Mineralogical, Elemental, and Spatial Variability of Volcaniclastics in Fluvio-Coastal-Aeolian Sedimentary Systems and Their Insights for Mineral Sorting on Mars

Ignatius Argadestya, Abduljamiu O. Amao, Candice C. Bedford, Pantelis Soupios, and Khalid Al-Ramadan

Abstract This study investigates the mineralogical, elemental, and spatial variability from source (proximal) to sink (distal) of Merapi basalt-andesitic stratovolcano (Java, Indonesia) to better constrain volcaniclastic mineral sorting in fluvial, aeolian, and coastal environments. Merapi volcaniclastics are products of an active volcano with an ongoing quadrennial eruption, which can provide insights to constrain Mars’ older and more recent volcanics by focusing on anorthite, albite, and pyroxenes found on Mars’ surface. We collected stream sediment samples across the Opak River that connects Merapi with the Indian Ocean. In addition to grain size analysis, all collected samples were subjected to X-ray diffractometer and X-ray fluorescence to quantify their mineralogical and elemental composition, respectively, like the CHEMIN instrument used by the Curiosity rover on Mars to investigate the geochemistry and mineralogy of geological units in Gale crater. Implementation of multivariate statistical analysis based on principal component analysis and Hierarchical Clustering of Principal Component are able to discriminate between fluvial, fluvio-coastal-aeolian, and marine influenced deposits. The quantitative assessment shows that the dominant mineralogy is influenced by pyroclastic materials dominated by plagioclase feldspars (albite and anorthite), followed by pyroxenes (augite and enstatite). Alteration modeling of Merapi samples favors a fluvial depositional environment rather than mass-wasting from the crater rim for Gale crater rocks (i.e., Pahrump Hills, Hartmann’s Valley, Karasburg, Sutton Island member) on Mars.

Plain Language Summary This research provides a detailed characterization of stream samples and surface deposits from the Opak River, the Parangkusumo Shoreface, and parabolic coastal sand dunes from an active Merapi stratovolcano (Java, Indonesia) transported from the source toward the sink. The paper aims to constrain pyroclastic mineral sorting from a basaltic to basalt-andesitic volcanic origin throughout fluvial, coastal, and wind-driven (aeolian) environments. We use similar methods as the MSL (Mars Science Laboratory) Team to investigate mineral sorting of volcaniclastic sediments in Gale Crater, specifically using X-Ray spectroscopy collected by CheMin. The results of our research suggest that mineralogical sorting occurs throughout the depositional subenvironments, and they are related to the geomorphology of the river. Furthermore, the aeolian environment provides an additional sorting mechanism for the sand grains deposited in the shoreface. We also discovered a similar weathering trend of Merapi volcanic sediments with the findings from Stimson and Murray formation in Gale Crater, which supports their origin as sediment transported by the river during the wet phase of Mars.

1. Introduction

Volcaniclastic dunes of reworked igneous materials are relatively less abundant on Earth as they require volcanic deposits to source the sand dunes. Java Island in Indonesia offers a natural laboratory for volcaniclastic sedimentary systems thanks to abundant active volcanoes formed within the island, offering observable volcaniclastic materials deposition from source (proximal) to sink (distal) area. We select Merapi stratovolcano for its basaltic to basalt-andesitic pyroclastic materials (Andreasutti et al., 2000; Berthommiere & Camus, 1991; Camus et al., 2000; Charbonnier & Gertisser, 2008; Lorenz, 1974; Surono et al., 2012; Voight et al., 2000), with similar mineralogy dominated by feldspar and pyroxene of reworked igneous origin as identified at Gale Crater (Bedford et al., 2020; Ehlmann et al., 2017; Payré et al., 2020; Rampe et al., 2018, 2020; Schmidt et al., 2014; Siebach et al., 2017;
Treiman et al., 2016) and Gusev Crater’s Home Plate on Mars (Squyres et al., 2007). Previous studies of Merapi pyroclastics' mineralogical and elemental composition previously stated are focused on the proximal setting, which leaves a gap in understanding how these deposits accumulate along their respective environments that eventually source the volcaniclastic dunes at the distal area. This study will fill the gap by investigating Merapi pyroclastics (proximal), Opak River channel bar deposits (medial-distal), Opak Estuary, Parangkusumo Shoreface, and the parabolic coastal sand dune (distal).

Whereas in situ studies provide ground truth in a few specific locations, orbiter-based spectral images allow for assessing mineralogical sorting over full transport pathways (Pan & Deanne Rogers, 2017; Stockstill-Cahill et al., 2008; Rogers and Bandfield, 2009). For example, datasets from THEMIS (Thermal Emission Imaging System) and TES (Thermal Emission Spectrometer) demonstrate that the Gale crater is abundant with plagioclase feldspar, pyroxene, olivine, high-silica, and sulfate minerals (Rogers and Bandfield, 2009). Furthermore, the THEMIS data set also reveals that olivine abundance will cause an increasing particle size in Martian dune fields (Pan & Deanne Rogers, 2017). Another region analyzed by THEMIS and TES called Amazonis Planitia in Mars shows that the spatial distribution of mineralogical variations is influenced by aeolian erosion from local intra-crater basaltic materials (Stockstill-Cahill et al., 2008). It is worth noting that the result from Amazonis Planitia was derived from low-albedo interpretation and is susceptible to dust obscuration (Stockstill-Cahill et al., 2008). The susceptibility from atmospheric and orbital-scale noise requires a ground-truth observation, as demonstrated by a combination of orbital spectrometry and in situ study from the Bagnold dune (Laporte et al., 2017), showing that differences in the dune's mineralogical variation may indicate aeolian sorting and mixing of several sand provenances (Laporte et al., 2017).

Merapi and its depositional environments represent an interaction between volcanic, fluvial, coastal, and aeolian sedimentary systems. Very few have looked into how volcaniclastic materials from more evolved volcanism and explosive volcanism is incorporated into these systems, despite its increasing evidence in the Mars geological record. Similar depositional environments were detected on Mars on which Merapi volcano can provide valuable insights, such as: (a) Pyroclastic flow deposits (Brož & Hauber, 2012) identified at Tyrrhena Patera (Gregg & Farley, 2006) and Home Plate, Gusev Crater (Squyres et al., 2007). (b) Fluvial and aeolian sediments on Mars (Carr, 2012; Fassett & Head, 2005; Greeley et al., 1992; Grotzinger et al., 2005; Laporte & Rampe, 2018; Payré et al., 2020; Schmidt et al., 2014). (c) The initiation of fluvial valleys on martian volcano (Alemanno, 2018; Gulick & Baker, 1990), and the missing link between fluvial and aeolian sediments of transported reworked igneous provenance in building up volcaniclastic dunes (Hooper et al., 2012). (d) A possible Northwestern lowlands paleo-coastline (Carr & Head, 2003). (e) Mineral sorting on Mars sedimentary systems, such as the provenance study of Bradbury Group (Bedford et al., 2019; Siebach et al., 2017), and Murray formation (Mangold et al., 2019) and Stimson formation, Gale Crater (Bedford et al., 2020; Rampe et al., 2020). These previous studies provide the basis of our semi-quantitative assessment to target specific minerals and element abundances from source to sink of Merapi volcaniclastic sedimentary systems, to better understand the Martian volcaniclastic settings.

Mount Merapi is an active stratovolcano formed as a result of the Java subduction zone where the Indo-Australian Plate is subducting under the Sunda Plate at a convergence rate of 6.7 cm/year (Kopp et al., 2006). Merapi volcanic eruptions are quadrennial, typically recurring every 4–6 years in their current state (Andreastuti et al., 2000; Surono et al., 2012; Voight et al., 2000). Volcaniclastic materials with a high amount of basaltic-andesite tephra, pyroclastic flow, viscous andesitic lava, and lahar are recorded as the main products of its eruption in the source (proximal) and eventually flows in SE direction from proximal to medial (0 to 20 km), and eventually in SW direction during medial to distal (20 to 45 km), shown in Figure 1a. Merapi’s modern eruption material is recorded with lithological unit Qmi throughout the study area (Figure 1b). Opak River forms Opak Estuary before discharging into the Indian Ocean (Figure 2a). The NE-SW motion of Opak River's discharge creates a tidal inlet (Figure 2b) within the washover barrier sand (Figure 2c). Sediments deposited on the estuary are transported further by the longshore current across Parangkusumo Shoreface, which supplied the backshore's parabolic sand dunes (Ray et al., 2005). These dunes are situated 300 m northward from the foreshore, with heights reaching up to 6–7 m (Figure 2d), and their lee side is dominated by vegetation in form of shrubs. We select one dune in this research since it is the only publicly available to conduct our work. Despite the limitation, the parabolic sand dune that we select is...
Figure 1. Geologic map featuring sampling locations from source to sink environments of Merapi—Opak River (a). Lithological units are based on Rahardjo et al. (1995) (b). Notice the latest deposition of young volcanic deposits (Qmi) overlying older volcanic deposits (Qmo) and tertiary sediments. The lava dome and avalanche deposits (d and na) are present in situ only on the proximal area of Merapi volcano.
representative as other dunes are similar in their overall geometry (e.g., their arc concaving against the prevailing NW wind, dark to light gray-colored sand, and shrubs on their lee-side) (Figure 2d).

