Supplementary Materials

Part 1. The Distribution of Outcrop

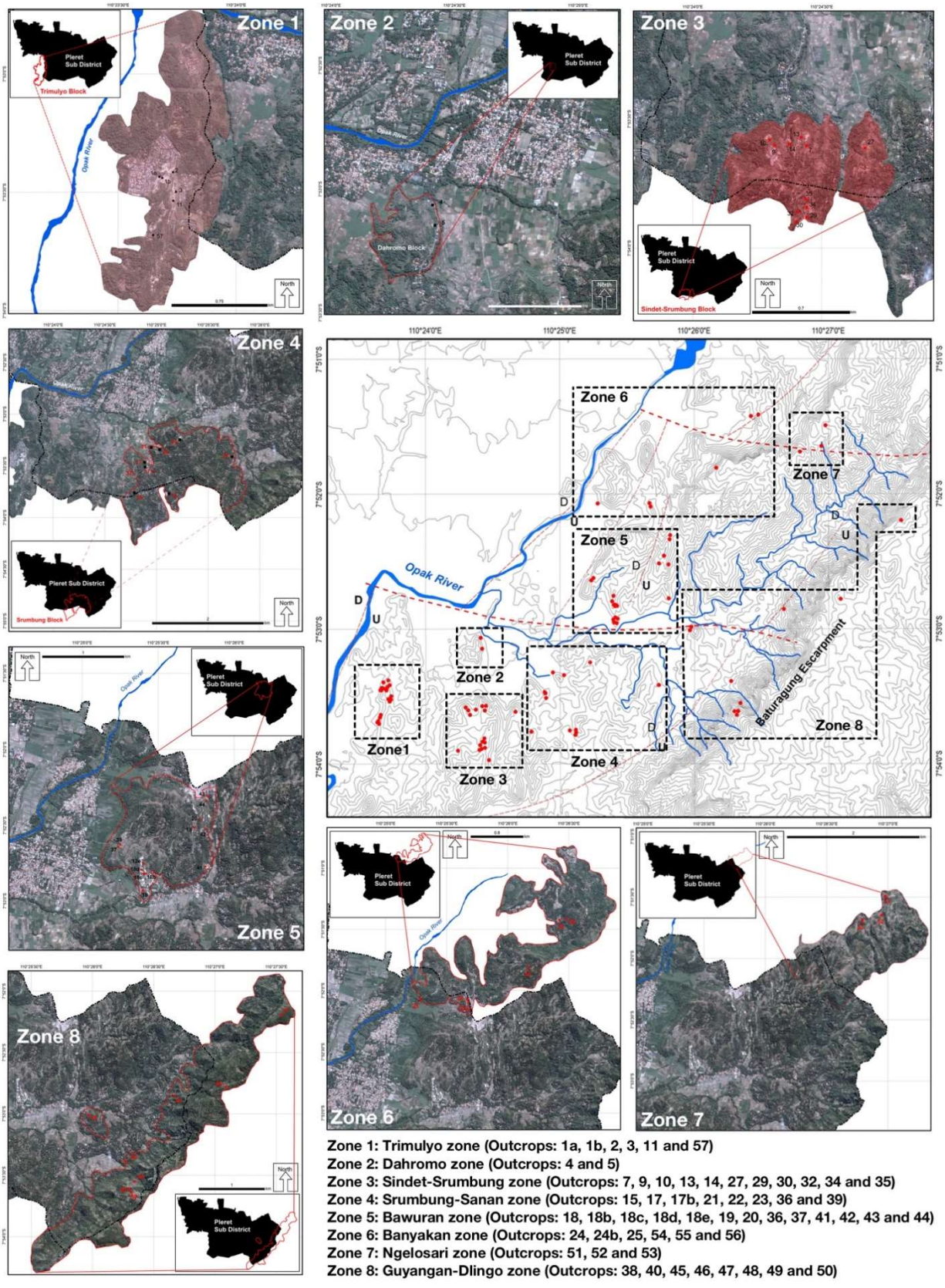

Figure S1. The Distribution of Outcrop.

Part 2. The Brief Description of Outcrop Type 1 Characteristics.

Outcrop 1 consists of two major outcrops, namely outcrop 1a (west) and 1b (east). According to the Geology map of Yogyakarta, the outcrop 1 belongs to Semilir Formation, which comprises of the interbedded layer between breccia pumice, volcanic sandstone, and volcanic mudstone. In the field, this outcrop is characterised as a light to the dark grey colour of the rock. The outcrops 1a and 1b have slightly different in term of colour. The west outcrop has lighter colour compared with the east outcrop due to the intensive mining activity in the west outcrops. Moreover, the weathering process has intensively occurred in the east outcrops. The weathered material turns to the darker colour and covers the outcrops surface. However, the same rock with the outcrop 1a is found in the inner layer (5-10 cm from the surface) of the outcrop. Using the visual interpretation of the SfM results and the fieldwork observation, a series of layers of very fine sand (fine tuff or volcanic mudstone) to cobbles matrix size (volcanic breccia) have been identified in this outcrop (Figure S2). From the bottom of the layer, the outcrop 1a consists of the interbedded layers between breccia pumice, dacite tuff, and tuffaceous clay. The breccia pumice is in the lower and the upper layers of the outcrop. Both the lower and upper layers of breccia pumice have horizontal lamination, which indicates that these layers are pyroclastic surge deposits. The middle layer of the outcrop 1a consists of interbedded of volcanic sandstone and volcanic mudstone. The volcanic sandstone or coarse tuff was generated from the coarse ash deposits (0.063-2 mm of grain size), and the volcanic mudstone or fine tuff was generated from fine ash deposits (<0.063 mm of grain size). Both volcanic sandstone and mudstone are closely related to the volcanic fall deposits, which is deposited on top of pyroclastic flow and surge. Most of the volcanic fall deposits show no depositional structure and vary in term of layer thickness.

