Active tectonics of the Yogyakarta area (Central Java, Indonesia): preliminary findings obtained from a tectonic-geomorphic evaluation

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Active tectonics of the Yogyakarta area (Central Java, Indonesia): preliminary findings obtained from a tectonic-geomorphic evaluation

S Pena-Castellnou1*, V Steinritz1, G I Marliyani2 and K Reicherter1
1Neotectonics and Natural Hazards, RWTH Aachen University, Aachen, Germany
2Geological Engineering Department, Universitas Gadjah Mada, Yogyakarta, Indonesia
*E-mail: s.pena-castellnou@nug.rwth-aachen.de

Abstract. Throughout the island of Java, several shallow faults located in the vicinity of densely populated areas accommodate the tectonic strain generated by the subduction of the Indo-Australian Plate beneath the Sunda Plate. These faults are characterized by a poor surface geomorphological expression due to the tropical climate that masks paleoseismological evidence making the identification of active faults in this environment challenging. We present preliminary data of a tectonic-geomorphic study that aims to identify and characterize active faults in the province of Yogyakarta (Central Java) as a basis to improve seismic hazard assessment. Here we focus on the Opak fault by describing its geomorphology and structure, using field data and remote sensing-based observations to contribute to the understanding of its geometry, kinematics, and tectonic activity. We show preliminary data supporting the Opak Fault as an active SW-NE transtensional left-lateral strike-slip reactivated normal fault consisting of several parallel fault strands. Although geomorphological expression of active tectonics is poor and diffuse, we found numerous field evidence of active tectonics ranging from tilted Quaternary fluvial terrace risers, triangular facets, and linear valleys to peculiar drainage patterns that allow us to provide evidence of the Holocene activity of the Opak Fault.

1. Introduction
Identification of active tectonics geomorphological features represents a challenge in slowly broad deforming areas with tropical climates like Java. Heavy rainfall and high humidity foster intense weathering, the development of thick tropical soils, high erosion rates, shallow water tables, and thick vegetation covers (including anthropogenic fertile rice fields) that erode and bury faults and their associative geomorphology. Hence, tectonic geomorphology in tropical areas differs from the conceptual models that we are used to, typical from drier climatic contexts where geomorphic markers are well exposed and preserved. Moreover, the tectonic strain on-shore of Java is accommodated by slow slip rate faults with long earthquake recurrence intervals [1], resulting in inherent poor surface expression.

Java forms part of the volcanic arc in the Sunda Plate adjacent to the Sunda trench, where the Indo-Australian Plate subdues at a rate of 7 cm/yr [2] (Figure 1a). Subduction controls Java's current stress field, leading to a north-south maximum stress direction, which has generated E-W trending thrust belts and re-activated SW-NE structures as slow strike-slip faults [3] that accommodate the tectonic strain generated by the deeper subduction mechanism within the volcanic arc. Inherited N-S structural features in the west and central Java were considered inactive because of a lack of recorded seismicity [4]. However, events such as the well-known Mw 6.3 shallow crustal earthquake in May 2006 in the...
province of Yogyakarta, which caused approximately 6000 fatalities, and up to 3 billion dollars of economic losses (e.g. [5]) are evidence of the activity of these faults.

Figure 1. a) Simplified tectonic setting of the Indonesian archipelago. b) Instrumental seismicity of the Java Island of the period 2010-2020 (USGS seismic catalog, https://earthquake.usgs.gov). The arrow and number show the convergence velocity of the Indo-Australian plate relative to the Eurasian plate fixed frame [2]. Black lines [4] indicate active faults. Abbreviations for major cities: JK: Jakarta, B: Bandung, YGK: Yogyakarta, SR: Surabaya, SM: Semarang. c) Overview of the study area, the province of Yogyakarta. Instrumental seismicity data from the online USGS seismic catalog (https://earthquake.usgs.gov) from 2006 to 2010, and from the online BMGK earthquake repository (https://repogempa.bmkg.go.id/) from 2010 to 2020, historical earthquake from [6]. Focal mechanism of the 2006 earthquake from Global CMT Harvard Catalog (https://www.globalcmt.org). In red, the Opak Fault from the regional geological map [7] and in black, faults from Setijadji et al. [8]. The epicenters of the aftershocks that followed the 2006 earthquake are from Anggraini [9]. The maximum horizontal stress direction, derived from earthquake focal mechanisms, from the World Stress Map [10].

