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Stratigraphical and Sedimentological Review of the Merawu Formation, Serayu Basin, Central Jawa, Indonesia

Surono Martosuwito[1], Syaiful Bachri[2], and Zakiyah Ainul Kamal[1]

[1]Universiti Malaysia Kelantan, Malaysia
[2]Geological Survey Institute, Geological Agency Bandung, Indonesia. Jln. Diponegoro No. 57 Bandung

Corresponding author: surono.m@umk.edu.my; suronomartosuwito48@gmail.com
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Abstract- Merawu Formation is widely distributed in the Serayu Basin, Central Jawa, Indonesia. The formation is dominated by fine-grained clastic sediments comprising interbedded mudstone, siltstone, and sandstone. In the field, these outcrops are well exposed and well bedded. Stratigraphically, the Merawu Formation is underlain by the Paleocene Worawari Formation and overlain by the Late Miocene Penyatan Formation. Contacts between the Merawu Formation and the Worawari Formation are always found as fault types. Twelve sections have been done during the field work. Two members were identified within the Merawu Formation (Sandstone and Mudstone Members) in the field, where they interfinger each other. Previously, researchers interpreted the Merawu Formation as a turbidite sequence of deep marine deposits and depicted Early - Middle Miocene in age. However, the interpretation from the present research shows that the Merawu Formation was deposited on a tidal flat environment and has Early Miocene - Pliocene age, based on foraminifers found in some sections.

Keywords: Merawu Formation, Sandstone Member, Mudstone Member, tidal flat

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Introduction

Merawu Formation, which is named as Merawu Beds by van Bemmelen (1937), widely crops out within the Serayu Basin, Central Jawa, Indonesia. Van Bemmelen (1949) named the Serayu Basin as North Serayu Range. The formation is dominated by fine-grained clastic sediments of alternating mudstone, siltstone, and fine-grained sandstone (van Bemmelen, 1937; 1949). Condon *et al*. (1975, 1996) and Djuri *et al*. (1996) named this formation as Rambatan Formation. Stratigraphically, the Merawu Formation is underlain by Paleocene Worawari Formation and in turn, underlies Late Miocene Penyatan Formation (Condon *et al*., 1975; Djuri *et al.,* 1996). However, contacts between the Merawu Formation and underlying unit of the Worawari Formation are always found as faults. Previous workers (*e.*g. Satyana and Armandita, 2006; Satyana and Asnidar, 2008) also interpreted the Merawu Formation as a turbidite sequence of deep marine deposits with Early - Middle Miocene age.

The main aim of the present investigation includes reviewing the stratigraphic relation between the Merawu Formation with its neigh-

bouring units, and reinterpreting the sedimentary environment of the Merawu Formation. The studied area is located in the middle part of Central Jawa, Indonesia (Figure 1). More than ten detailed sections (at different locations) were prepared during the field works with the total length of about 750 m. The best outcrops of the formation, which are presented in this paper, are along Kali (small river) Keruh (194 m thick), Kali Tulis (260 m thick), Kali Bombong (52 m thick), Kali Simpar (123 m thick), and Kali Tengah (26m). All of the outcrops are in the Banjarnegara District except Kali Keruh which lies near the Lor Agung Village, Kandang Serang Distric, Pekalongan. In some places, the outcrop along the Kali Tulis is teared by some faults or covered by thick soil.

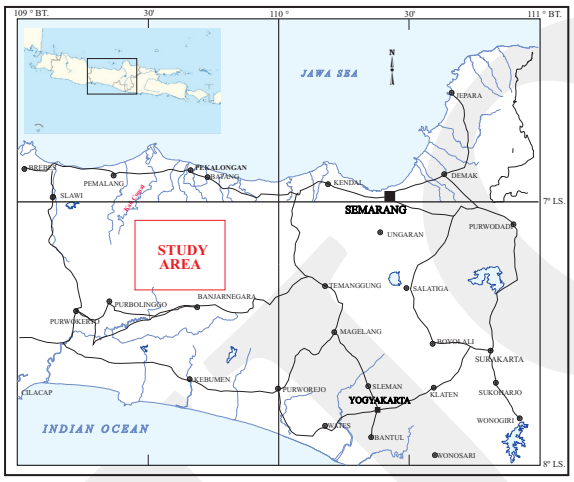

Figure 1. Locality map of the study area, in the Central Jawa, Indonesia.

Field Exposures

Two main members those are Sandstone and Mudstone Members, were identified in the field within the Merawu Formation, which interfingers each other. In the field, the distribution of Mudstone Member is more dominant than the Sandstone Member. All of the members show well-bedded appearance and their thicknesses vary from few cm to 30 cm. However, in some places (*e.*g. Kali Tulis), the sandstone beds have the thicknesses up to 1 m (Bachri *et al*., 2010). Mostly, the sandstone beds have dip between 10° - 30° in various directions.

Kali Keruh Section

The Merawu Formation crops out well along the Kali Keruh about 300 m without any gap, with the total thickness of 194 m (Figures 2 and 3). About 150 m upstream from the detailed section, there is andesitic lava overlain by volcanic breccia. Along the Kali Keruh, the formation is dominated by well-bedded, fine-grained sediments composed of mudstone, siltstone, claystone, marl, sandstone, and limestone. Foraminifers are abundantly found in the formation. Mostly, the thicknesses of these beds are from few cm up to 20 cm, but in some places the beds are up to 65 cm thick. Dip directions of the beds are generally toward the northeast with angles of 20° - 35°.