Based on the Non-genetic lithofacies terms and abbreviation, the lower layer of the outcrop 1a is mainly diffuse-bedded ignimbrite (dbLT) with the normal grading pattern of pumice. The middle layer consists of transitional parts into diffuse-stratified lapilli tuff or ash (dsLT) with very low-angle impersistent strata. This deposits are common and belong to most of the ignimbrites subordinate lithofacies [42] It is characterised by diffuse stratification which can be sub-parallel, gradual thickening and thin, and even splaying. It is commonly less stratification and consists of various portions of rounded pumices caused by abrasion (Figure S2A). The diffuse stratification indicates that the flow-boundary was typical of unsteady depositing current. The upper layers of this outcrop consist of interbedded layers of ash and thin layers of pyroclastic surge deposits. This upper layer can be classified as parallel bedded tuff or ash (T//b) and thin-bedded lapilli tuff or ash (bLT). The grain size of T//b is commonly from fine to coarse ash. These deposits form a layer from only millimetres to decimetres thick. The parallel bedded or laminated indicates that this deposit was formed from a direct fallout which was dominated by the flow-boundary zone of a fully dilute pyroclastic density current [42].

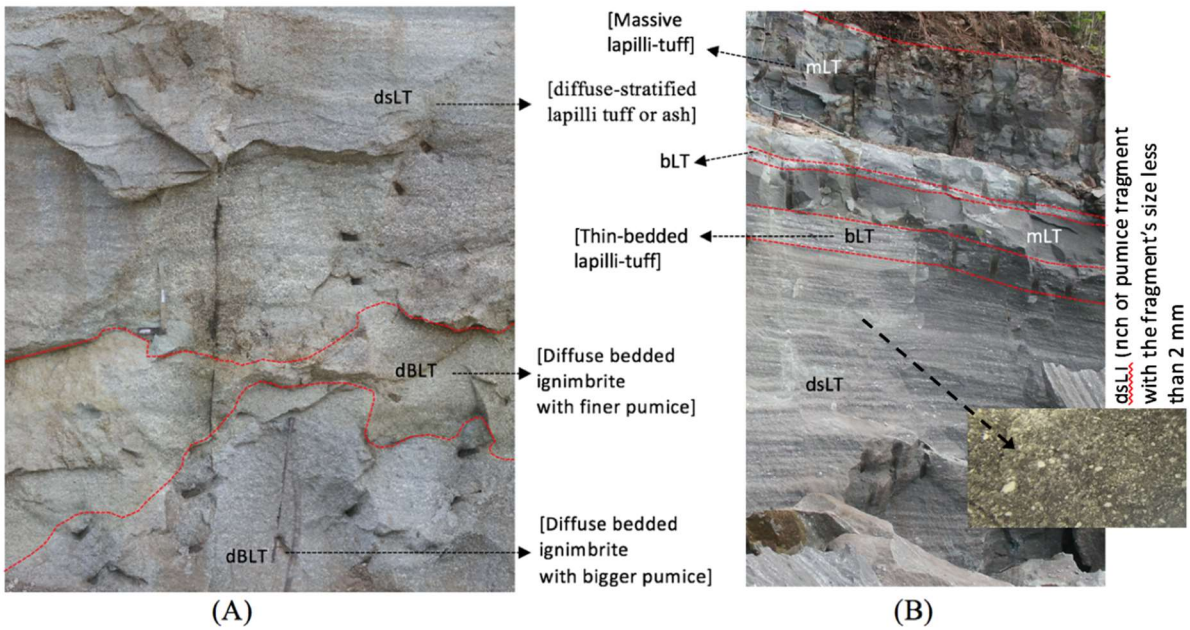

Figure S2. (**A**) Ignimbrite deposits of outcrop 1a at Trimulyo Zone (Diffuse bedding plan); (**B**) Ignimbrite deposits of outcrop 2 at Trimulyo Zone (more distinct bedding plane).

In general, the outcrop 1b has a dark colour and visually has only one massive layer from bottom to the top of the outcrop. However, this dark colour only sticks on the outer surface of the outcrop due to the rock weathering and alteration. The inner colour of the outcrop is similar to the western outcrop. The outcrop 1b consists of interbedded layers of breccia pumice, coarse and fine tuff. Based on the lithofacies this outcrop consists of interbedded layers of massive lapilli tuff (mLT), stratified tuff (//sT), thin-bedded lapilli tuff (bLT), and diffuse-stratified lapilli tuff (dsLT). The most bottom layer is //sT with the colour of light grey and the thickness of 5 cm. This layer has very well sorted and very fine ash (less than 0.0625 mm) grain size. The grain shape is very difficult to observe and has no pumice and lithic fragment. A bluish grey dsLT and rich of pumice fragments were deposited on top of that. These deposits have a well sorted coarse ash grain size and 50 cm of layer's thickness. The pumice fragments were spread randomly along the horizontal lamination. This deposit is typical of pyroclastic deposits (Figure S3). Above this layer, a poorly sorted deposit with the pyroclastic grains size of lapilli (2-64 mm) and has poorly pumice, and lithic fragments configuration was deposited. Based on the lithofacies, this layer can be classified as the massive lapilli tuff (mlT). These lithofacies configuration between //sT, dsLT, and mLT commonly occur in the ignimbrite deposits [43]. The other examples of similar lithofacies configuration of ignimbrite can also be found in the Mount St Helens ignimbrites, Taupo ignimbrite, Pinatubo ignimbrite, and Granadilla ignimbrite. The outcrop 1b has at least 29 layers which have repetition pattern of //sT, dsLT, and mLT lithofacies from lower to upper layer (Figure S3).

