

**DYNAMICITY OF VOLCANICLASTICS IN FLUVIAL -
COASTAL - AEOLIAN SEDIMENTARY SYSTEMS:
INSIGHTS FOR MAR**

BY

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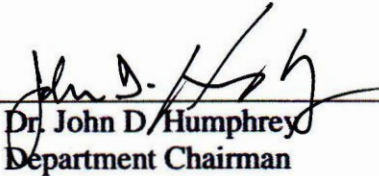
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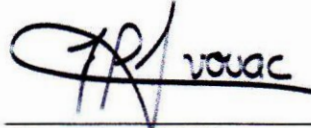


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2022

Dedication

Ad Maiorem Dei Gloriam

To my beloved family

And my significant other

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I am blessed to have finished my study at KFUPM, a feat that is unattainable without the help of many. First and foremost, to Prof. Khalid Al-Ramadan, my advisor, of whom he is a great educator, and even a more incredible friend. Through him, I have not only survived the magnitude of academic pressure in one of the toughest colleges in the Middle East, but also thrived. He shaped me into who I am today, and I am grateful for all the wisdom he taught me.

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For the Greater Glory of God,

Ad Maiorem Dei Gloriam

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ABSTRACT

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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 volcaniclastics by focusing on anorthite, albite, and pyroxenes found on Mars' crust. A multitemporal satellite imagery analysis (2017-2019) performed through COSI-Corr in the research area shows that the distal part of Merapi sedimentary systems is undergoing a more rapid bedform migration than the proximal and medial sites, despite having a phreatic eruption during 2018. This research samples stream sediment across the Opak River that connects Merapi with the Indian Ocean, and in addition to grain size separation, all collected samples were subjected to X-Ray Diffractometer (XRD) and X-Ray Fluorescence (XRF) to quantify their mineralogical and elemental composition, respectively, like the techniques

used by the Curiosity rover on Mars to investigate the geochemistry and mineralogy of geological units in the Gale crater. Implementation of multivariate statistical analysis based on Principal Component Analysis (PCA) and Hierarchical Clustering of Principal Component (HCPC) are able to discriminate between fluvial, fluvio-coastal-aeolian, and marine influenced deposits. The quantitative assessment shows that the provenance contains pyroclastic materials dominated by plagioclase feldspars (albite and anorthite), followed by pyroxenes (augite and enstatite). Alteration modeling from CIA and A-CN-K ternary diagram of Merapi samples favors the fluvially-deposited Gale crater rocks instead of gravitationally-driven from the crater rim.

ملخص الرسالة

الاسم الكامل: إغناطيوس دي لويولا إندي أرجاديسيتيا

عنوان الرسالة: ديناميكية المواد البلاستيكية البركانية في الرواسب الانسيابية الساحلية

الأنظمة: رؤى للمريخ

التخصص: الجيولوجيا

تاريخ الدراسة: مايو 2022

Merapi تبحث هذه الدراسة في التباين المعدني والعنصري والمكاني من المصدر (القريب) إلى الحوض (البعيد) لبركان البازلت والأنديزيت الطبقي (جافا ، إندونيسيا) لتقييد الفرز المعدني البركاني في البيئات النهرية والريالية والساحلية بشكل أفضل. البلاستيك البركاني ميرابي هو نتاج بركان نشط مع ثوران بركاني مستمر كل أربع سنوات ، والذي يمكن أن يوفر رؤى لتقييد أقدم وأحدث المواد البلاستيكية البركانية في المريخ من خلال التركيز على أنورثيت ، وألبيت ، والبيروكسين الموجودة على قشرة المريخ. يُظهر تحليل صور الأقمار الصناعية متعدد الأوقات (2017-2019) الذي الرسوبية يخضع لترحيل Merapi في مجال البحث أن الجزء البعيد من أنظمة COSI-Corr تم إجراؤه من خلال أسرع من المواقع القريبة والوسطى ، على الرغم من حدوث ثوران بركاني خلال عام 2018. عينات هذا البحث من الرواسب المتدفقة عبر نهر أوباك الذي يربط ميرابي بالمحيط الهندي ، بالإضافة إلى فصل حجم الحبوب ، تعرضت لتحديد X-Ray Fluorescence (XRF) و (XRD) جميع العينات التي تم جمعها لمقياس انحراف الأشعة السينية على المريخ Curiosity المعادن الخاصة بهم. والتكوين الأولي ، على التوالي ، مثل التقنيات المستخدمة من قبل مركبة تنفيذ التحليل الإحصائي متعدد Gale. للتحقيق في الكيمياء الجيولوجية وعلم المعادن للوحدات الجيولوجية في فوهة قادر على التمييز (HCPC) والتكتل الهرمي للمكون الرئيسي (PCA) المتغيرات بناءً على تحليل المكونات الرئيسية بين الرواسب النهرية ، النهرية الساحلية ، الإيولية ، والبحرية المتأثرة. يُظهر التقييم الكمي أن المصدر يحتوي على