Martosuwito and Fakhruddin (2014) divided the outcrop to lower, middle, and upper parts. The lower part (0 - 62.7 m) is dominated by mudstone with thin layers (few cm - 15cm) of sandstone intercalations. Limestone layers of 22 - 23 cm in thickness are found within the middle portion (Figure 3). Sedimentary structures commonly found within sandstone beds are parallel lamination, palimsed, wavy bedding, graded-bedding, and erosional surface. This part has been deposited in a lower part of mud zone.

The middle part of the formation (62,7 - 116 m) is dominated by fine-grained clastic sediments of mudstone and siltstone with sandstones intercalations. The sandstone layers are more in number and thicker upwards. The thicknesses of the sandstone layers range between about 2 mm up to 65 cm. Sedimentary structures, which are

Figure 2. Field exposure of tidal deposits along the Kali Keruh. The sequence is dominated by fine-grained sediments.

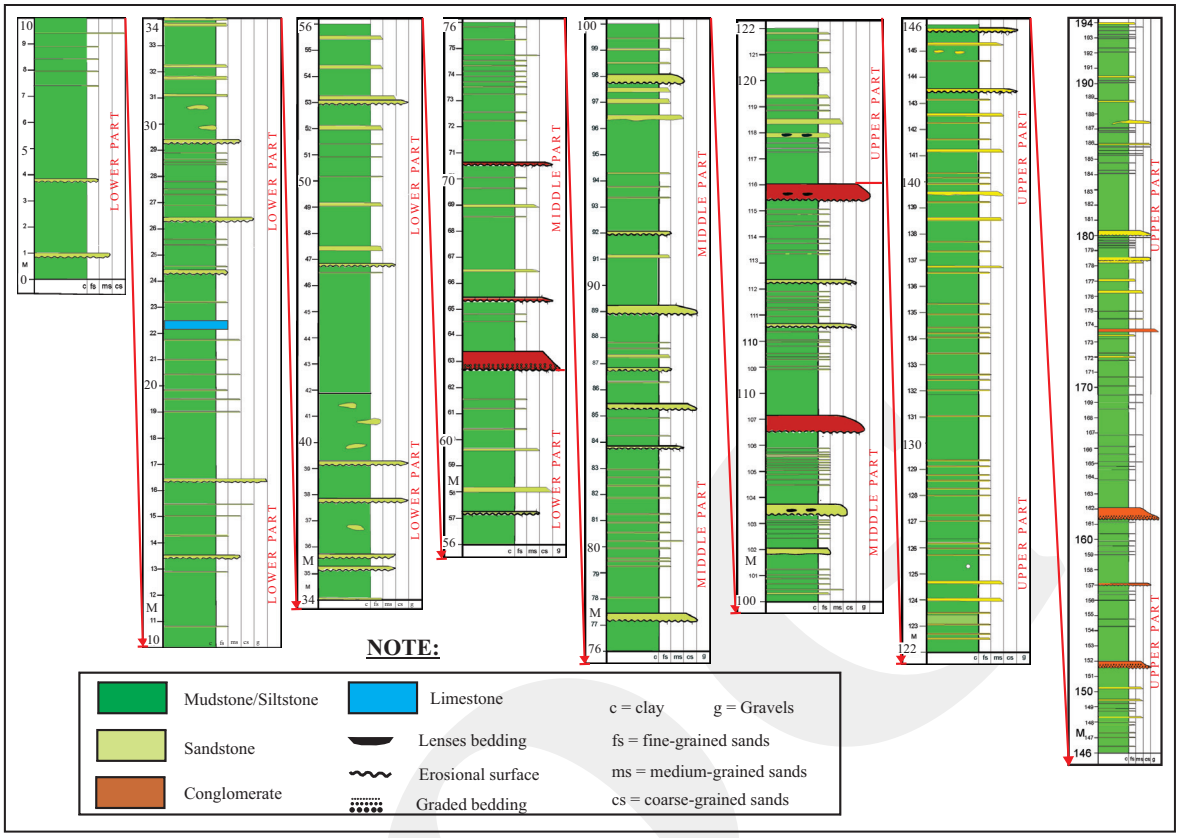

Figure 3. Detailed section of the Merawu Formation along the Kali Keruh (modified from Martosuwito and Fakhruddin, 2014).

commonly found within sandstone are erosional surface, lamination, cross-bedding, herringbone (Figure 4), flaser bedding, wavy bedding, and graded bedding. Erosional surface of channel structure is commonly found at the base of sandstone layers. Depositional environment of the middle part is mud zone, and it changes upwards gradually to sand zone.

The upper part of the section (116 - 194 m) is dominated by mudstone with sandstone intercalation. Sedimentary structures within sandstone are lamination, cross bedding, erosional surface, herringbone (Figure 4), graded bedding, lenses bedding, and flasser bedding. This part was deposited in mud zone, but its middle portion was deposited in mixed zone.