The province of Yogyakarta is, with more than four million inhabitants, Indonesia's fourth-most densely populated province and one of the fastest-growing provinces in terms of social and economic aspects [11]. It is exposed to several natural hazards, especially to volcanism and seismicity. The
province's northern area is situated at Mount Merapi's foot, one of Java's most active volcanoes. To the east, the boundary between the Southern Mountains and the Yogyakarta Basin (Figure 1c) is represented by the Opak Fault System. This area is characterized by shallow earthquakes of moderate to low magnitude, scant historical records, and absent paleoseismic data. The Opak Fault was thought to be the source of the devastating 2006 earthquake (e.g. [8]; [12]; [13]). However, the causative fault did not rupture the surface, and the major disaster area with a localized concentration of secondary effects (e.g., liquefaction, slope movements, and ground fractures) did not concur with the epicenter locations proposed by different seismological agencies and the aftershock sequence distribution (Figure 1), where no previous fault had been identified (e.g. [8]).

We aim to improve and complete the current tectonic map of the province of Yogyakarta and identify active faults that have the potential to generate seismic events with social impact in the future, as the first step to improve the assessment of seismic hazard in the area. In the present day, the location, geometry, kinematics, and total length of the Opak fault are not well understood; and offshore continuation remains unclear. Furthermore, in the area with the 2006 aftershock sequence distribution, no previous fault had been identified. We use field-based geomorphological and structural data together with GIS analysis of digital terrain models to recognize and examine geomorphological markers associated with the superficial expression of fault activity to characterize the mapped faults, providing insight into the challenges of the study of active faults in tropical environments.

2. Background - The Opak Fault
The Opak Fault is an SW-NE trending hypothesized normal fault located at the boundary between the Yogyakarta Basin and the Baturagung Range (part of the Southern Mountains) ([7]; [8]) (Figure 1), suspected to be responsible for the formation of a half-graben, the Yogyakarta Basin, where the city of Yogyakarta is based. Geologically, the Baturagung Range consists of volcaniclastic Oligocene and Miocene rocks, limited to the west by the Wonosari Basin, a limestone plateau from the Miocene, bedded clastic to the north, and massive reefal to the south constituting the Pegunungan Sewu Karst. To the east, the Yogyakarta basin is filled with Quaternary sediments of the Merapi volcano, and fluvial and alluvial Quaternary sediments. The seismicity of the area is moderate to low. However, two damaging earthquakes were recorded: the historical MMI IX 1867 earthquake, which resulted in 327 reported casualties and significant damages over the entire areas of Yogyakarta, Klaten, and Surakarta [6]; and the Mw 6.3 2006 earthquake that left more than 6000 casualties, and enormous damages throughout all the Yogyakarta Basin (e.g. [5]). The Opak Fault is considered to be the source of the 1867 earthquake.

The first mapping of the Opak Fault and other structures in its vicinity was carried out by Rahardjo et al. [7] and Surono et al. [14] and presented in the Regional Geology map issued by the Indonesian Center for Geological Research and Development, at a scale of 1: 100,000. The fault is interpreted to be normal and located following a NE-SW direction by the Opak River (hence its name) three kilometers to the west of the Baturagung Range foot (Figure 1c). After the 2006 Yogyakarta earthquake, the Opak Fault became the focus of several research efforts, with the aim of understanding this event and especially determining its source, investigating: hypocenter and aftershocks distribution (e.g. [9]; [13]; [15]), InSAR data to reveal surface deformation [16], GPS data of post-seismic deformation [17], macroseismic data [12], tectonic geomorphology [8], secondary effects such as landslides (e.g. [18]), local site conditions (e.g. [19]), and arqueoseismology [20]. The outcome led to the hypothesis that a fault located approximately ten kilometers to the east of Opak, in the Wonosari Basin where no previous fault was mapped, was likely to be the source of the earthquake.