Mars possesses a diverse sedimentary record indicating that rivers, lakes, glaciers, and potentially oceans existed in the past before its climate transitioned to the dry and aeolian-dominated sedimentary environments of today (Alemanno, 2018; Carr, 2012; Edgett & Lancaster, 1993; Fassett & Head, 2005; Greeley et al., 1992; Grotzinger et al., 2005, 2014; Hooper et al., 2012; Schmidt et al., 2014; Squyres et al., 2007). In particular, Mars' sedimentary
units deposited in fluviolacustrine settings have been targeted for in situ investigations with rover and lander spacecraft such as the NASA Mars 2020 Perseverance rover (Jezero crater, 2021) and the NASA Curiosity rover (Gale crater, 2012). To date, most Mars-like Earth mineralogical studies focus on basaltic environments (Table 1), but with the results from the Curiosity rover, it suggests that the Mars analog literature should be expanded to include evolved igneous provenances (Bedford et al., 2019; McSween et al., 2009; Sautter et al., 2015, 2016; Schmidt et al., 2014; Siebach et al., 2017; Treiman et al., 2016). Regardless, most Gale crater sediments contain high quantity of feldspar, with varying abundances of pyroxene (Rampe et al., 2020). As such, we will focus on the sorting of these minerals in the fluvial and aeolian sedimentary environments on Merapi and discuss their implications for sorting in Mars sedimentary systems.

2. Methodology

This research investigates the interaction between volcanic eruption, pyroclastic flow, and fluvial-coastal-aeolian systems through geological field observation, followed by geophysical, geochemical, and multivariate statistical analysis to interpret the mineralogical and elemental compositions along with their depositional environments.

2.1. Precursor Studies of Merapi Volcaniclastics

X-Ray diffraction analysis by Aini et al. (2019) had shown Merapi's plagioclase to bear 44% anorthite and 54% albite. Atomic Absorption Spectroscopy (AAS) measurements by Wahyuni et al. (2012) revealed Merapi's volcanic ash composition of SiO₂:Al₂O₃:CaO as 53:19:9 in distributive percentage, strengthening the calc-alkaline basalt-andesitic nature of Merapi volcaniclastics (Camus et al., 2000). Similarly, Wahyuni et al. (2012) included Inductively Coupled Plasma Mass Spectrometry (ICP-MS) to determine the minor elemental composition of the volcanic ash. These two combined methodologies of AAS and ICP-MS had recorded major elemental compositions (Al, Si, Ca, and Fe) and minor elemental compositions (K, Mg, Mn, Na, P, S, and Ti) (Wahyuni et al., 2012). Our hand specimen provenance rock samples show that anorthite and albite are dominating the proximal mineralogical assemblage with average abundances of 35% and 32%, respectively, and pyroxenes of augite (12%) and enstatite (18%) to follow. The difference of our finding with precursor research aforementioned might be influenced by sampling time difference of Merapi eruption, and the materials which the precursor research were sampled (volcanic ash) instead of pyroclastic ejectas like our research. More importantly, our research is the first to track the grain, mineralogical, and elemental distribution of Merapi volcaniclastics from source to sink across the Opak River as its sedimentary pathway.

2.2. Sampling and Processing

Stream sediment sampling follows the USGS field method for fluvial sediment measurement (Edwards & Glysson, 1999), with select sampling locations chosen according to the type of bars present (Figure 3a). Stream sediment samples were collected by scooping the top surface deposit regardless of their grain size, then stored in a 100 ml airtight vial. Sampling locations were plotted with elevation and distance from source to sink (Figure 3b). The samples were then dried in a vacuum oven at a temperature of 60°C for 24 hr to remove any fluids (water and brine). Details for each collected sample are presented in Table 2. We also acquired 2 GPR profiles along the
transect of the shoreface and parabolic dune, particularly to observe the internal structure of these sedimentary depositional environments (Figure S1 in Supporting Information S1).

To separate the grain size distribution, 25 g aliquots of each sample were sieved with a rotary shaker for 10 min. Six sieving racks stacked with phi number ($\phi$) ranging from 0 to +4 represent very coarse—very fine sand, whereas +5 and $\phi$ > 6 represent coarse—medium and medium—fine silt. We estimated the average grain size by multiplying the result from sieve analysis (Figure 5) with the grain size category (phi number), which will give a function of grain size relative to each sample net weight percentage. Bulk samples for XRD and XRF were pulverized prior to analyses using a rock crusher machine for 15 min. The bulk mineral abundance was identified with XRD (Panalytical Empyrean X-Ray Diffractometer) through two measurements performed per sample, and the results were tabulated as averages, calculated according to the average value for each peak in the spectrum (Table 2). To determine the abundance of major and trace elements, samples were first pulverized into powder, loaded into special cups and then analyzed on a MicroXRF setup (BRUKER M4 Tornado), equipped with a polycapillary optic (~20-μm spot-size) and a micro-focused rhodium source operated at 50 kV and 600 μA. The system employs two silicon-drift detectors to collect fluorescence spectra from the specimen under vacuum (20 mbar). Elemental spectra for individual atomic species were generated using the proprietary M4 software package. To ensure repeatability and data robustness, the entire sample surfaces were scanned with an X-ray beam capable of penetrating up to ~2 mm into the sample from the surface. Each sample was scanned in triplicate to ensure

**Figure 3.** Sampling methodology according to their channel bar type (a). The sampling locations are plotted with elevation and distance from source to sink (b). Notice the contrast of slope gradient between proximal – medial (S1–S5) compared to medial—distal (S6–S12). Slope angle is measured based on sampling location's plotted altitude versus distance.
the results are reproducible and after which the mean values were taken. In addition, the MicroXRF instrument is calibrated based on NIST 620 soda-lime glass reference material. Major and minor elemental concentration were also validated against the following certified reference materials (LGC 2700, CGL 002, SRM 41, CGL 010) before the commencement of analysis. Instrument stability and accuracy are well documented (Kaufhold et al., 2016; Raschke et al., 2013; Rodriguez et al., 2005). The principle of position-tagged spectroscopy guides the elemental distribution mapping of the samples. Data obtained were stored in a three-dimensional data cube (X-Y-Z), where X and Y represent coordinates and Z, the fluorescence spectrum of each pixel. This allows for later retrieval and post-processing of various 2D rendering combinations of elements in defined regions of interest.
2.3. Statistical Analysis and Chemical Alteration Modeling

We selected hand specimen samples (Table 2) as host rocks and calculated their average pyroxene/plagioclase feldspar ratio (Px/PF) as a cut-off value to determine the mineralogical sorting against their depositional environment. We combined the average grain size value with the Px/PF ratio to identify the relationship between mineral sorting against the grain size and its subsequent depositional distance. Subsequently, we discriminated the stream sediment samples as before and after the fault in order to understand the significance of the Opak River in altering the mineralogical and grain size sorting. We calculated the average Px/PF ratio of parabolic sand dunes and compare it with Px/PF ratio of modern aeolian on Mars (both inactive Rocknest dune and active Gobabeb and Ogunquit Beach dunes) and ancient (Stimson formation’s Big Sky, Okoruso, Greenhorn, and Lubango in Gale Crater) aeolian deposits on Mars. The pyroxene of Stimson formation on Mars was summed values from pigeonite and orthopyroxene (Rampe et al., 2020). We calculated the Chemical Index of Alteration (CIA, in molar proportions) based on the measured oxides from the XRF. We converted the wt% into molar by dividing the weight percent by molecular weight (Goldberg & Humayun, 2010). We used the CIA ratio (Nesbitt & Young, 1982) defined as follows: CIA = (Al₂O₃/Al₂O₃ + CaO* + Na₂O + K₂O) × 100 whereas the CaO is derived from silicates’ Ca content. We compiled the molar values from our findings to plot A-CN-K ternary diagram along with findings from Gale Crater (Mangold et al., 2019), Stimson formation (Bedford et al., 2020), Eldborgir lava field (Mangold et al., 2011) and Mars’ crust (Taylor & McLennan, 2009). The wt% and molar conversion of our data are available in Supporting Information S1.