مواد حلقيّة بلاستيكية يغلب عليها الفلسبار بلاجيوجلاز (ألبيت وأنورثيت) ، يليه البيروكسين (الأوجيت والإنستاتيت).
المنرسبة Gale صخور حفرة Merapi الرسم التخطيطي الثلاثي لعينات A-CN-K و CIA تفضل نمذجة التغيير من
..بالأنهار بدلاً من الجاذبية المدفوعة من حافة الفوهة

CHAPTER 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 volcaniclastics deposition (Fig. 1.1) from source (proximal) to sink (distal) area. Merapi stratovolcano is chosen for its basaltic to basalt-andesitic pyroclastic materials (Lorenz, 1974; Berthommier and Camus, 1991; Andreastuti et al., 2000; Camus et al., 2000; Voight et al., 2000; Charbonnier and Gertisser, 2008; Surono et al., 2012), with similar mineralogy dominated by feldspar and pyroxene of reworked igneous origin detected at Gale Crater (Schmidt et al., 2014; Treiman et al., 2016; Siebach et al., 2017; Bedford et al., 2020; Payré et al., 2020; Rampe et al., 2020) and Gusev Crater's (Fig. 1.2) Home Plate on Mars (Squyres et al., 2007). Previous studies of Merapi pyroclastics' mineralogical and elemental composition stated previously 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).

Merapi and its subsequent depositional environments represent an interaction between volcanic, fluvial, coastal, and aeolian sedimentary systems. Very few have looked into how volcanoclastic materials from more evolved volcanism and explosive volcanism are incorporated into these systems, despite its increasing evidence in the Mars geological record. Similar depositional environments are detected on Mars that Merapi volcano can provide valuable insights, such as: (1) Pyroclastic flow deposits (Brož and Hauber, 2012) identified at Tyrrhena Patera (Gregg and Farley, 2006) and Home Plate, Gusev Crater (Squyres et al., 2007); (2) Fluvial and aeolian sediments on Mars (Greeley et al., 1992; Fassett and Head, 2005; Grotzinger et al., 2005; Carr, 2012; Schmidt et al., 2014; Lapotre and Rampe, 2018; Payré et al., 2020); (3) The initiation of fluvial valleys on martian volcano (Gulick and Baker, 1990; Alemanno, 2018), and the missing link between fluvial and aeolian sediments of transported reworked igneous provenance in building up volcanoclastic aeolian dunes (Hooper et al., 2012); (4) A possible Northern lowlands paleo-coastline (Carr and Head, 2003), and (5) Mineral sorting on Mars sedimentary systems, such as the provenance study of Bradbury Group (Siebach et al., 2017; Bedford et al., 2019), and the hypothesis of the source and mineral sorting in Stimson formation, Gale Crater (Bedford et al., 2020; Rampe et al., 2020). These previous studies established the basis of our quantitative assessment to target specific minerals and elements from source to sink of Merapi volcanoclastic sedimentary systems, in conjunction of further insights for Mars volcanoclastics that can be observed from our study.

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 (Greeley et al., 1992; Edgett and Lancaster, 1993; Fassett and Head, 2005; Squyres et al., 2007; Carr, 2012; Hooper et al., 2012; Grotzinger et al., 2014; Schmidt et al., 2014; Alemanno, 2018). 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).