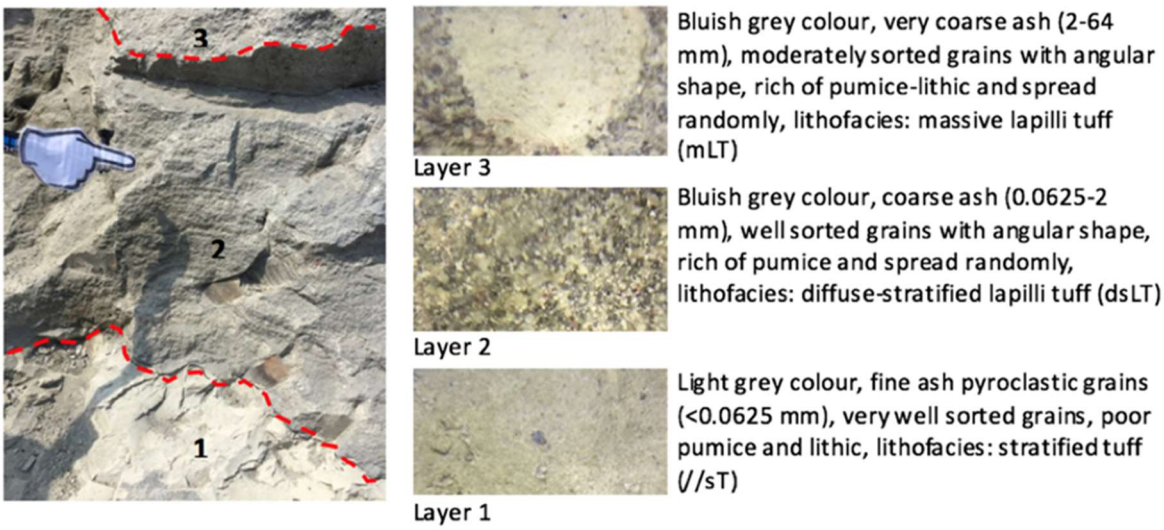

Figure S3. The lower layers of the Outcrop 1b (east outcrop)

Outcrop 2 consists of five segments. Each segment has an average dimension of 47.60 m (length) and 3,90 m (height). For example, outcrop 2 segment 1 has 2.55 m of height and consists of 12 layers. The bottom layer comprises the thin layer (90 cm) of bluish grey and coarse-grained, massive lapilli-tuff (mLT). This layer has the horizontal lamination of moderately sorted pumice fragment and reverses pumice grading. This layer can be categorised as a dsLT. The similar layer was also found on the lower layer of outcrop 1, 1b, and 57. The layer 2 is a thin layer (21.50 mm) of bLT. This layer is rich in pumice fragment with very small (less than 1 mm) pumice and the lithic fragment which spread randomly. It has fine ash grain size and well-sorted grain configuration. On the top of that, a similar layer was deposited. This layer 3 (4 cm height) has grey colour and rich of bigger pumice fragment. The pumice fragment's size varies from 1 mm to 2 cm pumice fragment. This layer also can be categorised as a bLT layer with the bigger fragment, poorly sorted, and rich in pumice fragment. The Layer 4 consists of the dsLT layer same with the layer 1. It has only 5 cm thickness. Layers 5-8 are the interbedded layer between light brown tuff and dark brown tuff layer. Both of them have very fine ash and well-sorted grain size. These layers are poor of pumice and lithic fragments. Based on the lithofacies, both of the layers can be classified as the stratified tuff deposits or //sT. On the top of that, 11 cm of bluish grey bLT layer is found. This layer is similar to the layer 2 of this outcrop. It also has random, coarse ash grain size, and very well sorted pumice fragment. The upper layer of this outcrop consists of interbedded layers of dark brown tuff (//sT), light grey and bluish grey lapilli tuff (bLT). The light grey bLT has a finer grain size and less pumice fragment rather than the bluish grey mLT. Moreover, we found also a lot of small lithic fragments (less than 1 mm) which spread randomly in this layer (Figure S4).

The middle layer of this outcrop has the similar characteristic with the upper layer of the outcrop 1a. This layer consists of interbedded layers of thin-bedded (bLT) and diffuse-stratified lapilli-tuff (dsLT) and massive lapilli-tuff (mLT) (Figure S2B). Similar to the outcrop 1a, this layer indicates that the deposit was formed during the unsteady phase of pyroclastic density current. However, this layer has the more distinct dsLT, bLT, and mLT rather than the middle layer of the outcrop 1a. dsLT frequently occurs within vertical gradation between mLT and sT [42]. The similar deposits with outcrop 1 and 2 were also found in the other places such as Minoan Ignimbrite at Monolithos, Santorini and Rio Caliente ignimbrite, La Primavera caldera fill, Jalisca, Mexico.

The outcrop 3 has similar layer configuration with the outcrop 1 and 2. This outcrop has three segments with the main outcrop's dimension approximately 36.60 m of length and 11.75 m of height. The main outcrop (segment 2) consists of 11 layers. In general, the lower layer has the similar characteristic with the upper layer of outcrop 1 and 2. The middle and upper layer of the main outcrops comprises of interbedded layers between pyroclastic surge and direct fallout deposits. Based on the lithofacies, the lower layer of the outcrop 3 is classified as the diffuse-stratified lapilli-tuff (dsLT) layer

same with the upper layer of outcrop 1 and 2. This dsLT layer has approximately 2 m of thickness with a normal grading of pumice fragments. This layer was deposited alternately with the stratified tuff (sT) until the upper layer of the outcrop. The bottom sT layer has 2 m thickness with the dark grey colour and aphanitic texture. This layer also consists typically of pumice-rich deposit. The layer configuration in the outcrop 1,2, and 3 (zone 1) is also found in the outcrops that located in zone 2, 3, and 5 (outcrops 1–14; 18– 20; 28–37; 41–43 and 57). The main characteristic of the outcrop type 1is the outcrop consists of fewer numbers of the layer and has thicker layer than the outcrop type 2. The general layer configuration of outcrop type 1 can be seen in the sedimentary log which is described in Figure S5 below.

