive phase forming Lower Kebo/Butak and Nglanggeran Formations by alternating effusive and small scale explosive eruptions during the Early−Middle Miocene. Furthermore, a destructive phase which in a very short time but very explosive Mega-Plinian eruptions formed Semilir Formation (Smyth *et al*., 2005; Mulyaningsih and Sanyoto, 2012). When the growth of the volcanic body reached its maximum height, the magma was no longer able to flow to the surface in a short travel time. Consequently, assimilation and differentiation took place and the composition of magma became more acidic and viscous. This allowed the magma to accumulate at the top of the volcano, forming a lava plug. In this case, the pressure of flow and supply of magma from the partial melting zone continued endlessly. As the result, the lava plug was no longer able to hold it. In this phase, a very explosive eruption may occur, followed by the destruction of most of the body to form a caldera with a diameter of more than 2 km at the top of the volcano. This eruption phase was very short but it produced a very large volume of volcanic material, called the destructive phase of volcano. At least, there were four times of constructive volcanism phase and three times of destructive volcanism phase in the Southern Mountain (Mulyaningsih and Sanyoto, 2012; and Smyth *et al.,* 2005). That is why the southern part of the researched area (which enters the Southern Mountains) has very strong deformations. Therefore, it has the potential of mass movements everywhere, especially during the rainy season. Most researchers agreed that submarine environment ended in the Middle Pliocene, then uplifted and formed mountain buldings which consisted of further deformed volcanic and nonvolcanic rocks (Mulyaningsih and Sanyoto, 2012).

According to van Bemmelen (1949), the geological setting of West Progo Mountain started with the shallow transitional marine environment, depositing shallow marine sandstones, calcareous sandstones, marls, lignite, and quartz sandstone with *Nummulites sp.* and *Discocyclina sp.*, which were grouped into Eocene Nanggulan Formation. During the Oligocene to Early Miocene, there were three to four stages of volcanism producing Old Andesite Formation (OAF). The OAF consisted of andesitic dikes, lava, breccias, and agglomerates that are exposed at Gunung Gajah (in the middle) as the oldest volcano, Gunung Kukusan (in the south) as the middle volcano, Gunung Menoreh (in the north) as the younger, and Gunung Gendol (in the northeast) as the youngest volcano (Bronto, 2010). Overlying them, there were calcareous sediments of Sentolo and Jonggrangan Formations deposited during the Early Miocene to Early Pliocene. Since Plio-Pleistocene the rock units have been uplifted.

Mulyaningsih (2006) described that Yogyakarta Region had been totally subaerial since 16,000 years B.P. It was lacustrine deposited black clay and sandy feldspatic organic rich sediments. The lacustrines had developed in two areas, *i.e.* the distal of West Progo Mountain and the distal of Southern Mountains. In the distal area of West Progo Mountain, the lacustrines were found along Progo River (east of Nanggulan) until Sileng River (north of Borobudur). The lacustrines have totally dried since 470 years B.P. (Mulyaningsih *et al*., 2006). Some researchers believed that the lacustrine formations and their draught were influenced by Merapi, Sumbing, and Merbabu Volcanic depositions (Newhall *et al*., 2000; Murwanto, 1996; Mulyaningsih, 2006). In the distal of Southern Mountain, the lacustrines were located around Berbah-Sleman (between Watuadeg and Bangkel Hills), and Gantiwarno (east of Prambanan) (Newhall *et al*., 2000; and Mulyaningsih, 2006). Figure 4 shows the geological evolution of Yogyakarta since the Eocene, the volcanism during Oligocene-Miocene, and the post volcanism after the Tertiary, while Figure 5 shows the geological evolution after the uplifting.

Van Bemmelen (1949) described two main faults connecting Central Java volcanic chains, *i.e*. Ungaran-Surapati-Telomoyo-Merbabu-Merapi and Sumbing-Sindoro-Merapi-Lawu-Kelud. Berthomier (1990) reported that the early volcanic eruption on Merapi was 0.56 Ma. Newhall *et al*. (2000) stated the explosive eruptions of Merapi was in 10 ka. Whilst Mulyaningsih (2006) identified six layers of paleosols covered by pyroclastic density currents exposed in the areas within the distance of 16−22 km from the summit of the Merapi Volcano. From the bottom to the top, the layers were 1,810 ± 50 years before present (B.P.), 1,445 ± 40 y B.P., 1175 ± 45 y B.P., 1,060 ± 40 y B.P., of 740 ± 50 y B.P., and of 360 ± 50 y B.P. lahars. Thus, the larger historical explosive eruptions of Merapi were determined to occur once in 100−150 years. The last larger eruption took place in 2010. It was reported as an explosive eruption of Plinian type with more than $4x10^6$ m^3 volcanic deposits (Anonim, 2011) that killed more than 275 people. Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) noted that the earthquakes had devastated Yogyakarta and Surakarta Regions in 1867, 1937, 1943, 1981, and 2006 with 5.6 - 8 SR. The epicentres were located around 8.7°S and 110.8°E. Unfortunately, those earthquakes have not been reported yet.