In order to reduce the relative effects of variables measured on different instruments, scales and ranges, the data-sets we obtained from XRD and XRF were all scaled and centered; that is, by subtracting each variable's mean from its individual score and then dividing by the variable's standard deviation. This linear transformation does not alter the correlations among the variables, and it is often recommended (Hussain et al., 2018). We employed two multivariate statistical techniques to find patterns in our high dimensional data set and establish relationships. First, we implemented Principal Component Analysis (PCA), using the singular value decomposition method. Second, we used Hierarchical Clustering of Principal Components (HCPC) based on Ward's method of agglomeration and Euclidean distance on our standardized data set that contains 32 stations and 21 variables (i.e., XRD and XRF data set). All analyses were conducted with the R statistical software v.4.3 (R Core Team, 2018) with the following packages: FactoMineR (Lê et al., 2008), factoextra (Kassambara & Mundt, 2016), FactoInvestigate (Thaleau & Husson, 2020), corrplot (Wei & Simko, 2017), Factoshiny (Vaissie et al., 2017), PerformanceAnalytics (Peterson et al., 2014), and tidyverse (Wickham et al., 2019).

3. Results

Beginning with the larger scale of geological observations, we will describe our findings in a sequence of grain size distributions, mineralogical and elemental compositions, and multivariate statistical analysis.

3.1. Field Investigations From Merapi Sedimentary Systems

Field data collection and measurements along the transect of Opak River from source to sink show reworked volcanioclastics from Merapi eruptions are transported by Opak River and deposited in channel-side bars within the proximal and medial sites, and a mid-channel bar before eventually accumulate as estuary deposits in the distal part (Figure 4). The shifting of Opak River trajectory from SE to SW during the medial stage is influenced by the presence of Opak Fault, where the river follows the normal fault's axis (Figure 1a). Slope angle also affects Opak River's depositional environment (Figure 4b) which shows a contrast between (a) proximal—medial steep slope angle (8.27°, 14.54%, bearing N 169.5°E) and a gentler slope of (b) medial—distal (0.32°, 0.52%, bearing N 219°E) based on the sampling plot against distance and elevation from field investigation (Figure 3b). A mid-channel bar is present in the distal site of Opak River, 5 km NE of the Opak Estuary (Figure 5a). The mid-channel bar is non-migrating and elongated, parallel to the flow of Opak River. Trenching in the mid-channel bar shows a planar cross-bedding with stratified gravels embedded in the foresets (Figure 5c) on the lower part of the trench. In contrast, the upper part shows a good sorting, finer planar cross-stratification overlain by the imbrication of crudely bedded gravel (Figure 5b). The NE-SW motion of Opak River’s discharge creates a tidal inlet (Figure 2b) within the washover barrier sand (Figure 2c). Parabolic sand dunes are present approximately 3 km southeast of Opak Estuary. The NE wind flow pattern coming from the south creates a shallow,
dish-shaped depression at the stoss side of these parabolic dunes, further classified as a saucer-type blowout surface (Hesp, 1999, 2002).

3.2. Grain Size Distribution

Grain size distribution is plotted against the distance from source to sink and the depositional environment (Figure 4). The proximal site has the average coarsest grains of all sites, with 24%–40% of its grain size fraction consisting of very coarse to coarse sand combined. The sediment of S6A (located before Opak Fault) has 44% of its grain size fraction made of very coarse sand, while sediments accumulated after the fault are 28%–48% medium-sized sand. The distal part of Opak River follows post-fault medial sand trend, having 28%–44% of its grain size faction in medium-sized sand. The northward interface of Opak Estuary adjacent to the river has 36%–48% average grains consisting of medium sand, however, the southward interface adjacent to the Indian

Figure 4. Grain size distribution from source to sink with its associated environments. Notice the inclusion of geomorphological expression such as Opak Fault and Berm which affect the distribution of grain size, and the prevailing wind direction for sand dune samples.
Ocean has 28% of its average grain size consisting of medium to fine sand. Sample S12 A, a surface deposit on top of the estuary, has the coarsest grain of all samples collected from source to sink, with an average of 60% of its grain size fraction consisting of very coarse sand. A gradual trend of average grain size variability occurs in the Parangkusumo shoreface samples, where the foreshore has an average of 48% medium sand, and two backshore samples consist of 64% fine sand and 44% very fine sand. The aeolian deposits are characterized by medium sand with an average of 40%–56% of their grain size fractions across the blow-out surface, stoss, and lee. It is worth to note that despite sharing a similar average grain size across the bedforms, the aeolian samples have a linear decreasing trend of very coarse-to-coarse and very fine-to-silt sized grains parallel to the direction of prevailing wind, whereas their medium-sized grains are gradually increasing.

3.3. Geochemical and Multivariate Statistical Analysis

Five main minerals are identified in the Merapi sediments based on their signature peak patterns from XRD analysis (Figure 6a), which include anorthite (CaAl₂Si₂O₈), albite (NaAlSi₃O₈), augite ((Ca,Na)(Mg,Fe,Al,Ti)(Si,Al)₂O₆), enstatite (Mg₂Si₂O₆), and calcite (CaCO₃). The quantification of bulk mineralogical composition is tabulated as averages for each sample (Table 3). A plot of mineralogical content with depositional distance (Figure 6b) shows an uneven distribution across the sedimentary pathway. To provide clarity in discerning this relationship, we grouped the anorthite and albite as plagioclase feldspar (PF) and augite and enstatite as pyroxene (Px), similar to the Mars analog study in Iceland (Sara, 2017; Thorpe et al., 2019) and Gale Crater investigation (Lapotre et al., 2017; Rogers & Bandfield, 2009).

In spite of larger plagioclase abundances relative to pyroxenes throughout the transect (Figure 6b), we observed variability in the sorting of these mineralogical compositions throughout the sedimentary systems by plotting a ratio of Px/PF against the depositional distance (Figure 7), with host rock average Px/PF ratio of 0.43. We combined Px/PF ratio against depositional distance with average grain size (Figure 8a). In the proximal site, the dominant plagioclase feldspar sorting (Px/PF ratio of 0.31–0.38) consists of coarse-to-medium sand deposited in channel-side bars. Sample S3A is marked as it is the only proximal sample inclined toward pyroxene sorting, despite retaining similar average grain size with the remaining proximal samples. The lowest Px/PF ratio (0.31) of all samples belongs to the proximal-medial interface sample (S6A). The before fault medial site still follows the trend of plagioclase feldspar sorting from the proximal site. The after fault medial site shows a strong pyroxene sorting (Px/PF ratio of 0.45–0.70), with average grain size function of medium-to-very fine sand. We marked sample S8A as it is the only post-fault medial sample inclined toward plagioclase feldspar sorting, while having the lowest average grain size (very fine sand) of all measured samples. The estuary samples are dominant in pyroxene sorting (Px/PF ratio of 0.47–0.63), and their average grain size function are between coarse-to-fine sand, which included the coarsest grain of all measured sample (S12 A), a top surface deposit within the estuary's washover barrier sand (Figure 2e). The shoreline sediments clearly distinguished foreshore sample from the backshore further passing the berm as foreshore sample has medium sand compared to backshores' fine-to-very fine sand despite having similar pyroxene sorting (Px/PF ratio of 0.53–0.60). In the wind-driven environment, aeolian process shows that sorting occurred both in mineralogical and average grain size function, as the Px/PF ratio variability is accompanied with lesser concentration of coarse sand and more concentration of medium sand across the stoss (downwind) and lee (upwind) (Figure 5). The pyroxene sorting trend is shifting (Px/PF ratio of 0.56 to 0.44) in the lee and stoss to plagioclase feldspar sorting in the blowout surface (Px/PF ratio of 0.42). This
Figure 6. XRD pattern of all samples and the identified peaks for each mineral (a). Notice the distinct intensity represented by higher counts for sample S12 B. The mineralogical pattern peaks show 5 distinct minerals, which are albite, augite, enstatite, calcite, and anorthite. Plotting of mineralogical net percentage value in accordance with distance of sedimentation and the associated environments (b). Calcite is recorded to have the least amount of content, whereas albite and anorthite dominates the bulk mineralogical composition from proximal to distal.
study's modern aeolian dune has an average value of $P_x/P_F$ ratio of 0.47, whereas the modern aeolian on Mars’ Bagnold and Namib Dune are between 0.55 and 0.75 (Rampe et al., 2020). The ancient aeolian units of Stimson formation has a $P_x/P_F$ ratio are 0.29–0.70 (Figure 8b).