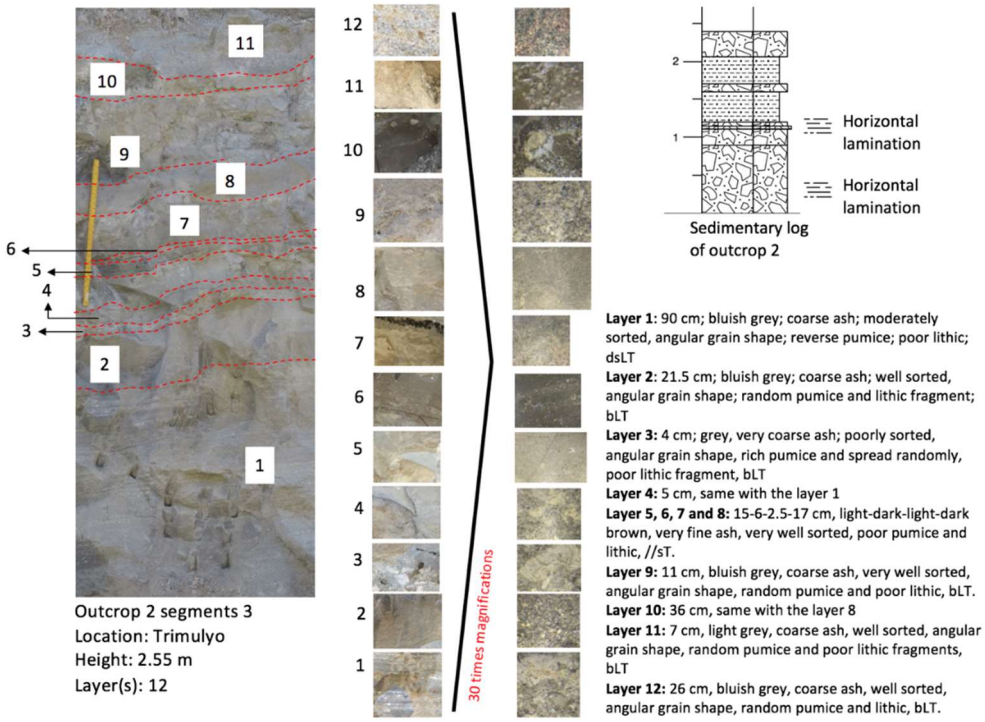

Figure S4. Layer configuration of outcrop 2 segments 3 (Trimulyo zone).