Results

Oblique, shear, and thrust faults occur along Sudimoro Hills (in Sindet residential area (Jetis), Wonolelo, and Giriloyo, and its surrounding areas (Pucung-Cengkehan-Nogosari, Imogiri). Most faults cut surface soils, triggering rockfalls, landslides, slumps, and rockslides. The faults have general directions of 260° - 285° NW. Some faults occur in dense populated areas in Cengkehan and Nogosari which are shown in Figure 6. Some taped-roots of teak and mahogany trees filled the cracks (*i.e.* normal faults and joints). Surface runoff also flows through the cracks,

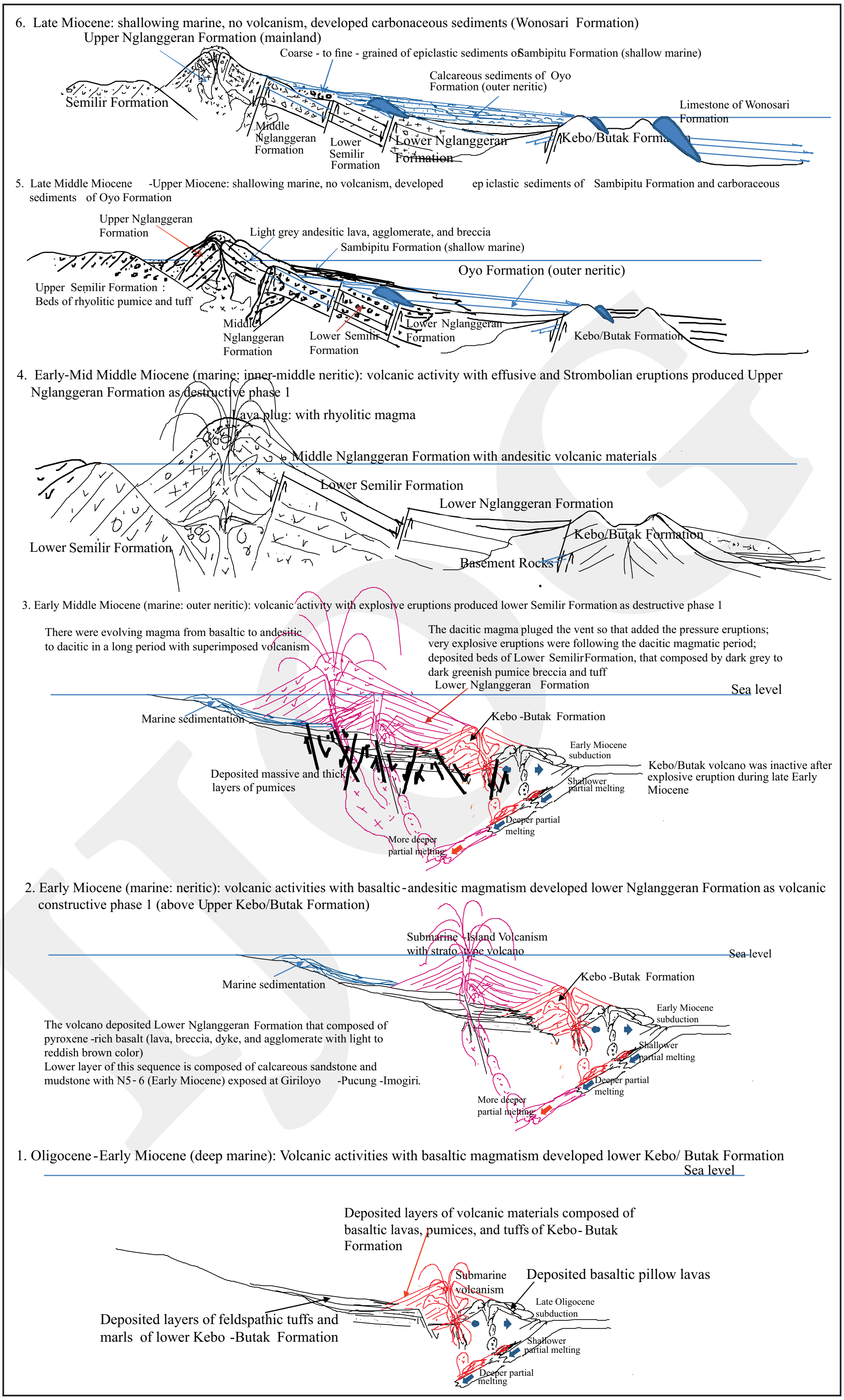

Figure 4. Area located in southern part of Yogyakarta Special Region slowly changing from deep marine (in Oligocene to Early Miocene) to shallow marine (in Late Miocene).

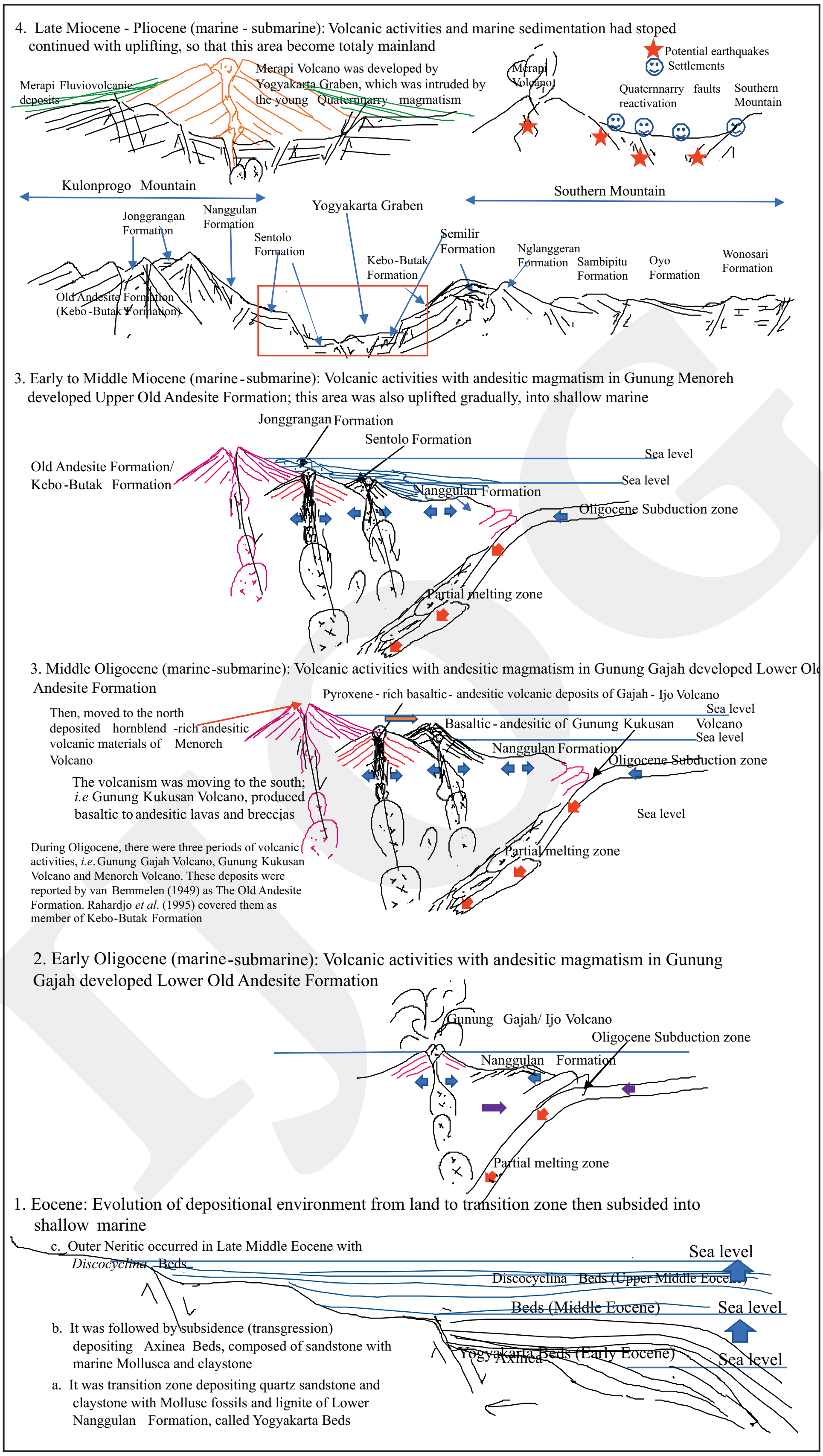

Figure 5. Area in western part of Yogyakarta Special Region changing from island to shallow marine, but since Pliocene the ocean was slowly lifted into mainland, then followed by Merapi Volcanism and post Tertiary tectonism.