Plot of major elemental (Al, Si, Ca, Fe) and minor elemental compositions (K, Mg, Mn, Na, P, S, Ti; Figure 9a) are presented with distance and depositional environment. In addition, oxides are also identified through XRF analysis (Figure 9b). The influence of Opak fault is clearly seen between samples S6A and S7A, where prior to the interface of the fault (S6A), Fe and Fe$_2$O$_3$ are increasing. However, post-fault S7A shows a major decrease in those elemental and oxide abundance. Sample S12 B also distinguishes itself from the rest of the measured samples because of the most abundant Fe and Fe$_2$O$_3$. It is also noticeable that the abundance of trace element SO$_3$ (measured in ppm) is increasing from 600 ppm to the highest (2,000 ppm) at the point bar of sample S8A (Figure 9b), and completely absent in the mid-channel and further downstream.

A hierarchical clustering (Figure 10a) of mineralogical components based on XRD and XRF data reveals three distinctive clusters. A PCA plot is shown to elaborate the clustering of the analyzed samples (Figure 10b). Interpretation of this clustering is derived from bulk mineralogical and elemental plot against depositional distance. A total of 93.99% variability resemblance shown by PC-1 has established three clusters each with its own distinction, in particular sample S12 B (Cluster 1, Figure 10). This distinction is a result of sample S12 B having the lowest albite (7.15%) and enstatite (7%) but highest anorthite (59.05%) from all measured samples, in addition to the sudden peak of minor elements (e.g., manganese, phosphorus, and titanium) across the study area. The second cluster (red color) is characterized by positive axis coordinate for PC-1 (Figure 10b), sharing a narrow range of albite (22.5%–28.9%) and anorthite (35.5%–39%), has the highest amount of iron (S10 A and S11 B) and all are in distal part. The last cluster (gray color) has negative PC-1 axis value, characterized by a wide range of albite (24%–48.35%) and anorthite (26.8%–44.3%), distributed widely in proximal, medial, and distal areas.

Results from the CIA and A-CN-K ternary diagram (Figure 11) show that Merapi volcaniclastics are categorized within a low chemical alteration, having an average of 45 CIA value, with sample S6A notably having the highest CIA value of 58. Average CIA value from Gale crater (Mangold et al., 2019) and Stimson formation (Bedford et al., 2020) samples show a cluster (dashed red line) of CIA ~ 50–56 when overlain with Merapi volcaniclastic samples (dashed blue line), whereas Eldborgir lava field samples are clustered shown clustered in dashed black line.

### 4. Discussion

We focused the discussion toward mineralogical, elemental, and spatial variability within each depositional environment on Merapi volcaniclastics. We then provide some insights on Mars sedimentary systems’ hypotheses based on the findings of our study.

#### 4.1. Merapi Volcaniclastics From Source to Sink

Summary of Merapi sedimentary system from source to sink is presented in Table 4. In the proximal site, Opak River geomorphology is affected by the lahar-carved subsidiaries (Figure 1). The variability of fluvial depositional subenvironments along the Opak River is influenced by the sedimentary depositional subenvironment
of the river, where in the proximal part, the river retained a relatively more linear flow as a direct influence of the steep slope angle from Merapi. In the medial part, as the river runs along a much gentler slope, the river's sinuosity started to increase. Further downsystem the river geomorphology is able to form mid-channel bar. In the distal part, the river is substantially wider (Table 2) and deeper than its proximal and medial counterpart, which provides an accommodation space for the non-migratory mid-channel bar to form. The trenching in this mid-channel bar (Figure 5) shows that variability in the vertical succession suggests a cyclic mechanism from different episodes of fluvial hydrodynamic flow. Gravel inclusions can be attributed to high energy in an upper flow regime due to downstream ebb accumulation which can transport heavier grain, whereas the fine planar cross-stratification is influenced by a lower flow regime. The Parangkusumo Shoreface and the parabolic dune both shared similar mineralogical and elemental compositions based on PCA and HCPC (Figure 10), suggesting the dune is a product of aeolian transport from the same provenance. The parabolic dune formed along the Parangkusumo coast is a product Merapi pyroclastics carried downstream by the Opak River. The river formed the Opak Estuary at its distal part, and longshore current transported the estuary’s sediments into the Parangkusumo Shoreface’s deposit through the motion of Indian Ocean waves with their eastward energy flux vector (Ray et al., 2005). Shoreface sediments are transported by the prevailing NW wind from Indian Ocean, resulting in the formation of parabolic sand dunes with their horns pointing SE.

4.2. Influence of Depositional Environments for Merapi Volcaniclastics

The grain size variability consists of decreasing particle size, starting from proximally very coarse-to-coarse grains before it reaches the Opak Fault (Figure 5). The interface between proximal to medial site of Opak River is essential as it provides the first evidence that sedimentary bedforms are strongly grain size controlled. The
Figure 8. A plot of pyroxene/plagioclase feldspar (Px/PF) ratio against average grain size and depositional environment (a). Comparisons between this study’s modern aeolian Px/PF ratio with modern and ancient aeolian found on Gale Crater (b).
Figure 9. Mean elemental (a) and oxides (b) plot with distance and environments derived from XRF. Notice the abundance for Fe and Fe₂O₃ in the sample S12 B compared to the rest of the samples. The trace element of sulfur trioxide is measured in ppm.
preferential of mineral sorting in the proximal site is plagioclase feldspar, whereas the medial and distal part is pyroxene (Figure 7), indicating plagioclase feldspar as the groundmass mineralogy in these systems and pyroxene as the phenocrysts, favorable to the findings from Preece et al. (2013). This could explain the pyroxene sorting “spike” in sample S3A (Figure 7), which might be the accumulation of a locally eroded and transported pyroxene from a more recent Merapi eruption.

Figure 10. Hierarchical Clustering on Principal Components (HCPC) dendogram (a) and Principal Component Analysis (PCA) plot (b) from geochemical analysis. Notice the three distinctive clusters in the dendogram represented in green, red, and black, and PC-1 correlation value of 93.99%.
In the medial site, Opak Fault alters the trajectory of the river from NE to SW and contributes to the most abundant silt-sized sediments in sample S8A (Figure 5). This is influenced by an upthrown block of Opak normal fault in the east side of the river. The eastern bank of the river is also known as an exposure for Semilir Formation (Tmsc) outcrop (Figure 1), consisting of finer material (tuff-breccia, pumice breccia, andesitic tuff) compared to the younger pyroclastic material from Merapi. The presence of weathered materials from Semilir Formation outcrop are shown in correspondence to the Opak Fault in CIA and A-CN-K ternary diagram (Figure 11), which explained the contrast of sample S6A CIA value. The finer tuff-breccia material is also an indication to explain

Figure 11. Ternary A-CN-K diagram of Merapi volcaniclastics in comparison with Gale Crater (Mangold et al., 2019), Stimson fm (Bedford et al., 2020), Eldborgir lava field (Mangold et al., 2011) and Mars' crust (Taylor & McLennan, 2009). CIA value is plotted as a vertical axis within the A-CN-K diagram. Blue dashed line is Merapi cluster, red dashed line is Gale crater cluster, and black dashed line is Eldborgir cluster.

In the medial site, Opak Fault alters the trajectory of the river from NE to SW and contributes to the most abundant silt-sized sediments in sample S8A (Figure 5). This is influenced by an upthrown block of Opak normal fault in the east side of the river. The eastern bank of the river is also known as an exposure for Semilir Formation (Tmsc) outcrop (Figure 1), consisting of finer material (tuff-breccia, pumice breccia, andesitic tuff) compared to the younger pyroclastic material from Merapi. The presence of weathered materials from Semilir Formation outcrop are shown in correspondence to the Opak Fault in CIA and A-CN-K ternary diagram (Figure 11), which explained the contrast of sample S6A CIA value. The finer tuff-breccia material is also an indication to explain
sample S8A as the sample with the lowest average grain size across the sedimentary system (Figure 9a). The increasing abundance of SO$_3$ within the channel-side bars in the proximal to medial and its absence in the distal area suggests that trace element from Merapi volcaniclastics is not mechanically and chemically resistant enough to be deposited by fluvial system into the estuary, presumably due to (a) the mixing of seawater and freshwater, and (b) the interaction between ebb and flow currents downsystm. 