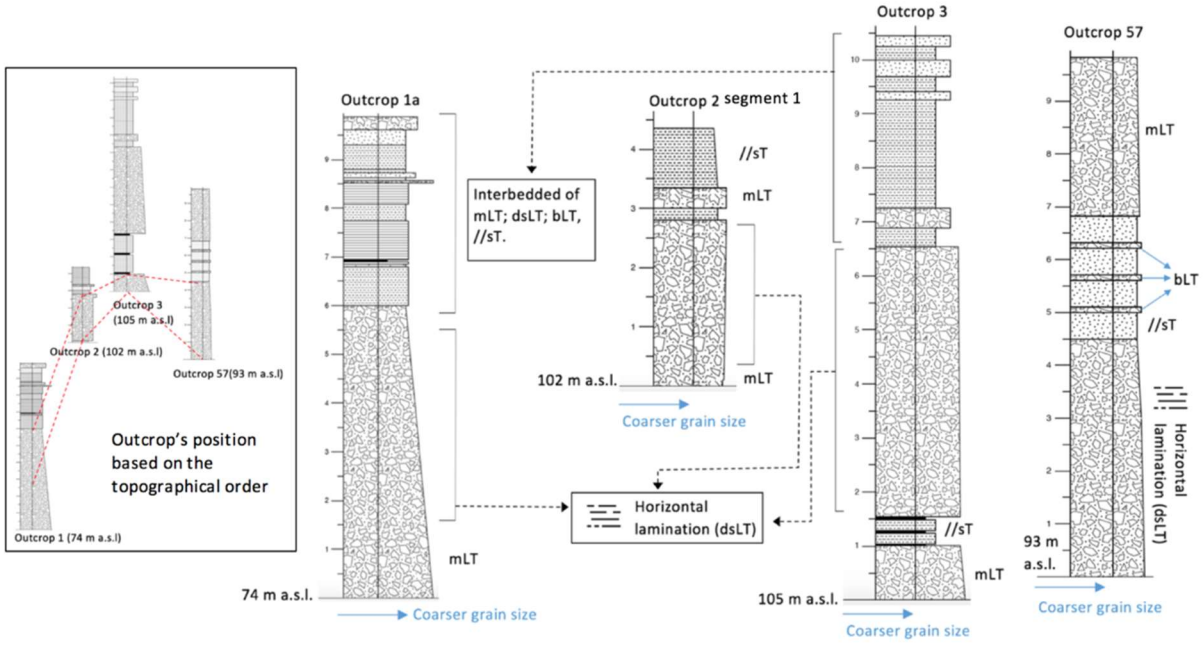

Figure S5. The general layer's configuration of the outcrop type 1 in study area

Geomorphologically, the outcrop 1a and 1b are located on the lower slope of denudation hill, the outcrop 57 is located on the middle slope of denudation hill, and outcrop 2, 3, and 11 are located on the upper slope of denudation hill. Based on the lithostratigraphic correlation between outcrop 1a, 1b, 2, 3, 11 and 57, it could be concluded that all outcrops in the zone 1 belong to one big sequence of the graded and stratified outcrop. This big outcrop is widely exposed in the lower, middle, and upper slopes due to the weathering, erosion and mining activities. The lower slope is well described with the outcrop 1a and 1b, the upper slope is well described with the outcrop 2, 3 and 11, while the middle slope is well described with the outcrop 57. Outcrop 2, 3 and 11 consists of interbedded layers between very fine tuff, coarse tuff, and the breccia pumice. The breccia pumice is deposited in the bottom of the layer of the outcrop 2 (102 m a.s.l.) and 3 (105 m a.s.l.), while in outcrop 11, a breccia pumice layer is absent. The upper layer of the outcrop 2 consists of interbedded volcanic mudstone (fine tuff), volcanic sandstone (coarse tuff) and the thin layer of breccia pumice. The bottom layer is dominated by approximately 2.5 m of the pyroclastic surge. The outcrop 3 also has the similar order of layer to outcrop 2, which consists of interbedded pyroclastic surge material, volcanic sandstone, and mudstone. The bottom pyroclastic deposits of breccia pumice on this outcrop is thinner than the bottom layer of outcrop 2. It signifies that the bottom layer of both outcrop 2 and 3 are typically pyroclastic surge deposits. This deposit is composed a low concentration of volcanic particles and gas which occur over topography and thicken in valleys (Nichols, 2009). The outcrop 11 is a small outcrop which was exposed naturally due to the erosion. The lithostratigraphic in this outcrop is closely associated with the middle layer of outcrop 3. The outcrop 11 consists only dacite tuff (very coarse tuff) and on the top of that is covered by volcanic mudstone. The outcrop 57 is located 360 m the south part of the outcrops 2.3 and 11. Same with other outcrops, the outcrop 57 is dominated by breccia pumice. In the bottom and upper layer, this outcrop consists of pyroclastic surge deposits, while the middle layer consists of the tuff deposits (Figure 22 in main text). The outcrop 57 can be divided into six segments. The last segment of this outcrop is the shortest outcrop in this zone. This outcrop is a residual segment of mining process in this area (Figure S6A). This segment has the same layer configuration with the other segments (Figure S6B,C). In general, the outcrop 57 segment 6 consists of 6 layers with 3.2 m of average height. The most bottom layer is the bluish colour deposit with the coarse ash grain size (0.0625–2 mm). This layer has 125 m of thickness and angular moderately sorted of grain fragment. It also has the normal grading of pumice and random lithic fragments. This deposit is closely related to pyroclastic surge with the dsLT lithofacies. The bigger fragment of lithic and pumice is also found in the layer 2. It also has coarse ash grain size with angular moderately sorted and rich in pumice and lithic fragment that randomly spread along this layer. On the top of that the repetition of dsLT on layer 2 was found in the layer 3 and 5 (Figure S6). The upper layer of this outcrop's segment consists of a massive (1 m) light brown, very fine (< 0.0625) grain size with very well sorted grain condition. This layer has the same characteristic with the middle layer of the opposite outcrop (east outcrop) (Figure S6B,C).

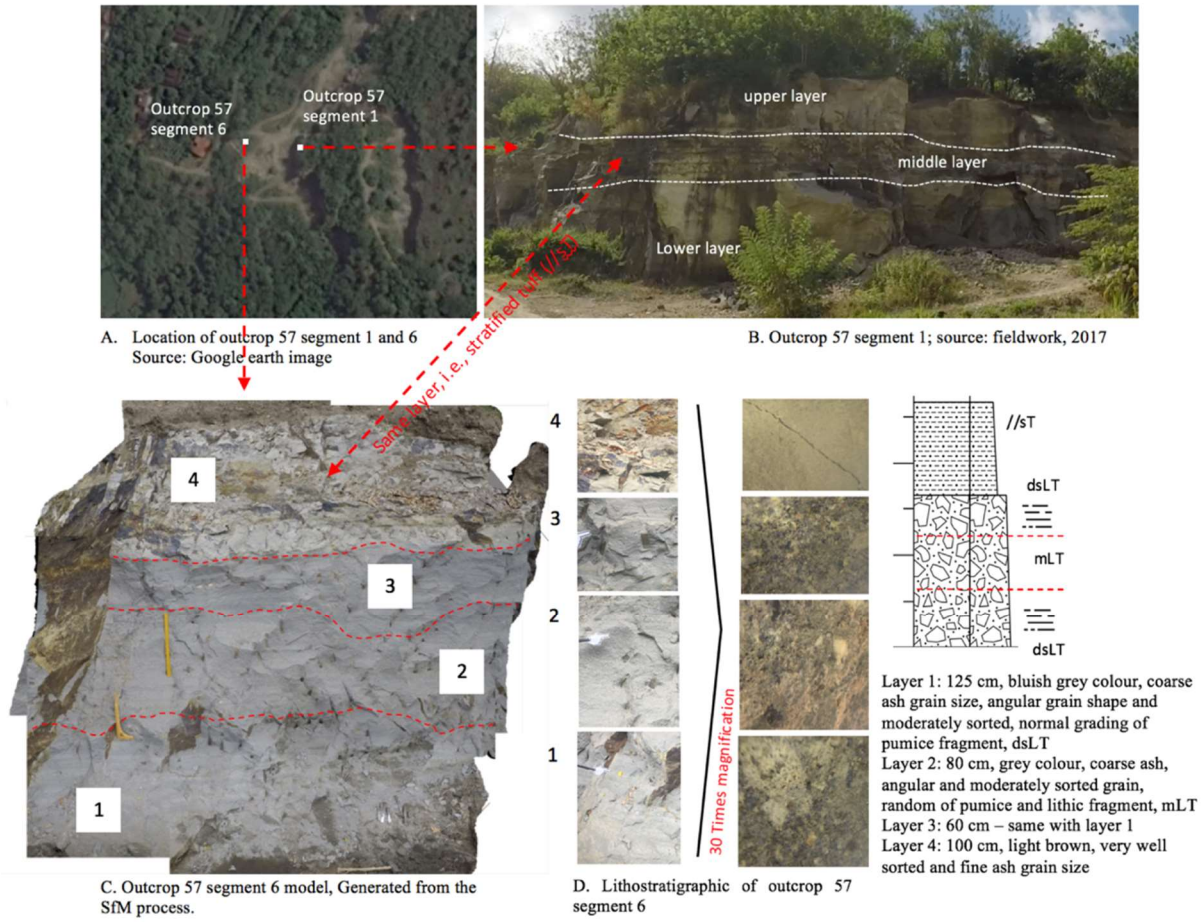

Figure S6. (**A**) The location of the outcrop 57 segment 1 and segment 6; (**B**) The photograph of outcrop 57 segment 1, (**C**) The surface model of outcrop 57 segment 6; (**D**) The lithostratigraphic of outcrop 57 segment 6.

Part 3. The characteristics of outcrop type 2.