Figure 6. Recorded active faults at study area. (a-b) Normal and shear faults sliding on March 17, 2017 at Giriloyo, Imogiri; (c-d) Slickenside of Kembangsongo Normal Fault and Sindet Normal Fault reactivated during the earthquake of May 27, 2006, exposed at Sindet, Trimulyo; (e-f). Gash fractures and a normal fault of Gunung Ireng, Patuk.

erodes cracks, and forms stream channels. Steep slopes (60^o - 80^o) within the layers of lapilli stone and tuff intersecting with lavas (Nglanggeran Formation) cause landslides and rock-falls to occur (Rahardjo *et al*., 1995).

From stopsite 1 to stopsite 2, three groups of volcano-stratigraphy are recognized: Lower Nglanggeran, Semilir Formation, and Upper Nglanggeran. The Lower Nglanggeran is overlain by layers of pumiceous breccia and tuff of Semilir Formation, so it is called Lower Nglanggeran. Semilir Formation comprises layers of crystal tuffs and lapilli stones that are similar to the volcanic rocks composing Kebo/Butak Formation in Tegal-rejo (Gedangsari, Mulyaningsih, 2016). These volcanic rocks of the Semilir Formation are also related to layers of deep deformed basaltic lava. Descriptively, they are almost similar to Kebo/Butak Formation than Semilir Formation. For this case, further isotopic analyses were required.

The volcanic rocks overlying Semilir Formation are called Upper Nglanggeran. A fault system separates Lower Nglanggeran and Semilir Formation with Upper Nglanggeran. Lower Nglanggeran is deeply weathered, while Upper Nglanggeran is less weathered. Most surface soils located in Sudimoro and its vicinities are faulted, of which the main directions are northwest−southeast as oblique normal faults. Figure 7 presents the lithologic profile of the Upper Nglanggeran and Lower Nglanggeran exposed in Cengkehan-Giriloyo (stopsite 1).

BMKG stated earthquakes with a magnitude of 5.9 occurred in Yogyakarta on 1867, 1937, 1943, 1981, and 2006 which damaged public facilities. Most stones of Kedulan Temple were lightly to severely damaged (Figures 8 and 9). The piles of stones at the bottom of the temple were greatly shaken and formed wavy floor. This condition also occurred at Gampingan Temple (Piyungan-Bantul), Plaosan Temple (600 m from Prambanan Temple to the east), Morangan Temple (Cangkringan-Sleman; Figure 10), and UII Temple (Figure 11). Opak Fault through Opak River is believed (by the most Indonesian geologists) as the main fault triggering the earthquake. The data were obtained through deformations, victims, broken and collapsed public facilities and houses mainly in Jetis (SC-2), Imogiri (SC1), Pleret (SC3), and Banguntapan (SC6) in Bantul Regency; Berbah and Prambanan (SC-8) in Sleman Regency; Pathuk, Gedangsari, and Playen in Gunung Kidul Regency. The undulated temple foundation (pilled-stones) and cracks within temple stones built around the Opak River, many fault scarps occurring along the Southern Mountain, and cracks that cross-cut the present layers of the PDC (1930 AD) prove the presence of natural disasters. The fault system had a general direction of N260°−310°E (SC-8 and SC-9).

The recent activities of Merapi Volcano are performed by forming and collapsing lava domes; occasionally by explosion forming caldera rims (Mulyaningsih and Sanyoto, 2012). The data recorded that lahars and volcanic ashes (co-PDC) buried and damaged temples and public facilities that were built in 1st–15th centuries (Mulyaningsih, 2016). Archaeological and geological investigations undiscovered dead bodies or fossils within deposits. As mentioned by Mulyaningsih (2006) and Mundardjito (1990), more than two hundred temples were located in distal to medial facies of Merapi Volcano, Southern Mountain (Ratu Boko Pal-