Firgure 4. Herringbone structure overlain by parallel lamination sedimentary structures within sandstone layer at Kali Keruh.

In general, tidal deposits along Kali Keruh are dominated by fine-grained sediments. However, sedimentary rocks above the channel are dominated by conglomerate and sandstone. The conglomerate layers are found as channel deposits of distributary tidal channels. Sandstone layers are mostly very thin and distributed from the lower to the upper parts of the section.

Kali Tulis Section

The Merawu Formation is well exposed along Kali Tulis (Figure 5). This formation is well-bedded and about 250 m thick, consisting of fine-grained clastic sediments of alternating mudstone, siltstone, and sandstone. Stratigraphic relation between the Merawu Formation and the underlying Worawari Formation is not clear yet

Figure 5. Tidal flat deposits of the Merawu Formation along Kali Tulis.

due to colluvium cover. However, at some locations, the stratigraphic relation between both formations is found as fault contacts.

The formation is shown in the upper part of the section (Figure 6; Bachri, 2010, 2017; Bachri *et al*., 2010). Bachri *et al*. (2010) divided the formation into two parts, lower and upper parts. The lower part is dominated by mudstone and siltstone, as the Mudstone Member, whereas, the upper part is dominated by sandstone, as the Sandstone Member. Based on foraminifera fossil contents, the formation has an age of Early - Middle Miocene.

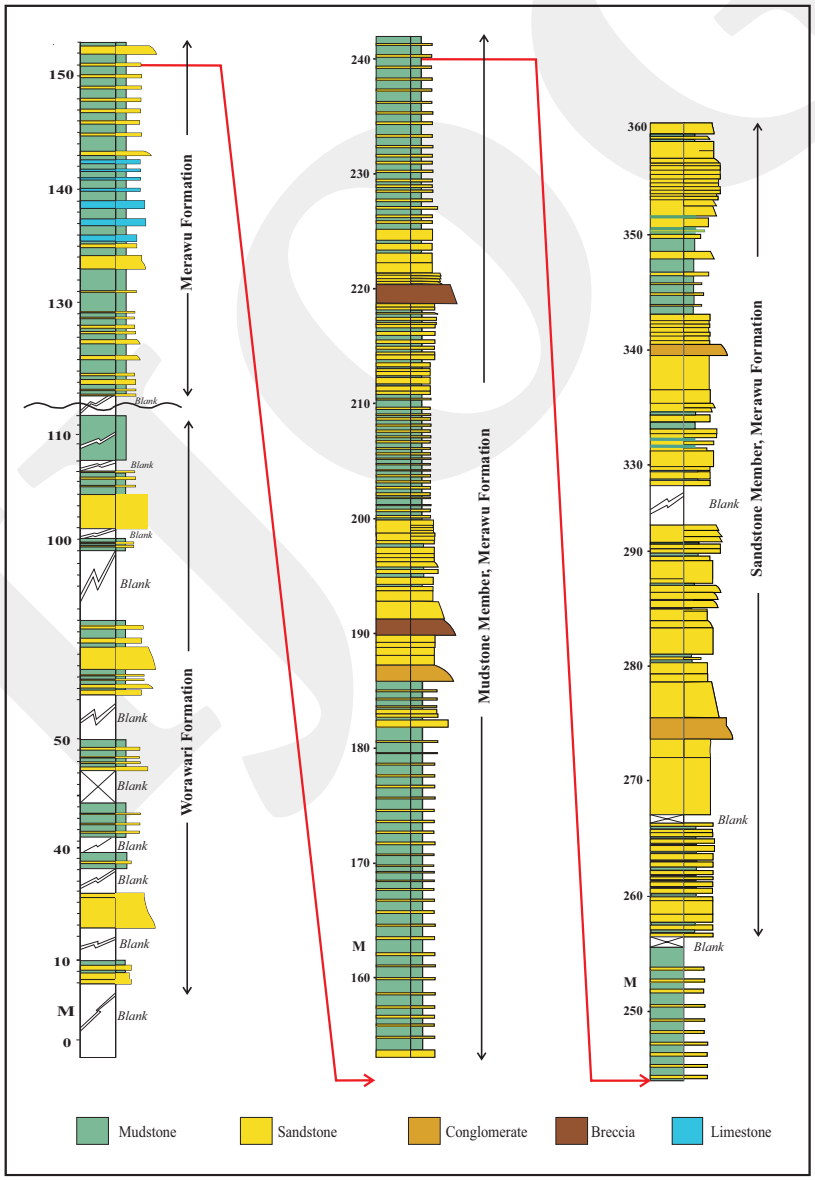

Figure 6. Detailed section of the Merawu Formation along the Kali Tulis (modified from Bachri, 2011).

The lower part or the Mudstone Member of the Merawu Formation (Figure 6), which is dominated by fine-grained sediments, occurs as thin sandstone layers, mostly of <30 cm thick. Limestone intercalates in the lower portion of the member. In some places, there are conglomerate and breccia intercalations of 50 - 90 cm in thicknesses. The sandstone, conglomerate and breccia are dominated by volcanic fragments. Herringbone, graded bedding, and bidirectional cross bedding (Figure 7) structures occur within the sandstone. Foraminifera and *Cruziana* trace fossils found in the middle part, indicate that the sediments were deposited in a shallow marine. All of the evidences mentioned above show that the Mudstone Member was deposited in a tidal flat, could be on the mud zone. In the middle portion, there is a sandstone sequence as mix zone deposits. Some diorite intrusions were found in the lower part. Condon *et al*. (1975) also found the same intrusion in many places surrounding the studied area. This lower part (Mudstone Member) of the Merawu Formation along Kali Tulis is similar to the formation cropping out along Kali Keruh.