1.1 MOTIVATION

To date, most Mars-like Earth mineralogical studies focus on basaltic environments, but with the results from the Curiosity rover (Schmidt et al., 2014; Treiman et al., 2016; Siebach et al., 2017; Bedford et al., 2020; Payré et al., 2020; Rampe et al., 2020), it suggests that the Mars analog literature should be expanded to include evolved igneous provenances. Regardless, most Gale Crater sediments contain high abundances of feldspar, with varying abundances of pyroxene (Rampe et al., 2020). As such, this research will focus on the sorting of these minerals in the fluvial, coastal, and aeolian sedimentary environments on Merapi and discuss their implications for sorting in Mars sedimentary systems.

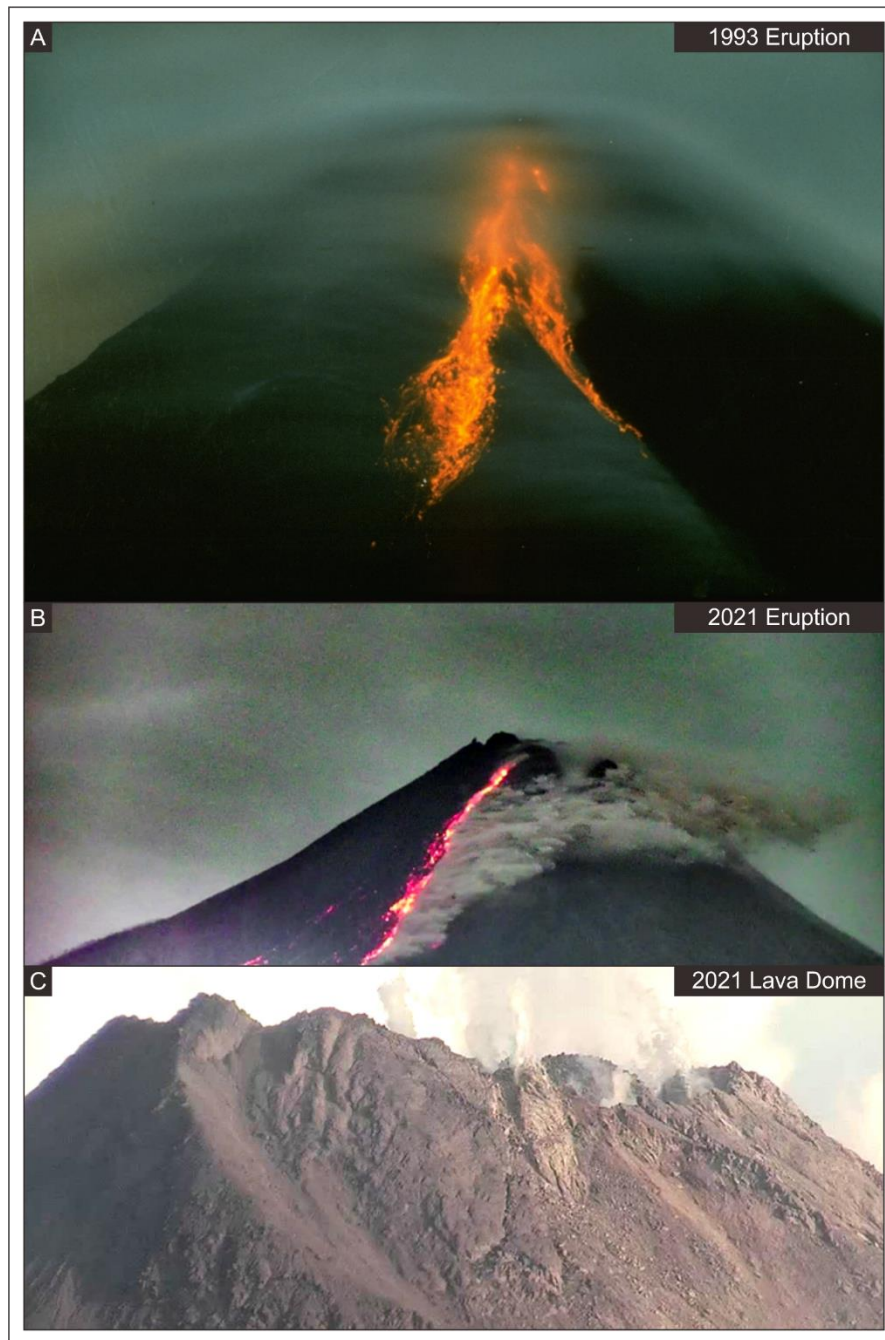


Figure 1.1 Volcanic activity of Merapi stratovolcano. Pyroclastic flow (A and B) of Merapi is produced by the collapse of Merapi's lava dome (C). Photographs are courtesy of Smithsonian Global Volcanism Program (volcano.si.edu).