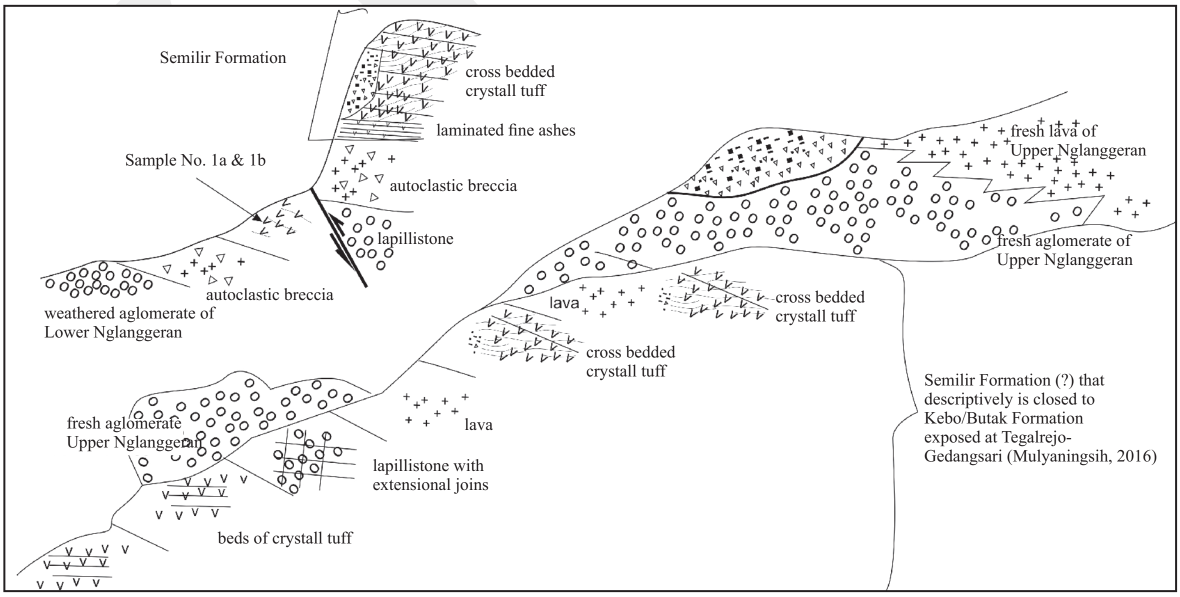

Figure 7. Lithologic profile explaining the relationship of the Upper Nglanggeran and Lower Nglanggeran exposed at Cengkehan – Giriloyo (stopsite 1).

Figure 8. Bumpy piles and floors of Kedulan Temple; interpreted were collapsed by earthquakes, then buried by materials of volcanic eruptions.

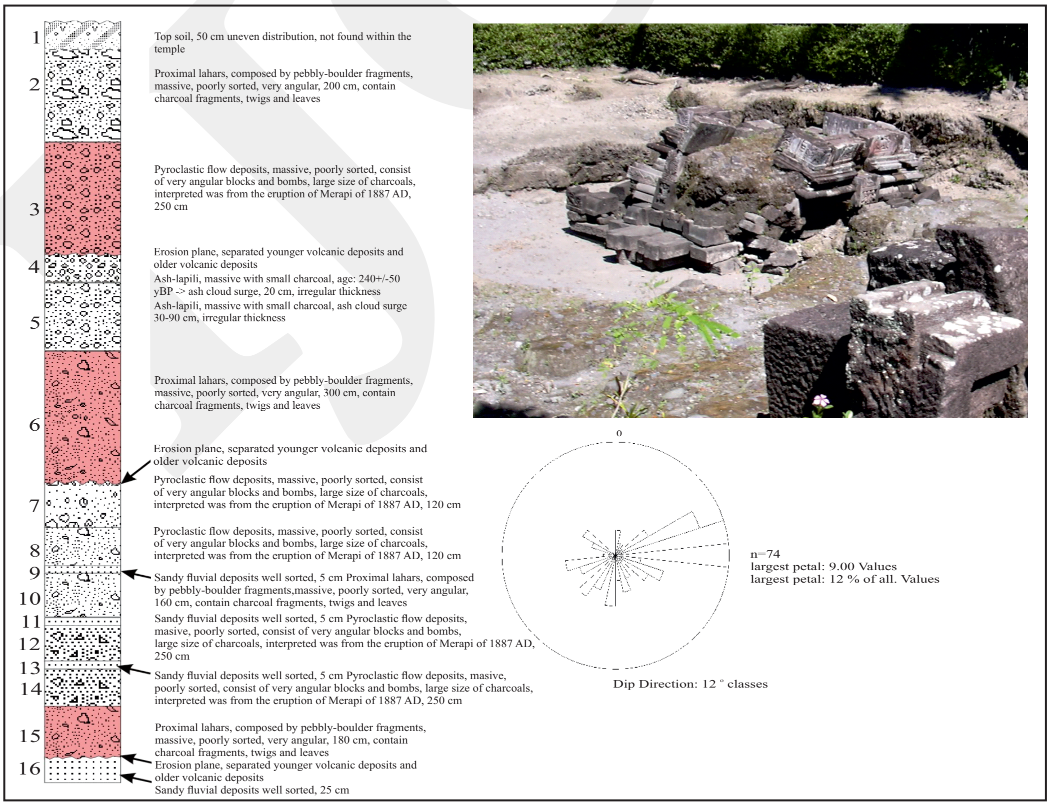

Figure 9. Bumpy floors of Kedulan Temple.