In the distal site, the abundance of very coarse to coarse sand from source to sink is notably decreased once the sediments are transported inland in the shoreface, due to the presence of the berm. The change of primary sedimentary transportation from fluvial and longshore currents to aeolian processes is shown clearly in the plot (Figure 6) where medium, fine, and very fine sand started to dominate sediment particles in the parabolic sand dune. Finer grains are more efficiently transported further landward in the coastal aeolian system, leaving an accumulation of the coarser materials in the foreshore, also visible as an average grain size plot in the blowout surface of the dune (Figures 4 and 9a). The abundance of Fe$_2$O$_3$ and anorthite in sample S12 B reflect the more mechanically resistant nature of plagioclase feldspar compared to the pyroxene, and can be partly related to either the abundance of iron oxides and to the augite pyroxene (26,35%) in this sample.

The decreasing grain-size trend, from very coarse to coarse and fine-to-silt sized grains, parallel to the direction of prevailing wind within the dune is consistent with the grainfall deposition of suspended-load sediments in the lee side, combined with the absence of grainflows on vegetated parabolic dune. The Px/PF ratio on the dune site can be attributed to the saucer-type blowout surface which acts as a catchment area for sediments carried out by the wind from the backshore (Carter et al., 1990). The blowout surface gradually develops slope gradient in the stoss-side until it reaches a threshold at the tip of the Crestline, where sediment particles are driven by gravity to move landward by settling in lee-ward side (Sloss, Shepherd & Hesp, 2012; Sloss, Hesp & Shepher, 2012). Another notable result is the presence of a linear decreasing trend from medium, fine, very fine sand, and silt throughout the blowout surface, stoss, and lee, which is parallel to the direction of prevailing wind (Figure 2d). The key finding of aeolian mineralogical sorting from Merapi is plagioclase feldspar seems to be concentrated in the blowout surface, and pyroxenes are more concentrated both in upwind (stoss) and downwind (lee) (Figure 7). The finding implies that wind-driven sedimentation is able to transport and re-deposit heavier grains (pyroxenes) parallel to the prevailing wind, hence lighter grains (plagioclase feldspar) are detected more abundantly in the blow-out surface.

The minor presence of calcite in Merapi pyroclastic was studied previously by using an experiment using time-variable decarbonation based on Merapi basalt-andesite and Javanese limestone to unravel the presence of CaCO$_3$ in Merapi's magma (Deegan et al., 2010). It is possible that carbonate minerals are present as a contaminant melt in xenoliths and Merapi feldspars (Deegan et al., 2010) thus their presence can be traced from the source toward the sink.
The combined results from bulk mineralogical composition and HCPC – PCA plot with PC-1 value of 93.99% confirmed the sediment provenance comes from calc-alkaline, basalt-andesitic Merapi source rocks (Camus et al., 2000). The high abundance of plagioclase feldspar represented by albite and anorthite can be attributed to the dominant groundmass phase of the Merapi volcaniclastics whereas augite and enstatite as the phenocrysts from modern Merapi eruptions (Camus et al., 2000; Preece et al., 2014; Wahyuni et al., 2012). Furthermore, the multivariate statistical analysis has successfully discriminated between marine-influenced deposit (cluster 1), mixed fluvio-coastal-aeolian deposits (cluster 2), and fluvial deposits (cluster 3).

Our observation suggests that mineral and sedimentary sorting that occurs throughout the entire sedimentary system is likely influenced not only by a single event (i.e., Merapi volcanism), but also from the depositional environments which the river flows and the complex interplay between estuary, shoreface, and backshore’s aeolian activity. For example, ancient pyroclasts from previous Merapi eruptions presumably get transported (i.e., as a suspended material or through bedload flux) downstream, deposited on a fluvial bar down system. Opak fault might excavate deeper sediments and continue to rework the sedimentary sorting processes. This is particularly observed with coarser grain-sized sediments accompanied with increasing pyroxenes from Opak fault to right before the Opak Estuary, while no trend is observed before the fault.

4.3. Significance of Studying Mars-Like Sedimentary Systems on Earth and Insights From Merapi Sedimentary System

Whereas our ability to answer questions regarding Mars’ hydrological and climate past is limited by the paucity of ground measurements on Mars, progress can be made through analog studies on Earth. This has been done previously such as mineralogical identification from field observation and laboratory analysis in Ka’u Desert, Hawaii (Seelos et al., 2010) which established analogous young basaltic materials from ancient lava flows on Earth and Mars. Dynjusandur sand deposit (Iceland) is considered analogous because basaltic minerals along with plagioclase feldspars and pyroxenes resembled Mars'crustal composition found in Gale crater’s Stimson formation (Mangold et al., 2011; Baratoux et al., 2013; Sara, 2017; Thorpe et al., 2021). Previous Mars studies have focused on solely basaltic environments, however, investigations in Gale crater (Bedford et al., 2019; McSween et al., 2009; Sautter et al., 2015, 2016; Schmidt et al., 2014; Siebach et al.,2017; Treiman et al., 2016) shows that Mars crust is more geochemically diverse with some locations containing pyroclastic deposits such as Home Plate, Gusev crater (Squyres et al., 2007). The Mars Exploration Rover, Spirit, encountered possible pyroclastic deposits on the NW flank of Husband Hill, on the Cumberland Ridge, and on Home Plate (Squyres et al., 2006, 2007). The deposits on Husband Hill and Cumberland ridge are part of the Wishstone class rocks which were investigated using the APXS (Alpha Particle X-Ray Spectrometer) instrument on the Spirit rover and were found to have a unique chemistry with a higher Al/Si ratio than any other rock type in Colombia Hills. This geochemistry was indicative of a high abundance of plagioclase with some pyroxene and olivine, and minor amounts of Fe oxides and oxyhydroxides (Squyres et al., 2006). Wishstone class rocks also contain poorly sorted mm-scale clasts within a fine matrix which include angular clasts indicative of either explosive volcanism in a pyroclastic eruption, or impact processes (Squyres et al., 2006). Evidence for pyroclastic deposits on Home Plate included bomb sags, rounded grains that were similar in appearance to accretionary lapilli, and spectroscopic infrared measurements that suggested a high abundance (45 wt%) of basaltic glass (Squyres et al., 2007). The Home Plate deposits have an alkali basalt geochemistry suggesting that they may have formed through a phreatmic eruption of alkali basalt lava (Squyres et al., 2007). Orbital evidence for pyroclastic deposits on Mars has also been found at the Medusa Fossae Formation which is a large, friable, eroded tephra deposit (Bradley et al., 2002; Greeley & Guest, 1987; Scott & Tanaka, 1986), and at the Cerberus Fossae fissure system in Elysium Planitia which is a low-albedo, high-calcium pyroxene-rich unit (Horvath et al., 2021).

A key insight from our research is to help test whether the Gale crater’s deposits such as Stimson formation and various members like Pahrump Hills, Hartmann’s Valley, Karasburg, and Sutton Island (Bedford et al., 2020; Rampe et al., 2020) were transported by fluvial process in the past. Gale crater sediments were hypothesized whether as an in situ, gravitationally driven reworked materials transported from its crater rim, or they were possibly carried by ancient fluvial (Aeolis mensae) system before it deposited within the crater itself (Bedford et al., 2019, 2020; McSween et al., 2009; Rampe et al., 2020; Sautter et al., 2015, 2016; Schmidt et al., 2014; Siebach et al., 2017; Treiman et al., 2016). To gain an insight for either of the hypothesis, in CIA and A-CN-K ternary diagram (Figure 11) we plot Merapi which represent modern fluvial sediment, the sediments of Gale
crater, and lava field sediments from Eldsborgir in Iceland (Mangold et al., 2011) which has been previously used as an analogous Mars site for its basaltic provenance. The site of Eldsborgir is chosen to represent sediments transported solely by aeolian and gravitational action, which resembles the hypothesis of crater rim-derived transported sediments (mass wasting) in Gale crater. Our finding favors the hypothesis of fluvially transported Gale crater sediments as shown by the superimposed clustering with Merapi sediments, in contrast with tightly clustered Eldsborgir lava field sediments (Figure 11). This implies that Gale crater sediments had been affected by progressive (although not heavily, as CIA shows) chemical weathering of a river, for example, increasing Al and reducing alkaline elements (Na, K) and alkaline-earth elements (Ca, Mg) downsystem (Nesbitt & Young, 1982).