The example of outcrop type 2 is outcrop 15, 24, 54, and 56. The outcrop 15 is located behind the Dengkeng Market. This area was the traditional mining area of breccia pumice in the southern part of Pleret Sub District. The outcrop dimension is quite big. It is approximately 163 m wide and 4 m of height. The outcrop 15 was divided into four segments of analysis namely segment 1, 2, 3, and 4. In general, this outcrop consists of multiple thin layers of interbedded mLT, dsLT, bLT and //sT. For example, outcrop 15 segment 1. This outcrop has a total of 32 layers, which consists of interbedded fine-grained (>0.0625 mm) dark tuff (//sT) and thin-bedded lapilli tuff (bLT) with coarse ash grain size (0.0625-2 mm). The bLT layers on this outcrop are dominated by the pumice-rich bLT deposits. The diffuse-stratified lapilli tuff that was found in the outcrop type 1, also can be found on the lower and upper layer of the outcrop 15 segment 1. However, the thickness of the dsLT layer in outcrop type 2 is much thinner than outcrop type 1. In the outcrop 15, the lower dsLT only has approximately thickness of 50 cm and 10 cm on the upper layer. The thin-bedded lapilli tuff with poor pumice fragment (bLT poor pumice) was also found on the upper layer of this outcrops. Additionally, the thin clay layer was also found in this outcrop. It indicates that outcrop 15 and surrounding areas were closely related to water depositional process and environment. However, there is still not enough evidence to conclude so. Therefore, a further investigation needs to be done to investigate the possibility of the ancient lake, pound, or river located surrounding this area.

The other big outcrops of type 2 are outcrop 24. This outcrop is located in the north part of research area near the Piyungan landfill. It has two big segments of outcrops with the average dimension of 11.80 m of height and 31.45 m width. Same with the other outcrops of type 2, outcrop 24 consists of 29

thin layers of interbedded mLT, dsLT, bLT and //sT. The lower layers are dominated by massive lapilli tuff (mLT) poor pumice which has fine ash grain size. The coarse-grained and rich pumice mLT can be found in the middle and upper layers of this outcrop. The tuff deposits (//sT) were found almost on every layer's alteration. Similar to the other outcrop type 2, the tuff deposits on the outcrop 24 has characteristic as a dark colour of tuff deposit, fine to very fine ash grain size, breakable or lose material, and exist as a thin layer (maximum 0.5 m thickness) on this outcrop. The dsLT layer with diffuse horizontal lamination was also found in the middle layer of this outcrop. Additionally, the thin-bedded of lapilli tuff layers with rich of pumice and has a coarse ash grain size were found in the middle and upper layer of this outcrop.

The outcrop 54 is also categorised as outcrop type 2. It has multi-layered thin deposits, which comprises of interbedded //sT, mLT, bLT, and dsLT. This outcrop has a dimension of 6 m height and 50 m width which consists of 19 layers. The outcrop 54 is located on the upper slope of Bawuran Hill in the middle of the study area. The lower layer of this outcrop is the fine grained, thin layer (9 cm) of tuff deposit (//sT). The thin layer of massive lapilli tuff (15 cm) which has coarse ash grain size was deposited on the top of that. The diffuse-stratified lapilli tuff (dsLT) with 16 cm of thickness has found lower part of this outcrop, above the interbedded layer of //sT and mLT. The dsLT layer of this outcrop has the same characteristic with the other dsLT layers of the outcrop type 1. It has coarse ash grain size, dark grey colour as a dominant colour, and several white thin layers as a horizontal lamination. The very fine white lapilli layer was also founded in the upper layer of this outcrop. The existing of lapilli layer in this outcrop indicates that there was an eruption with a big pyroclastic column which caused a pyroclastic flow and followed by a direct fall out of lapilli deposits [42].

The outcrop 56 is the northern outcrop which was founded in the study area. This outcrop is located in the Banyakan Village, the border area between Pleret Sub-District and Piyunagan Sub-District. Based on the geology map of Yogyakarta, this outcrop is still categorised as the Semilir outcrop which consists of ignimbrite deposits. Based on the lithofacies characteristics, this outcrop can be categorised as the outcrop type 2. It consists of interbedded layers between mLT, //sT, and dsLT. The outcrop 56 consists of 5 layers with the average outcrop's high of 6 m and the segment's length of 45 m. This outcrop is situated in the flat area of upper slope. It belongs to fresh outcrop, which is found in the construction site of the new settlement area. In general, this outcrop has a light bluish colour of the lower layer and light yellowish colour of the middle and upper layers. The lower layer is a thin layer (40 cm) of massive lapilli tuff (mLT) with rich of larger pumice fragments. On top of that, a 1.3 m of the diffuse-stratified lapilli tuff (dsLT) layer was deposited and followed by the small thin layer (25 cm) of tuff. The upper layers consist of the massive lapilli tuff which has a fine-grained grain size and poor pumice fragments. In this layer, we also found the direct fallout lapilli lithofacies evidence. A thick lapilli layer with the average thickness of 1.25 m was founded in this layer. The lapilli in this outcrop has the same characteristics with the lapilli layer in the outcrop 54. Therefore, it is maybe from the same source and eruption period. The characteristics of the outcrops type 2 and their layer configuration (outcrop 15, 24, 54 and 57) can be seen in the Figure S7.