Figure 7. Bidirectional cross-bedding within sandstone (left-bottom) at the Kali Tulis.

The upper part or the Sandstone Member of the Merawu Formation dominated by sandstone (Figure 6), is well bedded with thicknesses of beds range between 20 cm to 1 m. Conglomerate layers are found in the lower and upper portions with erosional surface at the base. Planar cross bedding, herringbone, erosional surface, convolute lamination, and wavy bedding are the most common sedimentary structures within the upper part. Their lithology and sedimentary structures show that the member was deposited within sand zone of a tidal flat. Commonly, their components of sandstone and conglomerate are dominated by volcanic materials. In the upper portion of the member, there is a mudstone sequence. This sequence may be deposited on the mix zone between sand and mud zones.

Kali Bombong Section

Along Kali Bombong, the Merawu Formation is also well-bedded, cropping out at its river bank with about 75 m long (Figures 8 and 9) and its thickness is 52 m. Lithologically, the formation is dominated by mudstone and siltstone with fine-to medium grained sandstone intercalations (Figures 8 and 9). Conglomerate and limestone are found in the lower part of the section. The sandstone layers are more common in the lower part of the section and getting rare upwards, and they are 5 - 25 cm thick. On the other hand, the conglomerate and limestone have the thicknesses of 3 - 20 cm. Mudstone and siltstone are most dominant in the section. All evidences above indicate that upwards the energy is quieter.

The mudstone is brownish back-black, very fine-grained, highly contains carbon fragments. The sandstone fragments are dominated by fine-

Figure 8. Field feature of the Merawu Formation along the Kali Bombong, showing alternating mudstone and sandstone.