The proximal environment of Merapi is home to more significant pyroclastic ejecta such as blocks and bombs. The recorded sedimentary texture of lower unit in Home Plate (Gusev crater) exhibits clast (referred to as bomb sag, Squyres et al., 2007) as inclusion within a parallel stratification, whereas the upper unit shows cross-stratification made of fine-grained and well-sorted materials. The bomb-sag is also present in the proximal area of Merapi, suggesting the Home Plate in Gusev Crater is located in either the vicinity of proximal volcanism, or to an extent of proximal to medial interface. It is common to see the bomb inclusion on the proximal area covered with pyroclastic sedimentary unit in Merapi (Figure 12). The reworked materials in Home Plate shows the presence of albite, anorthite, and pyroxene from APXS and CIPW normalization (Squyres et al., 2007), and the presence of bomb sag shows a product of explosive volcanism that eventually redeposited within the Gusev crater.

One notable way that explosive volcanism can impact sedimentary systems is through the incision of gullies on Merapi's surface from lahar flows which directs the initial trajectory of the Opak river tributaries, impacting the direction of any pyroclastic flows. Eruption of lava on Martian volcanoes have been reported to initiate valleys on Mars (Gulick & Baker, 1990), such as Alba Patera and Apollinaris Patera (Alemanno, 2018). Albeit not discussed in details from the magmatic properties (melt inclusion, phase equilibria, magma ascension, degassing, etc.) effusive volcanism is known to build up intact lava flows due to less viscous lava (Cassidy et al., 2018; Larrea et al., 2021), which later will build up igneous materials in the proximal site, compared to the more destructive nature of explosive volcanism which can initiate valley incision. In Merapi volcanioclastic sedimentary systems, our results show that explosive volcanism affect the sedimentary from source to sink as various fluvial depositional subenvironments are formed with definitive distance, (e.g., the channel-side bars in proximal and medial sites, and mid-channel bar in the distal part of the river). This suggests that on these volcanoes where similar eruptive have occurred, similar sedimentary deposits could form on the sides of these volcanoes provided sufficient water existed at the surface to support a river system. If pyroxene dominates the phenocryst mineralogy in these systems and feldspar dominates the groundmass, similar to what we see in Merapi, then we would expect to see the preferential sorting of feldspar in proximal units relative to pyroxene, and pyroxene over feldspar in medial-to-distal setting.

Figure 12. Comparison between Merapi’s bomb sag in the proximal site (a) with Home Plate’s bomb sag in Gusev Crater (b).
Volcanic eruption and aeolian processes impact the formation, migration, and evolution of volcaniclastic dunes (Edgett & Lancaster, 1993; Grotzinger et al., 2014; Hooper et al., 2012). The Parangkusumo coastal sand dune is a product of complex interaction between volcanic eruption and fluvio-coastal-aeolian sedimentary systems. Numerous studies of the Martian surface had shown the volcaniclastic dunes on Mars (Greeley et al., 1992; Grotzinger et al., 2005; Lapotre & Rampe, 2018; Payré et al., 2020; Schmidt et al., 2014), their mobility (Bridges et al., 2012) and the presence of ancient fluvial channels (Pondrelli et al., 2008; Williams et al., 2013; Balme et al., 2020; Lapotre & Ielpi, 2020; and Dickson et al., 2021) could be linked with transported volcaniclastics by the fluvial system on Mars in the past. A study at Sunset Crater, Arizona (Hooper et al., 2012) had described a challenge of the missing step in sedimentary transportation from the provenance to the aeolian system, and the involvement of possible fluvial processes that deposit these sediments. Our research shows that reworked volcaniclastic materials from the source is transported into distal aeolian deposits, with mineralogical and elemental similarity across the sedimentary system of 93.99% as shown by PC-1 value (Figure 10). In Gale crater, it has been hypothesized that the recycling of ancient fluvial deposits was an important contributor to aeolian sediments in the past (Bedford et al., 2020; Edgett et al., 2020). Our results support that fluvial deposits can contribute significantly to aeolian deposits in volcanic environments by transporting the reworked volcaniclastics as the provenance for the aeolian sand. It is worth noting, however, that our study has potential limitations due to shorter transport distances at Merapi sedimentary systems than on Mars, and potential errors due to the limited number of analyzed samples relative to the natural variability of sedimentary environments that we find on Merapi.

Whether or not the Northern lowlands of Mars held one or more oceans in the past is a hotly debated topic (e.g., Carr & Head, 2003; Clifford & Parker, 2001; Ghatan & Zimbelman, 2006; Head et al., 1999; Malin & Edgett, 1999). Horizontal terraces at the edges of the volcanic Northern plains have been interpreted as paleoshorelines, representing an ancient contact between land and the paleo-ocean (Clifford & Parker, 2001; Head et al., 1999). These contacts were visible from an orbiter since the geomorphological expression is distinctive from its surroundings with a topographically inverted terrain (Clifford & Parker, 2001; Di Achille & Hynek, 2010; Head et al., 1999; Hughes et al., 2019). If such an ocean did exist on Mars in the past, results from this research suggests that the distal part of fluvial discharges into a large standing water body would result in the build-up of a coarse sedimentary material with relatively higher pyroxene content compared to feldspar, such as what is seen at the geomorphological expression of the volcaniclastic shoreface in Parangkusumo shoreline. Moreover, our research demonstrated the ability of HCPC – PCA to distinguish mineralogical provenance (Figure 10) and CIA-A-CN-K diagram (Figure 11) to distinguish the fluvially transported sediments versus gravitationally settled (mass wasting) grains. If the hypothesis of Mars sedimentary rocks were carried across the studied basin was accompanied by fluvial transportation, the methods of principal component analysis and weathering model from CIA-A-CN-K ternary diagram is applicable to test the dominant sedimentary processes in future Mars study.

Drilled samples in Murray formation are dominated with plagioclase feldspar, and there has been discussion regarding alteration versus provenance effects for the ChemCam-derived interpretation of the drilling samples. Our results favor the interpretation of incongruent dissolution for plagioclase feldspar found within the Murray formation, Gale Crater (Mangold et al., 2019). Our study reveals that plagioclase feldspar dominance varies from source to sink, thus makes it possible to revisit the hypothesis of partial dissolution of plagioclase in Murray formation. It is believed that partial dissolution from plagioclase should be coupled with an observation of decreased in sodium (Mangold et al., 2019). This is consistent with our result from XRD and XRF, where decreasing abundance of plagioclase feldspar represented in proximal sample S2A and S3A (Figures 6b and 7) is followed with decreasing amount of Na (Figure 9a). The fluvially transported S2A and S3A makes it possible to assume that alteration occurred based on aqueous process.

Furthermore, we find pyroxene in a higher abundance relative to feldspar in medial and distal sites, deposited in channel-side bars, mid-channel bar, estuary, shoreface, and the lee and stoss of the parabolic sand dune. The pyroxene sorting from Merapi is found on an average grain size from coarse-to-fine sand. Evidently, the pyroxene sorting occurs in the gentler slope of Opak River, where the river started to lose the gravity-driven potential energy which is derived from the proximal’s steep-sloped angle. This suggests that fluvial sedimentary system is capable to transport pyroxenes further into the distal site as opposed to plagioclase feldspar, despite pyroxenes having higher density than plagioclase feldspar. This finding favors the hypothesis of fluvial sedimentary rocks as the source sediment for Stimson formation (Bedford et al., 2020). Another notable result from our study is the variability of Px/PF ratio across the blowout surface, stoss, and lee that is similar with the findings of CheMin.
measurement from barchanoidal dune (Bagnold Dune) (Rampe et al., 2020). Our study shows that the upwind part (stoss) of Parangkusumo parabolic sand dune has less plagioclase feldspar concentration compared to the blowout surface of the dune, and become a site of a relatively higher density mineral (pyroxene) to accumulate. This is consistent with the findings of Gobabeb and Ogunquit Beach samples (Figure 8b), where the upwind margin has less concentration of plagioclase feldspar compared to the downwind margin (Rampe et al., 2018).