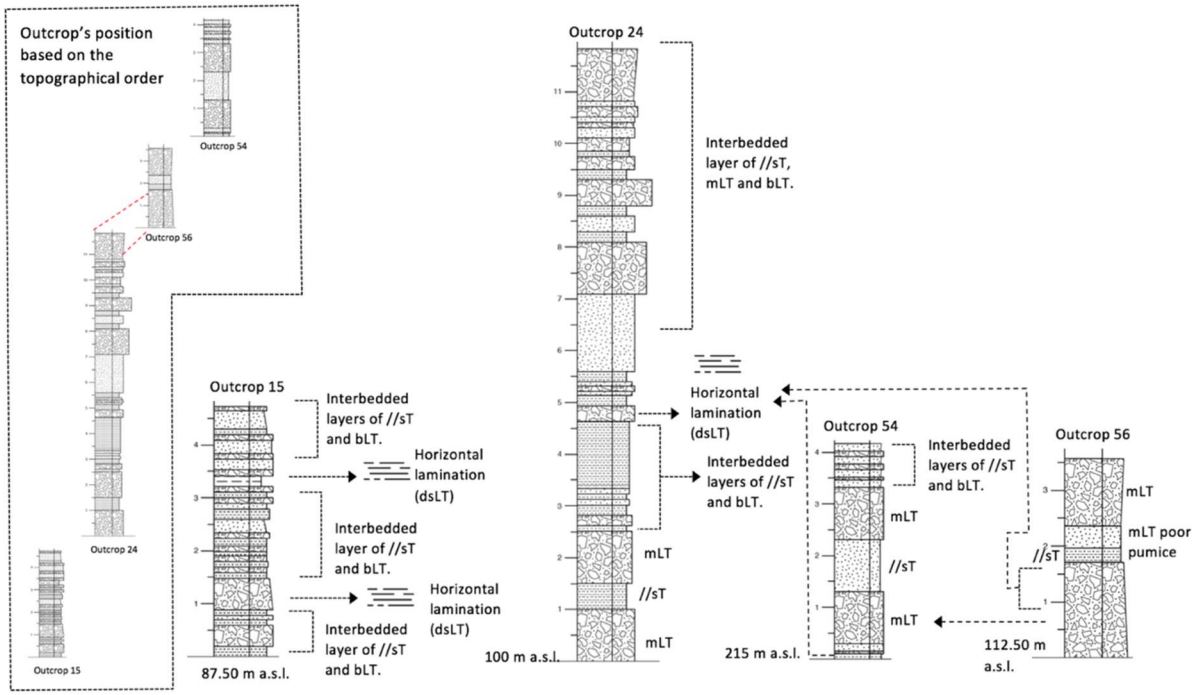

Figure S7. The general layer's configuration of the outcrop type 2 in study area.

Part 4. The characteristics of outcrop type 3.

Most of the outcrops type 3 are spatially distributed in the east part of the study area (on the top Baturagung Escarpment). However, some outcrops have the same characteristic with the outcrop 49 and 50 such as Gunung Gelap outcrops. These outcrops (Gunung Gelap, outcrop 49, and outcrop 50) have the transition characteristic of Semilir and Nglanggran Formation which indicates the existence of Opak Fault in the study area. The Gunung Gelap outcrop has three layers with the average height of 3.5 m. The bottom layer is well sorted angular mLT with 60 cm of thickness and has random pumice fragment with the coarse ash grain size. On the top of that, a 91 cm of dsLT was deposited. This layer has coarse ash grain size, well sorted-angular grain, and random pumice fragment. Both of these layers belong to Semilir Formation. On the top layer, the mlBr was deposited with the average thickness of 2 m. This layer has bigger and angular grain shape of breccia fragment (Figure S8).

The similarity of the lithological characteristic between the outcrop B, C, D (Figure S8) and the outcrops located on the summit of Baturagung Escarpment, indicate that these outcrops were originated from the same source. Based on the physical characteristics, these outcrops belong to the Nglanggran Formation. These outcrops consist of volcanic breccia, lava flow containing breccia, agglomerate rock, and tuff. The Nglanggran Formation has formed in the middle Miocene epoch or approximately 15.97-11.61 million years ago (Ma) [1]. Now, the Gunung Gelap have detached 3.5 km from the main Nglanggran Formation that located on the summit of Baturagung Escarpment. They also have a distinct difference in elevation. The highest point of elevation in Gunung Gelap is 100 m above sea level, while the highest point of Baturagung summit is 375 m above sea level (Fig 4A (A)). This fact proves that the Opak fault located between Gunung Gelap and Baturagung Escarpment is a normal fault. The east block is moving upward, and the west block is moving downward. Based on the planimetric distance, sloping distance, the difference of elevation and when it formed, the rough calculation of the average fault displacement of the Opak Fault can be calculated. Based on the calculation we know that the average fault movement is 0.022 cm per year. However, this calculation only used the simple method. Further analysis needs to be conducted to know the exact of average fault displacement.