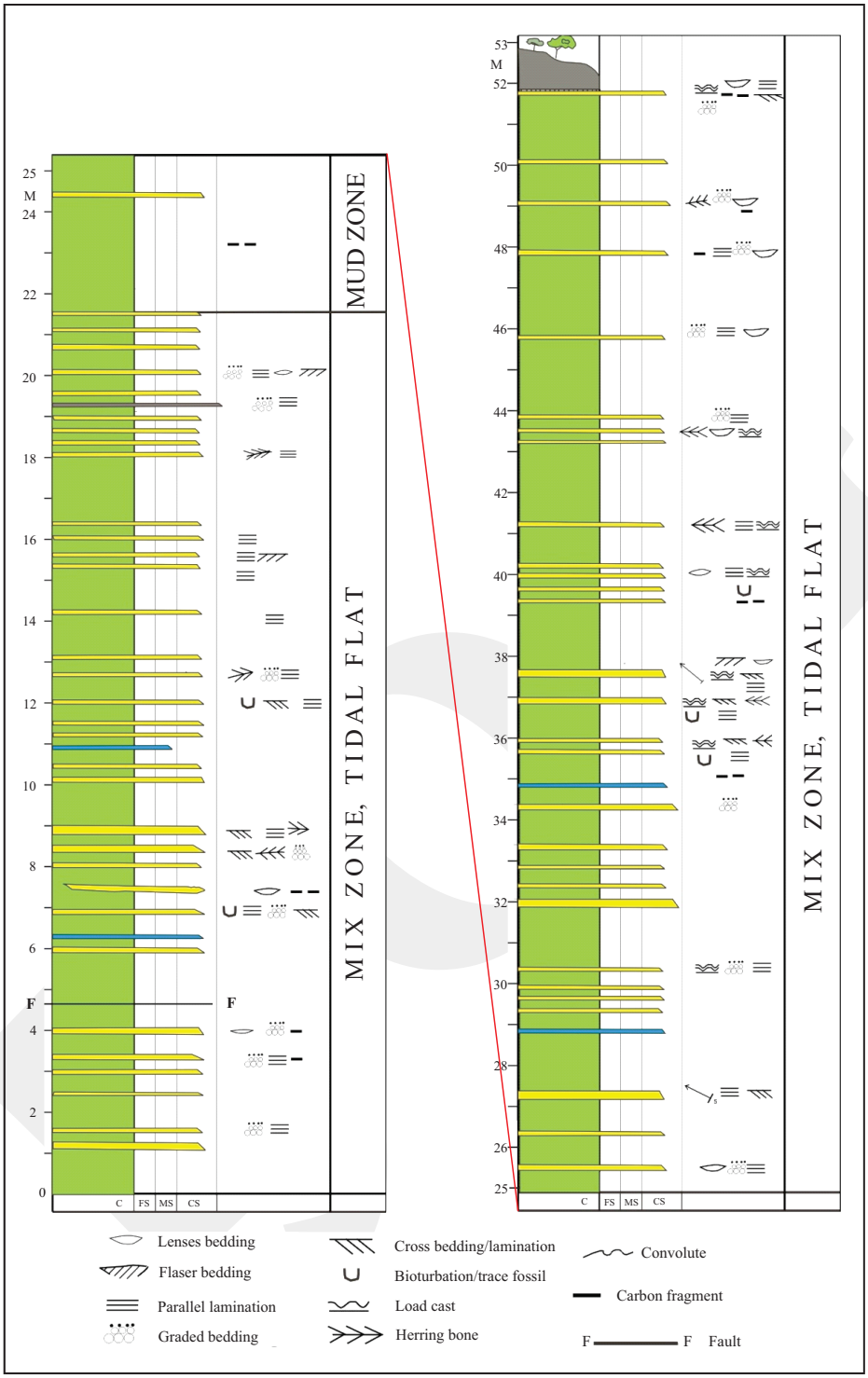

Figure 9. Detail section of the Merawu Formation along the Kali Bombong. Sandstone, limestone and conglomerate layers are shown in yellow, blue and brown colour respectively. Black arrows are paleocurrent directions.

to medium-grained, moderately to well rounded quartz. The conglomerate contains quartz and calcareous sandstone fragments, mostly well rounded. The limestones are mostly lime mud supported consisting of quartz and foraminiferal fragments.

Sedimentary structures, which are mostly found in the sandstone layers, are dominantly tidal structures, such as herringbone (Figure 10a), cross lamination, parallel lamination, flaser bedding, and lenses bedding. Graded bedding, load

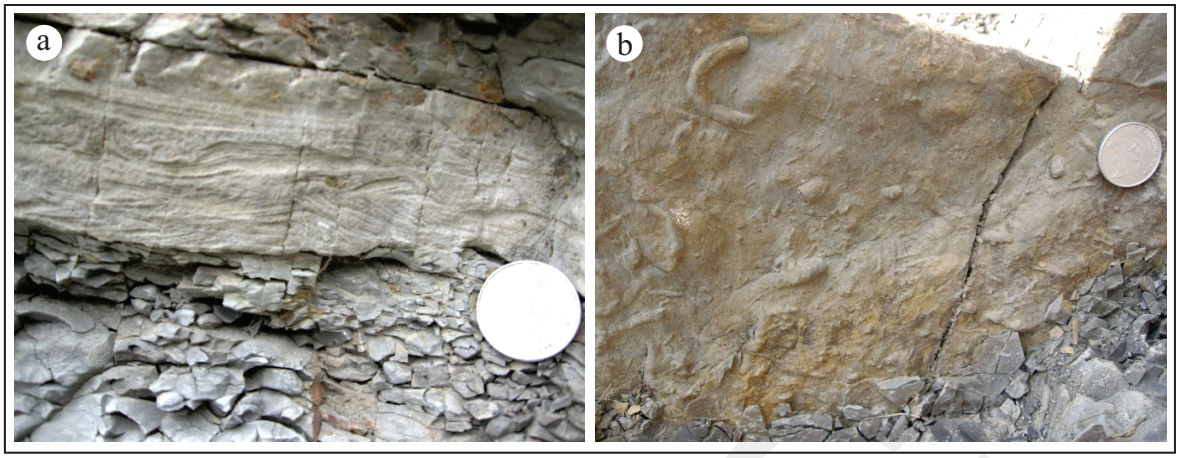

Figure 10. Sedimentary structures and trace fossils; (a) Herringbone structure at river bank of the the Kali Bombong and (b) trace fossils of *Planolites* in mudstone, of the Merawu Formation.

cast, convolute, foraminifera, and trace fossils of *Planonites* (Figure 10b) have been found in the section. Lithological composition, fossils, and sedimentary structures at the location show that the formation was deposited in a tidal flat environment, started from mix zone and ended by mud zone of intertidal flat.

Kali Simpar Section

The Merawu Formation also crops out well along the Kali Simpar with the thickness of 123 m (Figures 11 and 12). The outcrop is dominated by well-bedded sandstone layers with mudstone and siltstone intercalations. Conglomerate and limestone are found at separate locations.

The sandstones have various thicknesses of 2 - 85 cm, mostly fragment dominated, with carbonaceous and tuffaceous fragments in some layers. The fragments are sub-rounded to rounded quartz, of medium- to coarse-grained sizes, and few of volcanic materials. Some sandstones are micritic types.

Figure 11. The Merawu Formation cropping out at river bank of the Kali Simpar.

Three layers of the conglomerate had been found in the field, between the thicknesses of 31 - 33 m, 57 - 58 m, and 118 - 120 m. These conglomerates are well - bedded, having thicknesses of 20 - 70 cm, and fragments dominated. These fragments are subrounded-rounded, medium sorted of igneous rocks, quartz, sandstone, and siltstone. Erosional surface, lag deposits, and graded bedding had been found within lower part of the layers. This conglomerate is probably transported (by river) from volcanic-dominated source located in north of the Simpar section.

The limestone is well bedded with 3 - 20 cm thick. Microscopically, the limestone comprises packstone, sandy packstone, and grainstone. Quartz, feldspar, and pyroxene, of 5% occur as the grains of sandy packstone. The grainstone, is dominated by fragments of foraminifera and shell.