The most relevant study in terms of characterizing active faults in Yogyakarta is the work of Setijadji et al. [8] that locates the trace of the Opak Fault at the foot of the Baturagung Range as a segmented fault zone consisting of several faults with different styles and orientations. More recent studies have led by Supartoyo et al. [21], presenting a mapping of lineaments and interpretation of ERT profiles across the Opak Fault, where they show that the fault dips to the north-west without providing more details about kinematics or level of activity.
3. Methods

Large and great (Mw > 6.5) recurrent earthquakes produce characteristic geological evidence along faults (e.g. [22]; [23]). Evidence of paleoearthquakes can range from localized deformation along a crustal fault (e.g. fault scarp, laterally offset stream valleys) to indicators of the sudden uplift or subsidence of large regions above a plate boundary fault (e.g. uplifted or subsided shorelines), to stratigraphic and geomorphic effects of strong ground shaking, the so-called environmental earthquake effects, far from the seismogenic fault (e.g. landslides, liquefaction features, tsunami deposits) [22]. We perform detailed geomorphological and structural mapping of Quaternary deposits and different-scale paleoseismic features, combining field data with remote sensing observations based on the 8 m resolution DEMNAS DEM [24] and ~10 cm resolution DEM from unmanned aerial vehicle photogrammetry to identify and characterize active faults in the province of Yogyakarta. The geological mapping was conducted throughout the area comprising the Baturagung Range to collect structural data (bedding dip direction, micro-faults, and fracture patterns) and identify different lithological formations from more than 250 outcrops. At the same time, we corroborated and carefully mapped the geomorphological features previously recognized with remote sensing. Additional imagery was obtained from UAV surveys with the DJI Mavic Pro (12 MP sensor) and high-resolution DEMs that were created with the photogrammetry software AgiSoft PhotoScan (AgiSoft PhotoScan Professional, Version 1.2.6, 2016). We took several samples of charcoal and shells to date different levels of terraces exposed on the shores of Opak and Oyo rivers at one key study site. The dating was based on the radiocarbon method (C14). A total of nine samples were pre-processed in the laboratory at RWTH Aachen University and then sent to analysis at the University of California Irvine, Keck Carbon Cycle AMS Program.

4. Results - Geomorphological signature of ongoing tectonic activity

The province of Yogyakarta has distinct geomorphological landscapes, shaped by the interaction of sedimentation and erosion, volcanic activity, tectonics and, climate. On the center, the Yogyakarta Basin is characterized by gentle and uniform slopes where the Opak River develops in an approximate SW-NE mean direction. To the east rises the Baturagung Range, part of the Southern Mountains, with a linear hillslope of SW-NE direction that bends at its northern part to W-E. South, the Wonosari Basin with a circular shape is characterized generally by a low topography where the Oyo River incises extensively and junctions the Opak River crossing through the Baturagung Range. By the coastline, the reefal plateau forms the Pegunungan Sewu Karst with distinguishing geomorphology of dome-shaped hills result of the intense karstification. Within this landscape, the geomorphological expression of tectonic activity is weak and may have been masked by the aforementioned processes. However, we have identified several faults (Figure 2) based on various paleoseismic features, typical from the classic landform landscape of active normal and strike-slip faults (e.g. [22]; [23]).

The most prominent feature is the SW-NE well-defined western mountain front of the Baturagung Range, with steep slopes (60-75°) that contrast with the gentle eastern front (10-25°). There are secondary parallel lower ridges on the central part of the western front that also form SW-NE lineaments. Other lineaments have been mapped throughout the area corresponding to wind gaps and, linear ridges and valleys (Figure 2). The mapped lineaments exhibit three trends: a main SW-NE orientation, W-E, and a minor NNE-SSW; and vary in length from a hundred meters to dozen of kilometers. Besides, despite the dense tropical vegetation, triangular facets have been inferred (Figure 3c).
Figure 2. a) Geology of the SW-NE striking front of the Baturagung Range, including structural and stratigraphic data from field observations. Geological units are from Rahardjo et al. [7]. b) Active faults and identified paleoseismic features. Note the drainage patterns of the Oyo and Opak Rivers.