In addition to the geochemical aspect, geophysical investigation using ground-penetrating radar (GPR) was acquired to provide a GPR facies for the on-going Mars rover Perseverance's RIMFAX (Radar Imager for Mars' Subsurface Experiment; Hamran et al., 2020) GPR payload, and ESA EXOMARS WISDOM (Water Ice and Subsurface Deposit Observations on Mars; Hervé et al., 2020) which can yield non-destructive geophysical investigation on any planetary surface body (Ciarletti et al., 2007). Surface processes and migration of bedforms in Mars are visible through Mars' orbiter mission (Gregg and Farley, 2006; Brož and Hauber, 2012) such as the HiRISE MRO (Mars Reconnaissance Orbiter), which motivates this research to observe the spatio-temporal aspect of Merapi sedimentary systems using COSI-Corr (Co-Registration of Optically Sensed Images and Correlation, Leprince et al., 2007; Ayoub et al., 2009).

1.2 PROBLEM STATEMENT AND OBJECTIVES

This research aims to answer the following questions:

1. To observe the migration of bedforms from the source (proximal) to the sink (distal) area of Merapi volcanoclastics and its subsequent sedimentary systems.
2. To investigate the variations of elemental and mineralogical abundance along the Merapi stratovolcano, Opak River, Opak Estuary, Parangkusumo Shoreface, and Parangkusumo parabolic sand dune.

3. To obtain ground-penetrating radar facies of Parangkusumo Shoreface and parabolic sand dune.
4. To elucidate the insights from this research's area for Mars' past sedimentary systems.