The dominant sedimentary structures of the Merawu Formation in the location are tidally structures, such as lenses bedding, flaser bedding, herringbone (Figure 13a), parallel lamination, and cross lamination. Other sedimentary structures are graded bedding, erosional surface, lag deposits, load cast, bioturbation, and convolute lamination. Foraminifera and trace fossil of

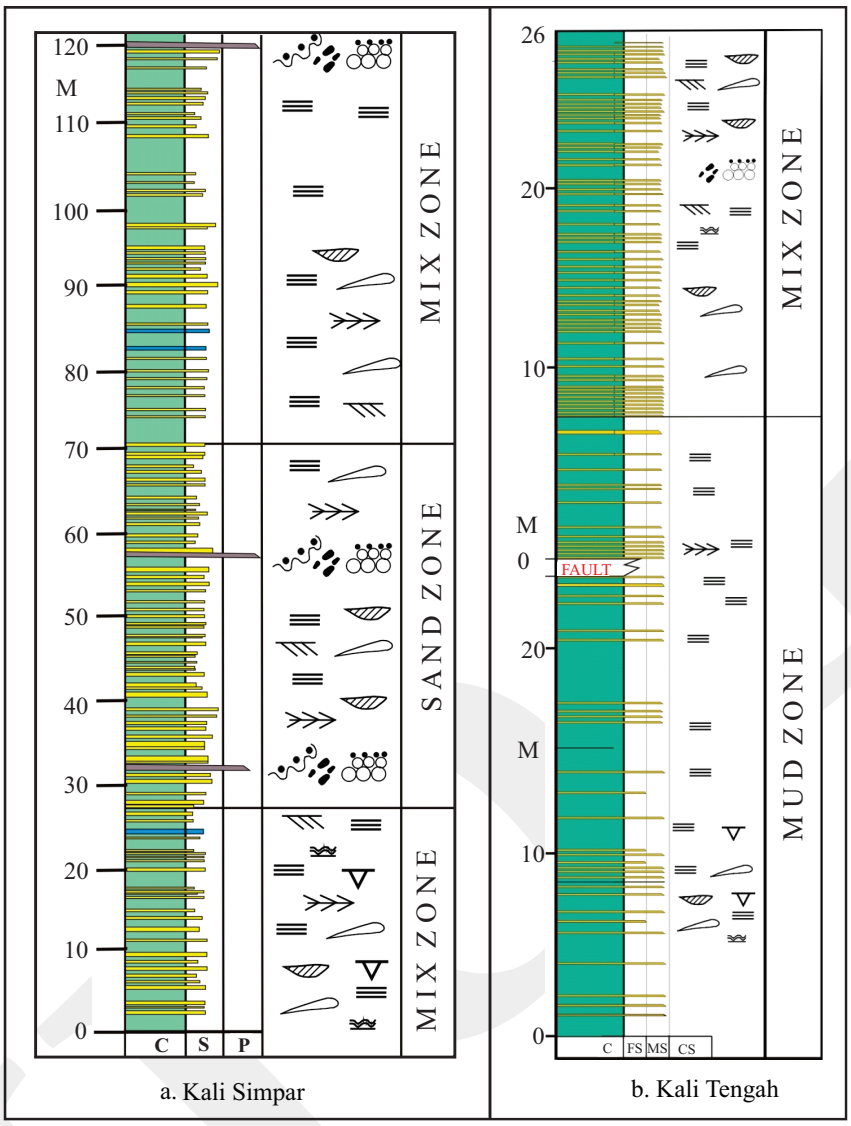

Figure 12. Detailed section of the Merawu Formation along (a) Kali Simpar, and (b) Kali Tengah. See Figure 9 for explanation and black layers in Figure 12b are thin layers of lignite.

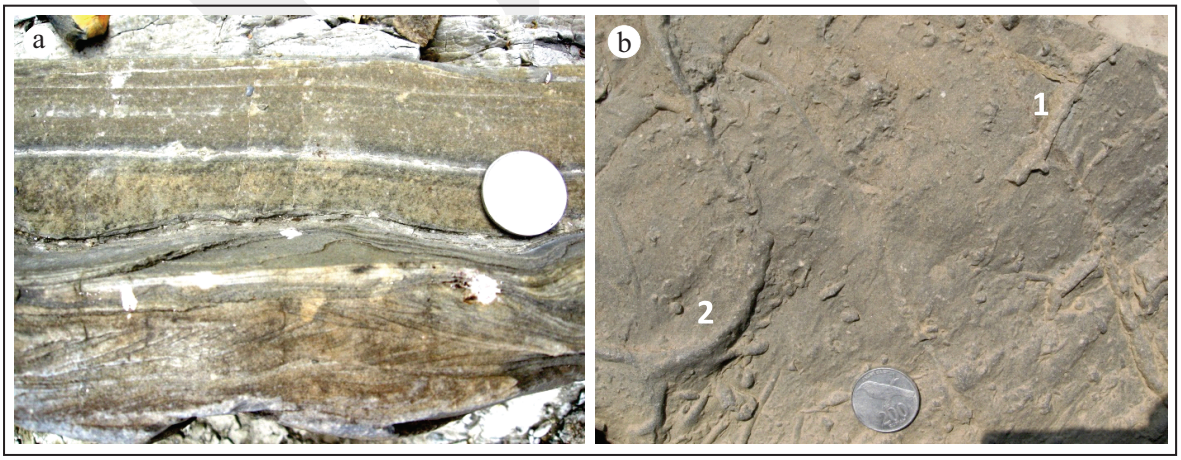

Figure 13. Sedimentary structures and trace fossils found along Kali Simpar; (a) herringbone within sandstone , and (b) trace fossils of *Thalassinoides* (1) and *Planolites* (2).