On the Opak River, the river sinuosity is low along its entire course and changes its direction on several locations where tectonic lineations have been mapped (Figure 2). Moreover, we have identified tilt-induced avulsion and migration of meanders to the east, in direction to the major fault trace (Figure 2) and slightly tilted quaternary terraces on several locations (e.g., Figure 3g-h). The Oyo River presents a peculiar drainage pattern often changing its sinuosity, from meandering to straight and back, and its course direction from north-south to east-west following lineations, at various locations along a restricted area (Figure 2); despite the fact that the lithology of calcareous sandstones and limestones does not change along the river’s course and there is no dip variation of the layers.
Figure 3. Examples of active tectonic features. a) Geomorphological expression of the Opak Fault; northwestern mountain front of the Baturagung Range. b) E-W fault in the Sewu Karst. c) Triangular facets on the northwestern hillslope of the Baturagung Range. d), e), f) Knickpoints. g), f) Tilted Quaternary terrace of Opak River. For locations see figure 2.
Throughout the streams that form the drainage system, we have identified several knickpoints of different magnitudes ranging from 0.5 meters to 30 meters (e.g. waterfalls), which we interpret to be caused by tectonic. Where the Oyo River meets the Opak River, a clear knickpoint can be identified on Oyo’s channel (Figure 4a-b). In this area, we have mapped, described, and dated several degradational fluvial terrace levels that give information on tectonic deformation. On the Opak River's right shore, the terraces appear uplifted with respect to the left shore by about two meters, indicating the existence of a fault by the river. Furthermore, we observe local deformation, such as a folded terrace (of age 6260 ± 30 years BP) that sediments on top of bedrock while tectonic activity was ongoing (Figure 4c).

Figure 4. Landscape view of the Opak-Oyo river junction and inferred fault trace. Shaded colours represent rock units of various ages, the relative ages were determined based on rock characteristic and stratigraphic relationship. Shaded in green: younger Quaternary terrace; in red: older Quaternary terrace; in purple: Miocene bedrock. b) One of observable knickpoint along the Opak River. c) Deformed Quaternary terrace accommodating across the fault.

5. Discussion
Geomorphological observations have helped to identify and map several fault traces in the study area. However, the characterization of these faults in terms of geometry, kinematics, and activity is challenging. Short-term (Quaternary to Holocene) tectonic evidence in the landforms is diffuse or lacking, partly because Quaternary deposits are scarce and intensely modified by anthropogenic activity (mainly agriculture – large extension of fertile rice paddies), resulting in poor preservation of recent faulting activity.

We interpret the Opak Fault as a normal fault composed of several fault strands dipping to the northwest at about 70 to 80°, reactivated during the Quaternary as transtensional strike-slip faults. The Opak Fault is located at the foot of the Baturagung Range and appears to be segmented in different SW-NE segments of different lengths (~1-10 km) that spread within a width of three kilometers. Its
geology has been inferred from the north-western hillslope of the Baturagung Range, which has slopes of about 60-75° and where triangular facets have been identified. Considering the dissection and degradation of the landscape, we interpret that the fault may dip at about 70 to 80° towards the northwest. The same applies to the fault strands located further from the mountain front, where the Opak River incises following the fault traces; the north-western hillslopes of the smaller isolated hills located north of the study area (Figure 2) have the same slope gradient as the main front of the Baturagung Range.

We have mapped volcanic breccia from the Nglanggran formation along the parallel hills on the central part of the Baturagung Range close to the Opak River (Figure 2a) that was not previously documented on the regional geological map [7]. These outcrops are located approximately 300 meters below the Baturagung Range hilltop, where the Nglanggran formation outcrops and extends along the hillslope. This has direct implications on the interpretation of the kinematics history of the Opak Fault, suggesting normal tertiary faulting. The triangular facets on the mountain front of Baturagung Range are also evidence of normal faulting. Besides, we have identified SW-NE linear valleys, more typical of strike-slip landscapes. We have not found any other evidence of strike-slip tectonics, such as laterally displaced streams. However, we believe that the Opak fault has reactivated during the Quaternary as a left-lateral strike-slip fault with a significant normal vertical component in agreement with the present maximum stress direction.