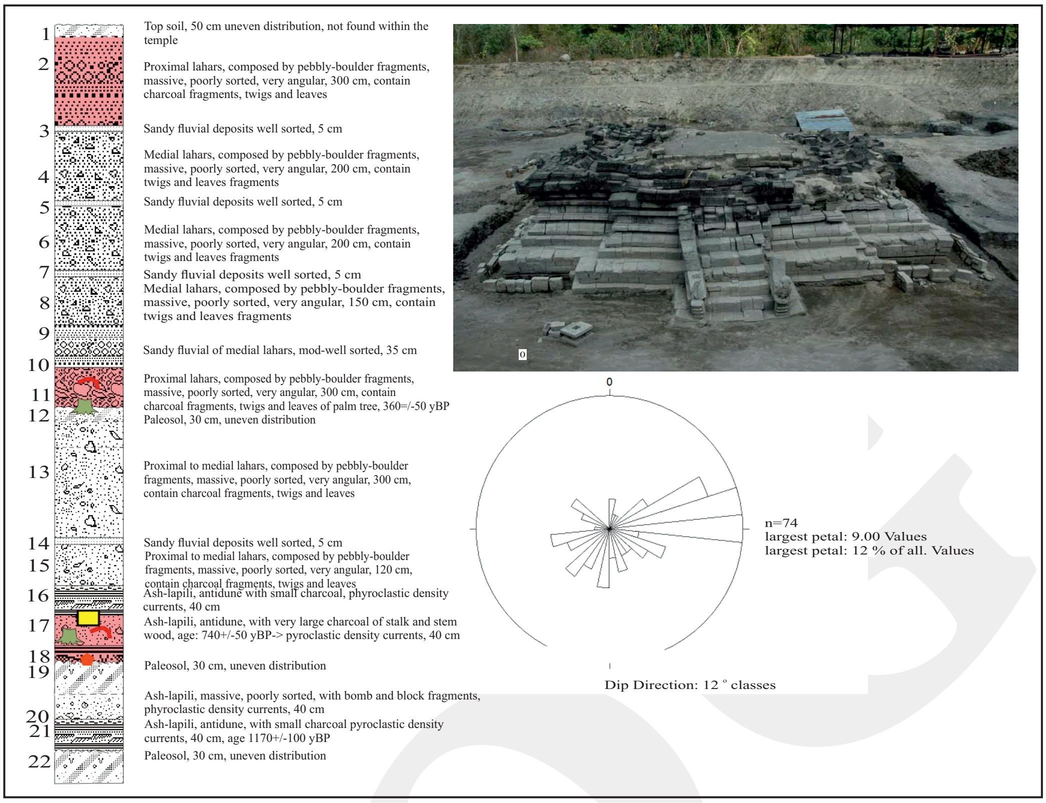

Figure 10. Bumpy piles and floors of Morangan Temple.

Figure 11. Bumpy floors of UII Temple that buried by the volcaniclastic materials; not show collapsed by an earthquake.

ace), and West Progo Mountain (Gunungwukir, Gunungsari, and Gunungwungkal). When the temples located on the hilly topography were firstly discovered, they were mostly deeply damaged and covered by thin layers of gray, orange, and yellow volcanic ash. The ashes are determined by the sources whether they were derived from Merapi, Sumbing, Merbabu, or Kelud Volcanoes. The ashes which came from Kelud Volcano (in 2013) are yellowish colour, very smooth, more dusty, and very light. The ashes which came from Merapi Volcano (2010, 2018, and 2019) are gray, glassy but rich in crystal minerals, heavier, very pointed, and sharp. The ashes which came from Merbabu Volcano (with the outcrops located in Tegalrejo and Chepogo/ Boyolali) are orange, havier than those from Merapi, and more weathered. Sumbing volcanic ashes, exposed at Tulungagung, Wonosobo, and Parakan, are yellowish–orangish and purple, light weathered, and more widely distributed than those from Merbabu. Merbabu volcanic ashes are heavier than those from Merapi, less glassy and not too sharp; while the Sumbing volcanic ashes are more similar in nature to the ashes from Merbabu Volcano. Both contain more basaltic glasses.