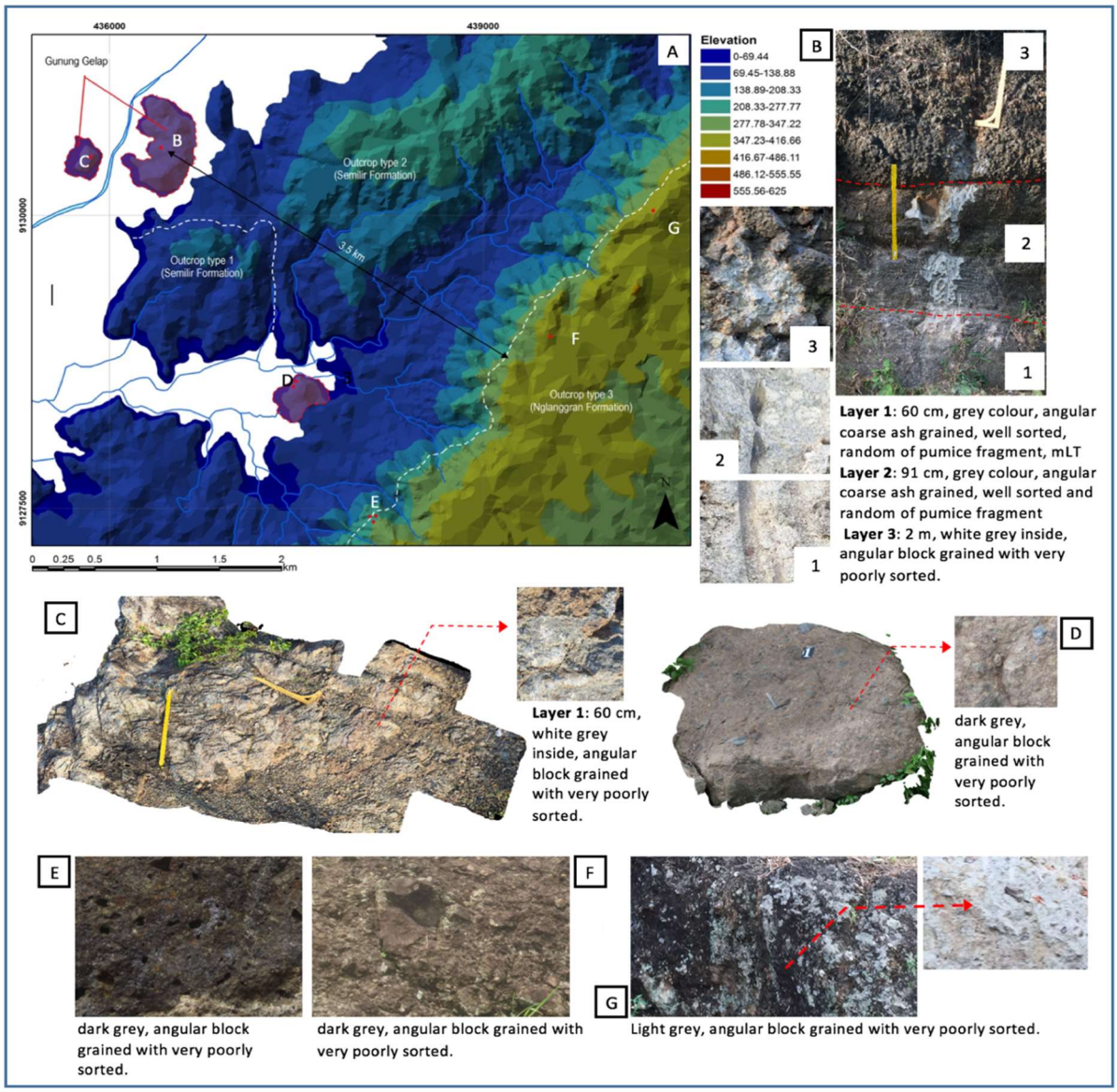

Figure S8. (**A**) The location of Gunung Gelap and Baturagung Escarpment; (**B**) The Gunung Gelap outcrop B West side of Opak River; (**C**) The Gunung Gelap outcrop C west side of Opak River; (**D**) The outcrop 38 (Wonolelo); (**E**) The outcrop 49 and 50 (Upper slope of Baturagung Escarpment; (**F**) The outcrop 46 (Dligo); (**G**) The outcrop near the Becici summit.

Part 5. The Tentative of Polygonal Micro-fault in Study Area.

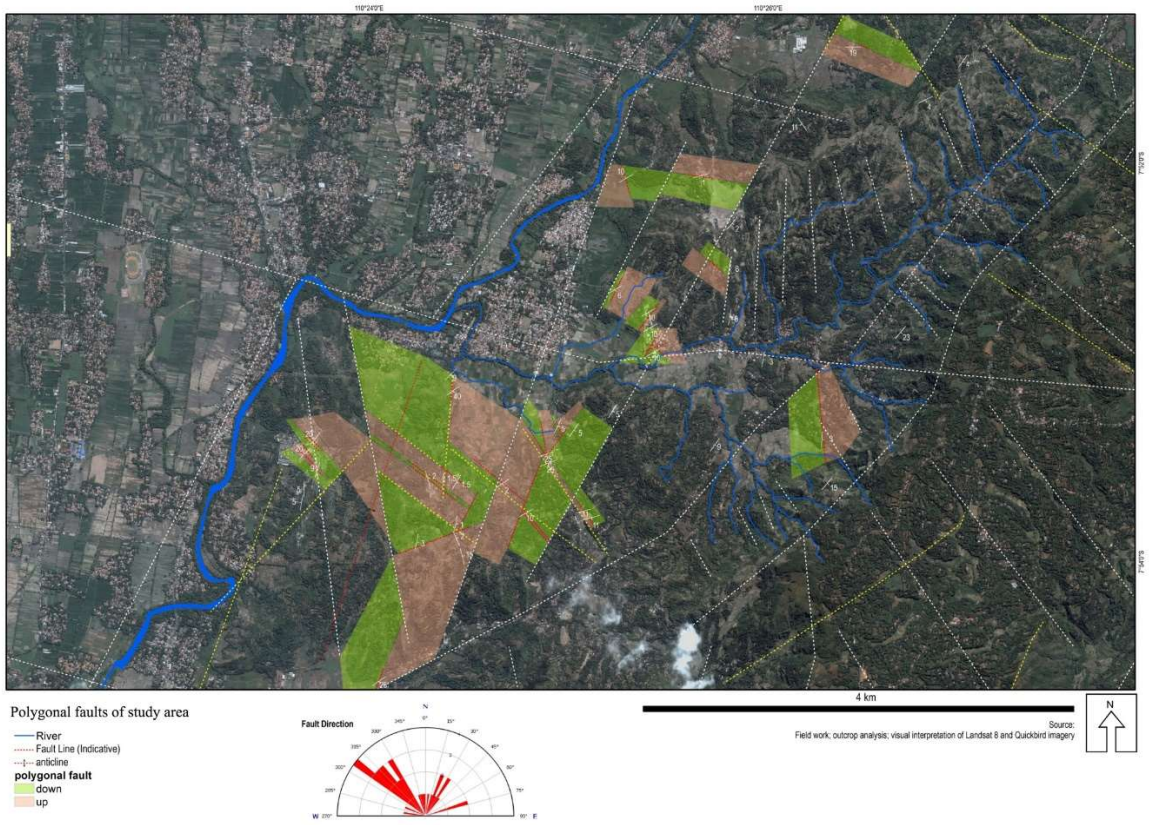

Figure S9. The Tentative of Polygonal Micro-fault in Study Area.

1. Lewis, A.; Marchant, D.; Ashworth, A.: Hemming, S.; Machlus, M.L. Major Middle Miocene Global Climate Change: Evidence from East Antarctica and the Transantarctic Mountains. *Geol. Soc. Am. Bull.* **2007**, *119*, 1449–1461.