Regarding tectonic activity, we can affirm that several fault segments of the Opak Fault have been active during the Quaternary, evidenced by: 1) tilted Quaternary terraces (Figure 3g-h and 4); 2) the peculiar drainage pattern of Opak River that is very linear and changes its course direction following major lineations - its drainage evolution has been clearly driven and controlled by tectonics; 3) tilt-induced avulsion and migration of meanders in Opak River; and 4) knickpoints – abrupt changes in channel gradient; that are transient as the channel adjusts to its equilibrium profile within time periods of $10^4$ to $10^6$ years depending on the erosional efficiency of the system and the nature of the perturbation ([25]; [26]). We could not find clear displaced tectonic markers to infer slip rates. However, we believe that the fault slip is slow and has long recurrence intervals since the present-day low seismicity does not agree with the tectonic geomorphological imprint in the landscape. Considering the length of the segments of the Opak Fault and using the empirical equations of Wells and Coppersmith [27], we can expect earthquakes of $M_\text{w} 6-7$.

Concerning the other faults located west of the Baturagung Range, two minor structural trends stand out. North of the Opak and Oyo rivers' junction, lineations with N-S to NNE-SSW directions are interpreted as normal faults that form topographic steps. We have not found any marker to assess its level of activity. Other faults follow an E-W trend (e.g. Figure 3b) and seem to block the Opak River that has to find its way drifting its course towards the west; therefore, we believe that these faults might have been active during the Quaternary.

To the east of the Baturagung Range, a well-defined SW-NE fault delineates the boundary between the Baturagung Range and the Wonosari Basin. Paleoseismic features related to this fault are knickpoints and linear valleys. Structurally, it separates two blocks with different bedding dips suggesting normal faulting during the Tertiary. Activity during the Quaternary cannot be discarded due to the presence of knickpoints and significant topographic morphological expression. Parallel to this fault and three kilometers to the east, along the area where the aftershocks sequence of the 2006 Yogyakarta earthquake concentrated (Figure 1), a notable change in topography may indicate the presence of a fault. On the center of the Wonosari basin, an SW-NE fault that may play a role in the Oyo River's evolution is insinuated by a very subtle lineation. In addition, we identified several NNW-SSW normal faults that control the drainage evolution of the Oyo River, forcing the change of its course direction on several locations.

6. Conclusion

The Opak Fault is an active SW-NE transtensional left-lateral strike-slip reactivated normal fault consisting of several parallel fault strands. Detailed geomorphological and structural mapping of Quaternary deposits and paleoseismic features, combining field data with remote sensing observations, allowed to the preliminary characterization (in terms of geometry, kinematics, and relative activity) of
the Opak Fault and other faults in the province of Yogyakarta. Quaternary geomorphological expression of tectonic activity is diffuse as a result of the combination of several factors: Quaternary deposits are scarce and intensely modified by anthropogenic activity; the tropical environment hastens landscape degradation (due to, e.g. intense weathering, high erosion, and sedimentation rates, dense vegetation cover); faults have slow slip rates [28] and long earthquake recurrence intervals (although the period covering the historical record is short, the only documented event is the MMI IX 1867 earthquake) resulting in inherent poor geomorphological manifestation and poor preservation of faulting markers. Despite these factors, we were able to identify several paleoseismic features such as lineaments, tilted Quaternary fluvial terrace risers, triangular facets, linear valleys and ridges, migration of meanders, wind gaps, peculiar drainage patterns, and knickpoints to prove the existence of active faults within the area of Yogyakarta.

Additional studies are needed to provide a better understanding of the hazard associated with these faults. Geophysical studies (e.g. electrical resistivity tomography profiles) are essential to corroborate the locations of the different segments of the faults, as well as to select suitable locations for paleoseismological trenching that will contribute to extending the seismic record and to the determination of slip rates, maximum expected earthquake magnitude and recurrence intervals. We aim to highlight the importance of improving seismic hazard assessment with regional studies characterizing active faults, especially in densely populated areas like Yogyakarta and where faults can be underestimated because of poor geomorphological expression and low seismicity due to long earthquake recurrence intervals.

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