The volcanic deposits covering the top soils near Gendol, Kuning, and Bedog Rivers are composed of lahar and ash layers (SC-7, SC-9, SC-10, SC-11). The lahar consists of medial to distal types (SC-9 - SC14). Those volcanic deposits have total thickness between 3 - 9 m, from the north (at Bedog-Krasak, near Salam; SC-14) to the south (SC-12 near Kalibawang), and they become thinner and change to be fluvial (Figure 12). The volcano-stratigraphy shows that the deposits are dominated by lahars which overlie the co-PDC deposited during $8^{th}-13^{th}$ centuries. Those deposits were found during the temple excavations about 15 - 20 km from the summit. No human and animal fossils/bones were found in those deposits, like at Tambora eruption in 1815 that killed 80,000 people (Cole-Dai *et al*., 2009), Krakatau eruption in1883 that killed 49,000 people (Mandeville *et al*., 1996; Tanguy *et al*., 1998), and Vesuvius eruption in 79 A.D. that killed more than 10,000 people (Gurioli *et al*., 2005).

Discussion

Active faults are recorded in Sudimoro Range located in Imogiri and Pleret, started from Opak River−Gendol River in the southern plain of Merapi Volcano to the south in Giriloyo (Imogiri). The faults move as landslides and rockfalls as shown in Giriloyo, Wonolelo, Karangtalun, Dlingo, and Mangunan. Most movements comprise andesitic-basaltic volcanic rocks consisting of weathered breccia, lava, dike, and agglomerate. Based on the distribution of the active faults, mass movements, and the distribution of the cracks around the Opak-Gendol Rivers, it can be clarified that earthquakes and their derived hazard potentials occurred in Yogyakarta Region periodically, once in tens years, and they would be more fre-