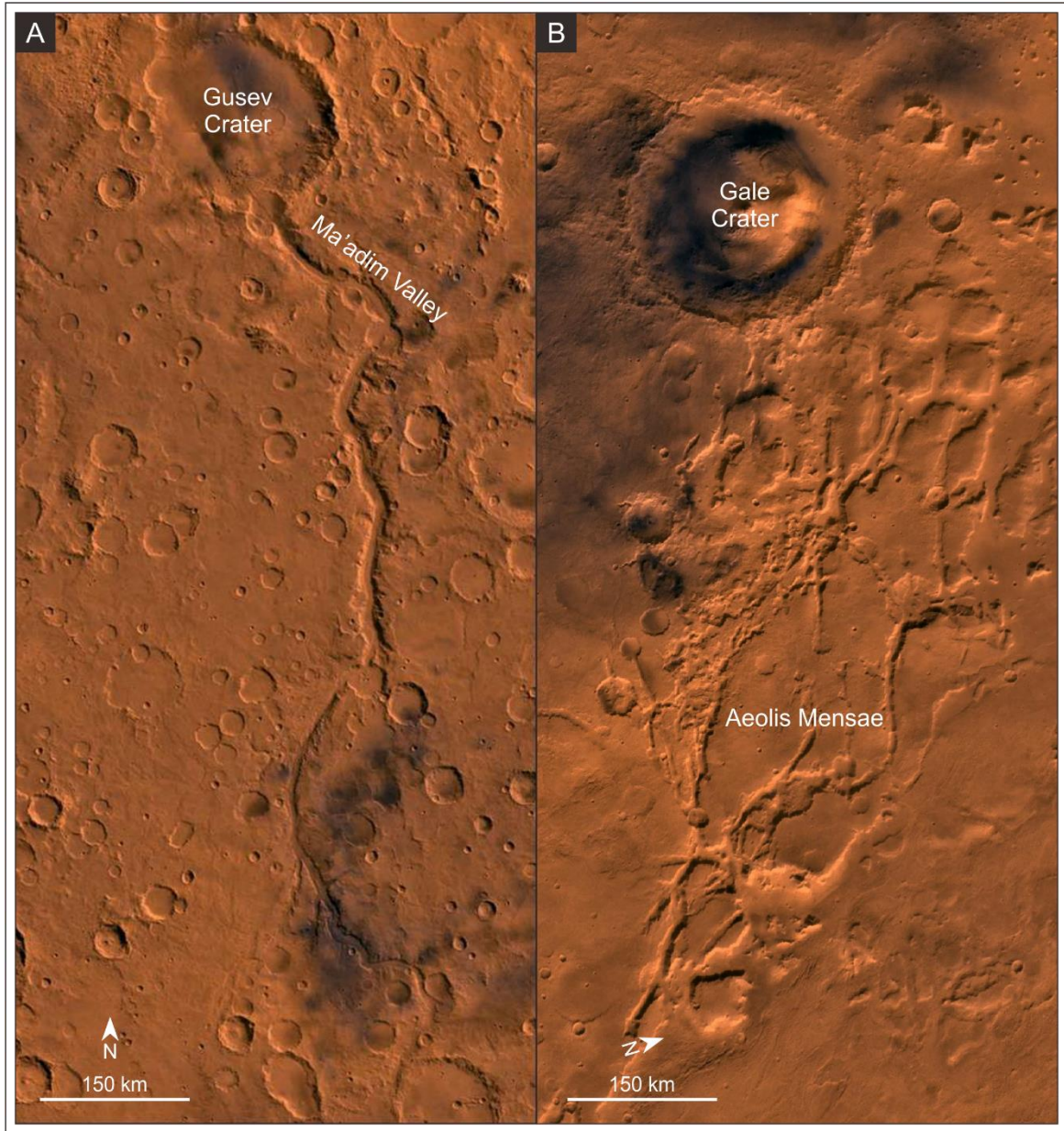


Figure 1.2 Gusev Crater (A) and Gale Crater (B) images captured by HiRISE-MRO (Mars Reconnaissance Orbiter). Notice the surface features of valley and river-like morphology surrounding the craters.

CHAPTER 2

LITERATURE REVIEW

2.1 REGIONAL GEOLOGY OF MERAPI SEDIMENTARY SYSTEMS

Merapi sedimentary systems studied in this research are categorized spatially from proximal, medial, and distal, which consist of Merapi Stratovolcano, Opak River, Opak Estuary, Parangkusumo Shoreface, and Parangkusumo parabolic sand dune.

2.1.1 Merapi Stratovolcano

Mount Merapi is an active stratovolcano situated in the middle of Java Island (7.54°S, 110.446°E). Merapi 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 on average, typically recurring every 4 to 6 years in its current state (Andreastuti et al., 2000; Voight et al., 2000; Surono et al., 2012). 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 (Lorenz, 1974; Surono et al., 2012). Mount Merapi is classified as an andesitic stratovolcano based on the growth and collapse of its summit dome with various explosive and effusive eruption (Camus et al., 2000; Charbonnier et al., 2008).

Table 1 Latest recorded observation of Merapi eruption.

Recorded Activity	Activity Cease	Remarks
December 2020	(still continuing)	Steam plumes rising
May 2018	June 2020	Phreatic eruption
March 2014	April 2014	Lava dome collapse
November 2013	November 2013	Major ash emission
October 2010	October 2010	Uplifting 0.3 mm/day

In the source area, Merapi pyroclastic flow is produced as a result of gravitational collapse of its lava dome (Camus et al., 2000). Lahar flows during eruption will create incised gullies, which later act as tributary streams at the foot of Merapi (Lavigne et al., 2000). This topographic depression will become a catchment area for pyroclastic flows that travel further southwards as the elevation decreases. Prior to the sample collection of this research, the latest eruption of Merapi occurred on May 2018, which recorded a phreatic type of eruption (Smithsonian Institution National Museum of Natural History Global Volcanism Program, 2019). 5 latest recorded observation of Merapi volcanic activity is presented in Table 1, and the entire volcano monitoring can be accessed online from Smithsonian Global Volcanism Program (<https://volcano.si.edu/volcano.cfm?vn=263250>).