Planolites and *Thalassinoides* present at some places (Figure 13b). Lithological composition, fossils, and sedimentary structures of the Merawu Formation along the Kali Simpar show that the formation was deposited on an intertidal flat. While, the lower and upper parts were deposited on a mixed zone, and middle part was on a sand zone (Figure 12a). Probably, the river energy is dominant in the middle part of the section.

Convolute structure is found in some sandstone layers in this section. The same structure is also found within sandstone layers in detailed sections of Kali Bombong and Kali Keruh (Martosuwito and Fakhruddin, 2014). Mostly, they are found together or near herringbone and lense bedding structures in channel deposits. It is presumed that these were due to an unstable steep bank channel sliding to the bottom of the channels.

Kali Tengah Section

The Merawu Formation cropping out along the Kali Tengah is well bedded with the thickness of 26 m (Figures 12 and 14). Lithologically, the Merawu Formation at the location is dominated by fine-grained sediments of mudstone and siltstone, intercalated by medium-grained sandstone. Thin layers of lignite are found within the lower section.

Sedimentary structures in the section are parallel lamination, flaser bedding, lenses, herringbone (Figure 15a), graded bedding, lag deposit, mud crack, and cross lamination. Trace fossils of *Planolites* (Figure 15b) are found in some places. Based on lithological composition, fossil contents, and sedimentary structures within this sequence, the Merawu Formation along the Kali Tengah, were deposited on an intertidal flat. Both the lower and upper parts were on mixed zones (Figure 12b).

Figure 14. Outcrop of the Merawu Formation along the Kali Tengah showing fine-grained sediments as the dominant lithology.

Sedimentary Environment

The Merawu Formation outcrops show well bedded (Figures 2 - 10), and their bed thicknesses range between 2 - 30 cm. The thicknesses of the sandstone layers are commonly thicker (up to 65 cm) than the fine-grained sediments of mudstone and claystone. Sedimentary structures found within the formation, mostly in sandstones, are erosional surface, graded bedding, cross bedding, lenses beddings, flaser bedding, herringbone, bidirectional cross-bed, lag deposits, and wavy bedding. Slump structures are found in some places, especially in sandstone beds.

Sedimentary structures of lenses, flaser bedding, herringbone, bidirectional cross-bed, and wavy bedding (Figures 3, 9, and 12) are as tidalites (Klein, 1971; 1972; Longhitano *et al.,* 2012) and are commonly found within tidal flat sediments. Fossils of foraminifers are abundant in some beds along the Kali Tulis, Kali Keruh, Kali Bombong, Kali Simpar, and Kali Tengah, which indicate the formation was deposited under the influence of open marine. These lithologies, sedimentary structures, and fossil contents within all of the sections, tend to indicate that the sedimentation process of the Merawu Formation was influenced by tidal current on an intertidal flat.

Discussions

Foraminifera fossils are abundantly found in some locations of detailed sections, *e.g.* along Kali Keruh, Kali Simpar, Kali Bombong, and Kali Tulis. Along Kali Keruh, these fossils are

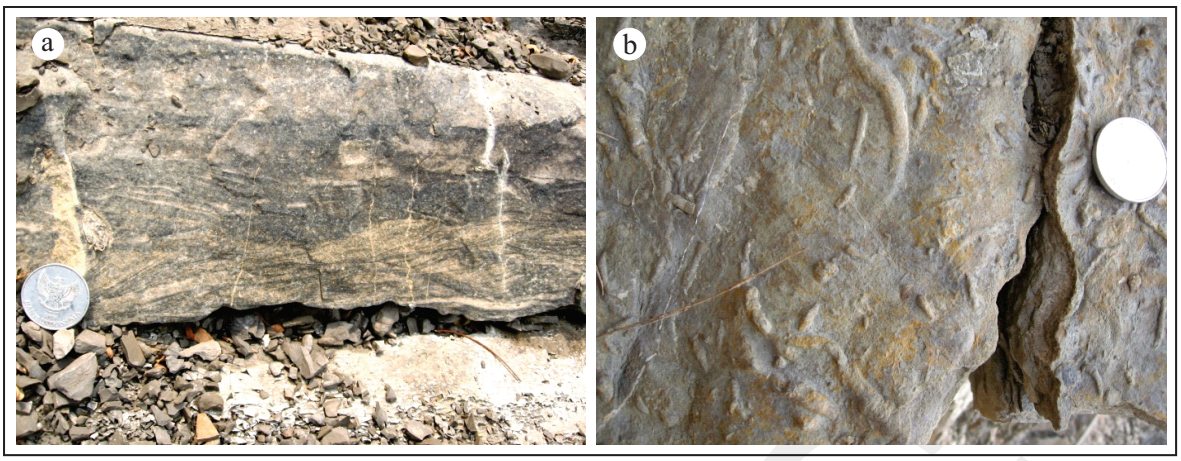

Figure 15. Sedimentary structures and trace fossils found along the Kali Tengah; (a) herringbone within sandstone, and (b) trace fossils of *Planolites*.

distributed from the bottom to the top of the section. These evidences indicate that the tidal flat environment is well connected with an open sea. According to Bachri *et al*. (2010), along Kali Tulis, the Sandstone Member lies at the upper part of the section (Figures 5 and 6), and their fragments within sandstone layers are dominated by volcanic rocks. Along Kali Keruh, fragments of sandstone are dominated by quartz. Probably, these indicates that during the time of deposition the volcano centre was located at the southern part of the studied area.