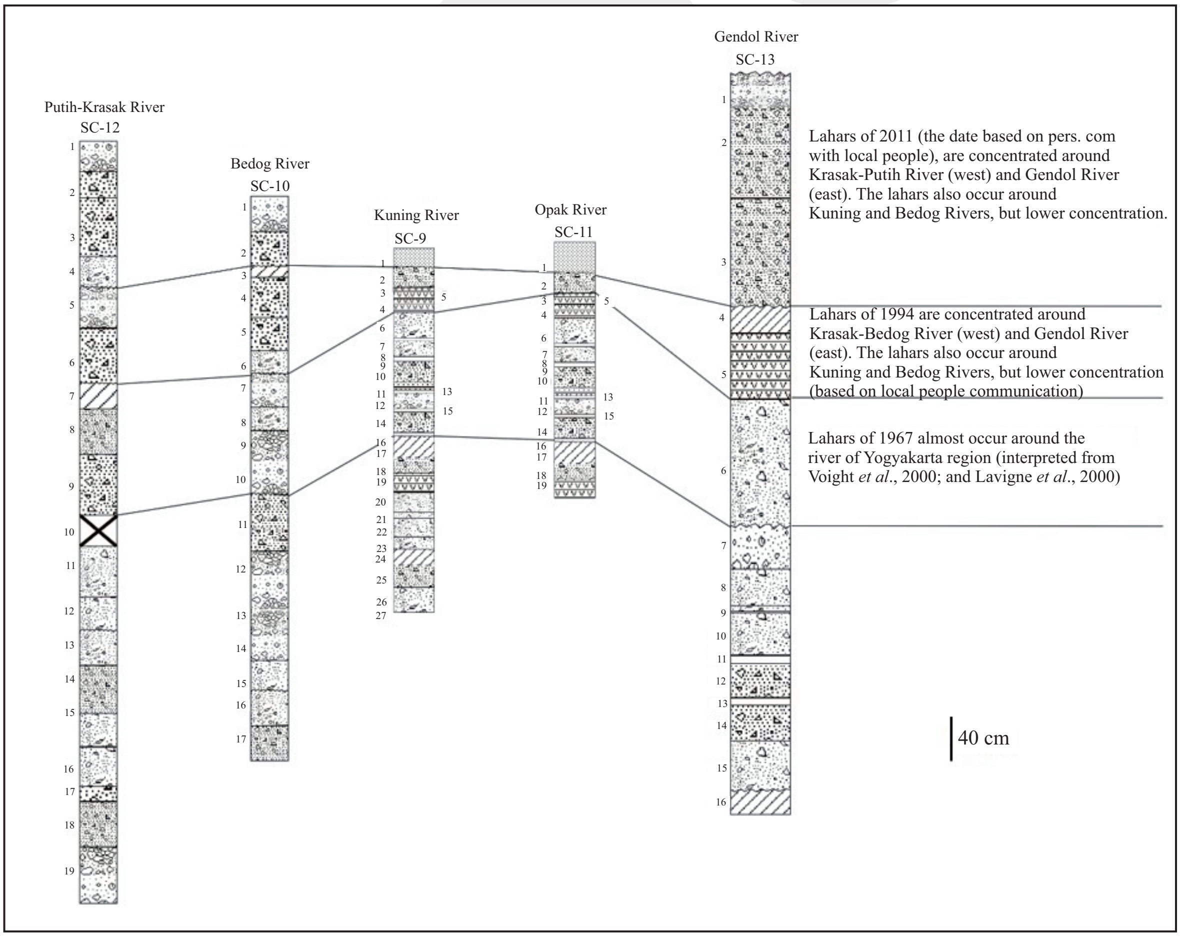

Figure 12. Merapi volcaniclastic deposits interpreted as lahars are exposed at SC-12 (near Krasak-Putih River), SC-10 (near Bedog River), SC-9 (near Kuning River), SC-11 (near Opak River), and SC 13 (near Gendol River), informing recent lahars reached to study areas (stop sites see Fig.2).

quent and more intense. Larger and more intense earthquakes require a longer time to accumulate enormous energy, but logically new deformations would occur more intensely and more frequently in areas with older deformations. It would require a shorter time than 2006 earthquake, maybe less than 45 years ([20+70]:2), *i.e.* before year 2046. Larger volcanic eruptions occur once in 50−100 years, but logically it would be less frequent but more intense. Larger eruption with more Vulkanian-Subplinian type would occur in year 2010+50 or around 2060.

Lahars occur in every large eruption. Merapi eruptions occurring in rainy seasons will have higher hazard potential than in dry seasons. Unconsolidated volcanic deposits will more effectively move in saturated water. Now PVMBG (Centre for Volcanology and Geological Hazard Mitigation) monitores the early warning system to potential lahar hazard. Moreover, people should be educated to cope with the impact of the potential disasters.

Other geological problems related to climate in the studied area are mass movements in the distal of Sudimoro Range and Piyungan Range. They focus on the fault system located in Southern Mountains and Opak Fault System. Developing a vulnerable zone into a good environment zone can be done through geological conservation and developing special interest in geopark management which can be done in the Giriloyo areas (Imogiri), Ngelo-Wonolelo-Cegokan (Pleret), Sentong-Pagerjurang (Piyungan), and Candisari (Prambanan). Further hazard management should be applied immediately to develop geoparks based on geological studies.

The earthquakes caused extended damages to the old buildings/temples (Mulyaningsih, 2006). At that time, the temples might not have entirely collapsed. After the coming of Islam in the 15thcentury, the local people no longer used the temples as worship places, so those temples were abandoned. After those temples were buried by the volcanic materials and/or shocked by earthquakes, no efforts to rebuild them. The people let the buildings/temples remain buried.

Learning from the previous geological disasters, using the concept “the present is the key to the past and the future”, future potential hazards are necessary to be studied. It depends on the cultures, local wisdoms, and social economy. The education for hazard managements should be synergized with the local resources. The motto "life in harmony dealing with geological disasters" should widely be understood by all Indonesian people living around them. People should independently learn how to survive and realize that they live in disaster-impacted areas.

Conclusions

Yogyakarta Special Region has the future potential hazards, *i e*., earthquakes, mass movements, and volcanic eruptions. Earthquakes have occurred since the upliftings of the Southern Mountain, and continue to occur until now. The evidences of earthquakes and mass movements followed the uplifting and proved the existence of tectonic reactivation. They occur periodically, but more frequently and more intensely. The volcanic eruptions also occurring periodically are often followed by avalanches triggering lahars (floods). Lahars can reach places of more than 20 km from the Merapi crater, and are able to collapse buildings and public facilities around Gendol-Opak, Kuning, Bedog, and Krasak-Putih Rivers. Especially for Gendol-Opak River, it is also potentially impacted by the reactivation of Opak Fault that is sometimes shaken by earthquakes.

The awareness of the local people for the potential disasters is required in order to make them be able to live in harmony with the disasters. Chain-message approach in emergency learning for people who live in the impacted- areas will greatly help to minimize the risk.

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