5. Conclusion

Merapi volcanioclastics are a product of an active volcano that could provide insights to constrain Martian older and more recent volcanioclastics by focusing on unaltered anorthite, albite, and pyroxenes found on Martian crust. We conclude that:

1. Mineral sorting variability can be observed in bedforms regardless of its grain size distribution and the depositional environment of its sedimentary system. It is exhibited by three examples; (a) The proximal-medial interface of Opak River; (b) Shoreface samples retained dominant pyroxene sorting across the foreshore and backshore, however, the berm that separates the two bedforms is able to sort different average grain size from medium sand in the foreshore and fine-to-very fine sand in the backshore; (c) The parabolic dune samples (blowout surface, stoss, and lee) are all on average have medium-sized grains, however, the blowout surface contains more plagioclase feldspar compared to the pyroxene-dominant stoss and lee.

2. Quantification of mineralogical and elemental composition analysis from volcanioclastic stream sediment samples shows that plagioclase feldspar dominates the mineral composition at the proximal site, whereas pyroxene are dominant in the entire medial-distal site. In the aeolian environment, blow-out surface is dominated by plagioclase feldspar once again, whereas both the upwind and downwind side are dominated by pyroxenes.

3. The result from multivariate statistical analysis shows a promising insight as a method of its own to establish provenance study, showing a favorable result with cluster analysis-based provenance studies in Gale crater.

4. The interconnected surface processes of volcanic cyclic eruption, fluvial discharge, longshore current, and coastal volcanioclastic aeolian sand dunes are all interconnected from shaping the sedimentary pathway of a reworked volcanioclastic terrain in Merapi sedimentary systems.

5. Fluvial sedimentary system is capable to transport pyroxenes further into the distal site, despite pyroxenes having higher density than plagioclase feldspar.

6. Wind-driven sorting in aeolian environment shows both mineralogical and average grain size function are gradually changing across the bedforms, parallel to the direction of prevailing wind, despite having similar average grain size.

Data Availability Statement

The data provided in this research is available to download in supplementary section, and the raw data set for Merapi volcanioclastics (Argadestya, 2022) is archived in Mendeley Database with Digital Object Identifier (https://doi.org/10.17632/3jfp4xnjr1). We support fair-use of our archived data and we are open to future research collaboration.

References

Aini, L. N., Soenarminto, B. H., Hanudin, E., & Sartohadi, J. (2019). Plant nutritional potency of recent volcanic materials from the southern flank of Mt. Merapi, Indonesia. *Bulgarian Journal of Agricultural Science*, 25(3), 527–533.

Alemanno, G. (2018). Study of the fluvial activity on Mars through mapping, sediment transport modelling and spectroscopic analyses. PhD dissertation thesis, Cornell University. Earth and Planetary Astrophysics. arXiv:1805.02208v1. https://arxiv.org/abs/1805.02208

Andreatusi, S. D., Alloway, B. V., & Smith, I. E. M. (2000). A detailed tephrostratigraphic framework at Merapi volcano, central Java, Indonesia: Implications for eruption predictions and hazard assessment. *Journal of Volcanology and Geothermal Research*, 100(1–4), 51–67. https://doi.org/10.1016/S0377-0273(00)00133-5

Argadestya, I. (2022). "XRD and XRF dataset for Merapi volcanioclastics", Mendeley Data. V1. https://doi.org/10.17632/3jfp4xnjr1

Balme, M. R., Gupta, S., Davis, J. M., Fawdon, P., Grindrod, P. M., Bridges, J. C., et al. (2020). Aram Dorsum: An extensive mid-Noachian age fluvial depositional system in Arabia Terra, Mars. *Journal of Geophysical Research: Planets*, 125(5), e2019JE006244. https://doi.org/10.1029/2019JE006244

Baratoux, D., Toplis, M. J., Monnereau, M., & Sautter, V. (2013). The petrological expression of early Mars volcanism. *Journal of Geophysical Research (Planets)*, 118, 1–6. https://doi.org/10.1002/2012JE004234
Bedford, C. C., Bridges, J. C., Schwenzer, S. P., Wiens, R. C., Rampe, E. B., Frydenvang, J., & Gasda, P. J. (2019). Alteration trends and geochemical source region characteristics preserved in the fluvulacustrine sedimentary record of Gale crater, Mars. *Geochimica et Cosmochimica Acta*, 246, 234–266. https://doi.org/10.1016/j.gca.2018.11.031

Bedford, C. C., Schwenzer, S. P., Bridges, J. C., Banham, S., Wiens, R. C., Gasnault, O., et al. (2020). Geochemical variation in the Strom bol formation of Gale Crater: Provenance, mineral sorting, and a comparison with modern Martian dunes. *Icarus*, 341, 113622. https://doi.org/10.1016/j.icarus.2020.113622

Berthommeir, P., & Camus, G. (1991). Les eruptions historiques du Merapi (centre Java indonesie). *Bull. Sect. Volcanol. Soc. Geol. Fr.*, 23, 1–11.

Bradley, B. A., Sakimoto, S. E. H., Frey, H., & Zimbelman, J. R. (2002). Medusa fossae formation: New perspectives from Mars global surveyor. *Journal of Geophysical Research*, 107(E8), 5058. https://doi.org/10.1029/2001JE001537

Bridges, N., Ayoub, F., Avouac, J. P., Leprince, S., Lucas, A., & Mattson, S. (2012). Earth-like sand fluxes on Mars. *Nature*, 483(7398), 339–342. https://doi.org/10.1038/nature10112

Brož, P., & Hauber, E. (2012). A unique volcanic field in Tharsis, Mars: Pyroclastic cones as evidence for explosive eruptions. *Icarus*, 218(1), 88–99. https://doi.org/10.1016/j.icarus.2011.10.030

Camus, G., Gourgaud, A., Mossand-Berthommier, P.-C., & Vincent, P.-M. (2000). Merapi (central Java, Indonesia): An outline of the structural processes and associated CO2 release at Merapi volcano, Indonesia: Insights from experimental petrology. *Journal of Petrol*, 31(5), 1027–1051. https://doi.org/10.1093/petrology/egp10

Di Achille, G., & Hynek, B. M. (2010). Ancient Ocean on Mars supported by global distribution of deltas and valleys. *Nature Geoscience*, 3(7), 459–463. https://doi.org/10.1038/ngeo891

Dickson, J. L., Lamb, M. P., Williams, R. M. E., Hayden, A. T., & Fischer, W. W. (2021). The global distribution of depositional rivers on early Mars. *Geology*, 49(5), 504–509. https://doi.org/10.1130/0091-7613(2021)00494857.1

Edgett, K., Banham, S., Bennet, K., Edgar, L., Edwards, C., & Fairen, A. G., et al. (2020). Extraformational sediment recycling on Mars. *Geosphere*, 16(6), 1508–1537. https://doi.org/10.1130/GEOSF224

Edgett, K., & Lancaster, N. (1993). Volcaniclastic aeolian dunes: Terrestrial examples and applications to Martian sands. *Journal of Arid Environments*, 25(3), 271–297. https://doi.org/10.1016/0047-2693(93)90136-1

Edwards, T. K., & Glysson, G. D. (1999). Field methods for measurement of fluvial sediment. Techniques of water-resources investigations of the U.S. Geological survey, book 3, applications of hydraulics. Chapter C2. ISBN 0-607-89738-4.

Ehmann, B. L., Edgett, K. S., Sutter, B., Achilles, C. N., Litvak, M. L., Lapotre, M. G. A., et al. (2017). Chemistry, mineralogy, and grain properties at Namib and high dunes, Bagnold dune field, Gale Crater, Mars: A synthesis of curiosity rover observations. *Journal of Geophysical Research: Planets*, 122(12), 2510–2543. https://doi.org/10.1002/2017je005267

Fairfield, C. A., Head, J. W., & Schon, J. H. (2004). Surficial depositional processes of Gale crater, Mars: A synthesis of curiosity rover observations. *Journal of Geophysical Research*, 109(I), 2134. https://doi.org/10.1029/2003JE002384

Ghatala, G. J., & Zimbelman, J. R. (2006). Paucity of candidate coastal constructional landforms along proposed shorelines on Mars: Implications for a northern lowlands-filling ocean. *Icarus*, 183(1), 171–196. https://doi.org/10.1016/j.icarus.2006.06.007

Goldberg, K., & Humayun, M. (2010). The applicability of the chemical index of alteration as a paleoclimatic indicator: An example from the Permian of the Paraná basin. *Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology*, 293(1–2), 81–89. https://doi.org/10.1016/j.palaeo.2010.05.015