Almost all locations of the sections, in the southern part of the studied area, except Kali Keruh that is located in the northern part of the studied area, far away from the other sections. Fossils, especially foraminifera, are more abundant in the Kali Keruh section, from the lower to the upper parts. Based on foraminifera analysis along the Kali Keruh section, the age of the formation is N17 - N19 or latest Late Miocene- latest Early Pliocene (Martosuwito and Fakhruddin, 2014). On the other hand, also based on foraminifer analysis, the age of formation resulted from the Kali Simpar and Kali Bombong sections analyses show N4 - N13 or Early Miocene - Middle Miocene (Bachri, 2011, and 2017; Bachri *et al.*, 2010). These all evidences above suggest that the Merawu Formation developed from Early Miocene until Early Pliocene, and during the time of deposition, the Kali Keruh section is interpreted to be closer to the sea than the other sections. Such interpretation is supported by the presence of volcanic centres, as the source of the volcanic fragments, located at the southern part of the studied area.

These different age results show two posibilities, first, the detailed sections along Kali Tulis, Kali Bombong, Kali Simpar, and Kali Tengah, are as the lower part of the Merawu Formation, and the Kali Keruh section is the upper part of the formation. The second possibility is that there is a local unconformity between the sections as interpreted by Martosuwito and Fakhruddin (2014). However, mostly the tidal flat environment has a very gentle slope and stable environment. Therefore, deposition can be continuous during a long period. Geological structures within the studied area are very complex. The formation has experienced shortening more than 200% causing the formation to be thickened considerably (Nursecha *et al*., 2014). Based on that case, the first possibility is the more possible and valid one than the second one. According to Djuri *et al.* (1996), the Merawu Formation is overlain by Late Miocene Penyatan Formation. The discussion above shows that the upper part of the Merawu Formation maybe interfingers with the lower part of the Penyatan Formation.

The Kali Tulis lies in the southern part of the studied area, while Kali Keruh is located in the northern part. The stratigraphic section along Kali Tulis (Figure 6) shows that the lower part of the

Merawu Formation is dominated by the Mudstone Member and it changes to be the Sandstone Member in the upper part. The age of the formation at Kali Keruh is N8 - N9 or Early - Middle Miocene (Bachri *et al*., 2010).

Along Kali Keruh, the Merawu Formation is dominated by the Mudstone Member (Figure 3), and the age of the formation is N17 - N19 or latest Late Miocene- latest Early Pliocene. Although the middle part of the formation is not found yet, the tidal deposits of the Merawu Formation change relatively from sandstone dominated in the lower part (along Kali Tulis) to be mudstone dominated in the upper part (along Kali Keruh). This indicates that its depositional environment is shallowing upwards. Foraminiferas are abundantly found in the Kali Tulis and Kali Keruh sections, indicating the depositional environment was affected by an open marine. There are two types of open-coast tidal flats, those are muddy and sandy open-coast tidal flats (Fan, 2012). These evidences show that the environment of the Merawu Formation is an open-coast tidal flat. Both outcrops along Kali Tulis and Kali Keruh, are assumed to be deposited in a muddy open-coast tidal flat. In Kimberley and Northern Territory, Australia, this type of tidal flat ranges from 50 – 2,000 m in width (Short, 2015). The location of the Kali Keruh is separated >1,000 m from the others. Probably, the Merawu Formation basin is also distributed in a wide area.

Along the Kali Keruh, the Merawu Formation is dominated by mudstone, as the Mudstone Member (Figure 3). The Merawu Formation cropping out along the Kali Keruh can be proposed as a type location of the Mudstone Member of the Merawu Formation. The authors propose a formal lithostratigraphy name for this member as Kali Keruh Member. However, Bachri *et al*. (2010) suggested the lower part of the Merawu Formation, exposed along Kali Tulis, is the Mudstone Member whereas for the upper part as Sandstone Member (Figure 6). Comparing to the Mudstone Member along the Kali Tulis, the same member along the Kali Keruh is much better exposure, sedimentary structures, and fossil content than other section locations.

Conclusion

The Merawu Formation in the Serayu Basin is dominated by fine-grained sediments and sandstone with thin beds of conglomerate, limestone, and breccia intercalations. The formation could be deposited on an open-coast intertidal flat during Early Miocene to latest Early Pliocene. During the time of deposition, there were volcanism activities with their centres were located in the southern part and the sea was towards the northern part of the studied area. The stratigraphic relation between the Merawu Formation and the underlying Worawari Formation is always found as a fault contact. The upper part of the formation interfingers with the Penyatan Formation.

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