Greeley, R., & Guest, J. E. (1978). Geologic map of the eastern equatorial region of Mars. *IMAP 1802-B*. https://doi.org/10.3133/i1802B

Greeley, R., Lange, N., Lee, S., & Thomas, P. (1992). Martian aeolian processes, sediments, and features. In *The international journal of Mars science and exploration, February 1992*

Grotzinger, J. P., Arvidson, R. E., Bell, J. F., Calvin, W., Clark, B. C., Fike, D. A., et al. (2005). Stratigraphy and sedimentology of a dry to wetolian depositional system, Burns formation, Meridiani Planum, Mars. *Earth and Planetary Science Letters*, 240(1), 11–72. https://doi.org/10.1016/j.epsl.2005.09.039

Grotzinger, J. P., Sumner, D. Y., Kah, L. C., Stack, K., Gupta, S., Edgar, L., et al. (2014). A habitable fluvio-lacustrine environment at Yellowknife bay, Gale crater, Mars. *Science*, 343(6169). https://doi.org/10.1126/science.1242777

Gulick, V. C., & Baker, V. R. (1990). Origin and evolution of valleys on Martian volcanoes. *Journal of Geophysical Research*, 95(B9), 14325–14344. https://doi.org/10.1029/90JB095223

Head, J. W., III, Hiesinger, H., Ivanov, M. A., Kreslavsky, M. A., Pratt, S., & Thomson, B. J. (1999). Possible ancient oceans on Mars: Evidence from Mars orbiter laser altimeter data. *Science*, 286(5447), 2134–2137. https://doi.org/10.1126/science.286.5447.2134

Hope, R. A. (1999). The beach backshore and beyond. In *A. D. Short (Ed.), Handbook of Beach and shoreface morphodynamics*. John Wiley and Sons.

Hus, P. A. (2002). Foredunes and blowouts: Initiation, geomorphology and dynamics. *Geomorphology*, 48(1–3), 245–268. https://doi.org/10.1016/s0169-555x(02)00184-8

Hooper, D. M., McGinnis, R. N., & Neumann, A. (2012). Volcaniclastic aeolian deposits at Sunset Crater, Arizona: Terrestrial analogs for Martian dune forms, *Earth Surface Processes and Landforms*, 37(10), 1090–1105. https://doi.org/10.1002/esp.3238
Sautter, V., Toplis, M. J., Beck, P., Mangold, N., Wiens, R., Pinet, P., et al. (2016). Magmatic complexity on early Mars as seen through a combination of orbital, in situ and meteorite data. Lithos, 254, 36–52. https://doi.org/10.1016/j.lithos.2016.02.023

Sautter, V., Toplis, M. J., Wiens, R. C., Cousin, A., Fabre, C., Gasnault, O., et al. (2015). In situ evidence for continental crust on early Mars. Nature Geoscience, 8(8), 605–609. https://doi.org/10.1038/ngeo2474

Schmidt, M. E., Campbell, J. L., Gellert, R., Perrett, G. M., Treiman, A. H., Blaney, D. L., et al. (2014). Geochemical diversity in first rocks examined by the Curiosity Rover in Gale Crater: Evidence for and significance of an alkali and volatile-rich igneous source. Journal of Geophysical Research: Planets, 119(1), 64–81. https://doi.org/10.1002/2013JE004481

Scott, D. H., & Tanaka, K. L. (1986). Geologic map of the Western equatorial region of Mars. IMAP 1802-A. https://doi.org/10.3133/i1802A

Seelos, K. D., Arvidson, R. E., Jolliff, B. L., Chemtob, S. M., Morris, R. V., Ming, D. W., & Swayze, G. A. (2010). Silica in a Mars analog environment: Ka’u Desert, Kilauea volcano, Hawaii. Journal of Geophysical Research, 115, E00D15. https://doi.org/10.1029/2009JE003347

Siebach, K. L., Baker, M. B., Grotzinger, J. P., McLennan, S. M., Gellert, R., Thompson, L. M., & Hurowitz, J. A. (2017). Sorting out compositional trends in sedimentary rocks of the Bradbury group (Aeolis Palus), Gale crater, Mars. Journal of Geophysical Research: Planets, 122(2), 295–328. https://doi.org/10.1002/2016JE005195

Sloss, C. R., Hesp, P., & Shepherd, M. (2012). Coastal dunes: Aeolian transport. Nature Education Knowledge, 3(10), 21.

Sloss, C. R., Shepherd, M., & Hesp, P. (2012). Coastal dunes: Geomorphology. Nature Education Knowledge, 3(10), 2.

Squires, S. W., Aharonson, O., Clark, B. C., Cohen, B. A., Crumpler, L., de Souza, P. A., et al. (2007). Pyroclastic activity at Home Plate in Gusev crater, Mars. Science, 316(5825), 738–742. https://doi.org/10.1126/science.1139045

Squires, S. W., Arvidson, R. E., Bollen, D., Bell, J. F., Bruckner, J., Cabrol, N. A., et al. (2006). Overview of the opportunity Mars exploration rover mission to meridiani planum: Eagle crater to paddy rille. Journal of Geophysical Research, 111(E12), E12S12. https://doi.org/10.1029/2006JE002771

Stockstill-Cahill, K. R., Anderson, F. S., & Hamilton, V. E. (2008). A study of low-albedo deposits within Amazonis Planitia craters: Evidence for locally derived ultramafic to mafic materials. Journal of Geophysical Research, 113(E7), E07008. https://doi.org/10.1029/2007JE003036

Surono, J. P., Pallister, J., Boichu, M. M., Buongiorno, F., Budisantoso, A., Costa, F., et al. (2012). The 2010 explosive eruption of Java's Merapi volcano—a ‘100-year’ event. Journal of Volcanology and Geothermal Research, 241–242, 121–135. https://doi.org/10.1016/j.jvolgeores.2012.06.018

Taylor, S. R., & McLennan, S. M. (2009). Planetary crusts: Their composition, origin and evolution. Cambridge University Press.

Thorpe, M. T., Hurowitz, J. A., & Dehouck, E. (2019). Sediment geochemistry and mineralogy from a glacial terrain river system in southwest Iceland. Geochimica et Cosmochimica Acta, 265, 140–166. https://doi.org/10.1016/j.gca.2019.09.003

Thorpe, M. T., Hurowitz, J. A., & Siebach, K. L. (2021). Source-to-Sink Terrestrial Analogs for the Paleoenvironment of Gale Crater, Mars. Journal of Geophysical Research: Planets, 126(2). Portico. https://doi.org/10.1029/2020je006530

Thuleau, S., & Hussin, F. (2020). Automatic description of factorial analysis. Retrieved from https://search.r-project.org/CRAN/refmans/FactoInvestigate-package.html

Treiman, A. H., Bish, D. L., Vaniman, D. T., Chipera, S. J., Blake, D. F., Ming, D. W., et al. (2016). Mineralogy, provenance, and diagenesis of a potassic basaltic sandstone on Mars: CheMin X-ray diffraction of the windjana sample (Kimberley area, Gale crater). Journal of Geophysical Research: Planets, 121(1), 75–106. https://doi.org/10.1002/2015JE004932

Vaisse, P., Monge, A., & Hussin, F. (2017). Perform factorial analysis from FactoMineR with a shiny application. R package version 1.0.6. Retrieved from https://CRAN.R-project.org/web/packages/FactoShiny/FactoShiny.pdf

Voight, B., Constantine, E. K., Sismowidjoyo, S., & Torley, R. (2000). Historical eruptions of Merapi volcano, central Java, Indonesia, 1768–1998. Journal of Volcanology and Geothermal Research, 100(1–4), 69–138. https://doi.org/10.1016/S0377-0273(00)00134-7

Wahyuni, E. T., Triyono, S., & Suherman. (2012). Determination of chemical composition of volcanic ash from Merapi Mt. Eruption. Journal of People and Environment, 19(2), 150–159. https://doi.org/10.22146/jpal.18531

Wei, T., & Simko, V. (2017). R package ‘corrplot’: Visualization of a correlation matrix. Version 0.84. Retrieved from https://github.com/Taiyun/Corrplot

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., Francois, R., et al. (2019). Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686. https://doi.org/10.21105/joss.01686

Williams, R., Grotzinger, J. P., Dietrich, W. E., Gupta, S., Sunner, D. Y., Wiens, R. C., et al. (2013). Martian fluvial conglomerates at Gale crater. Science, 340(6136), 1068–1072. https://doi.org/10.1126/science.1237317