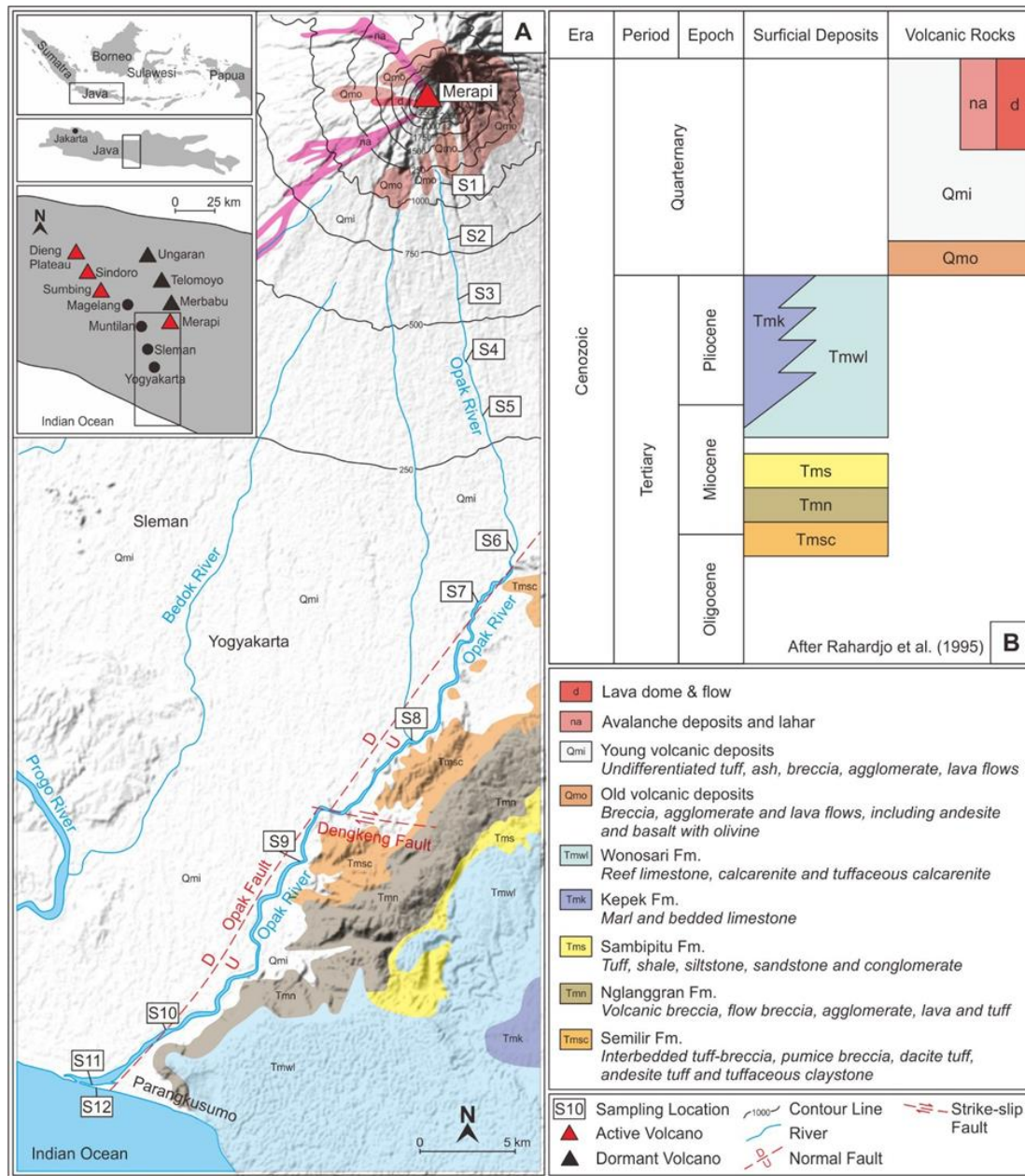


Figure 2.1 Geologic map of Merapi – Opak River and sampling locations. Lithological units (A) are based on Rahardjo et al. (1995) (B). Notice the latest deposition of young volcanic deposits (Qmi) overlying older volcanic deposits (Qmo) and tertiary sediments. The lava dome and avalanche deposits (d and na) are present in-situ only on the proximal area of Merapi volcano.

2.1.2 Opak River

Pyroclastic materials from the eruption of Mount Merapi are actively transported downstream by tributary rivers. The trajectory of Merapi tributaries is affected by lahar flows formed during a Merapi eruption. The Opak River became prominent as the tributaries join into a larger stream, and the linear characteristic of the proximal (0-20km) tributaries changed to a meandering river at the medial site (20-45km) in the system. During its course, a normal fault throw caused by the active Opak Fault created a zone of less-resistance in which the river prefers to traverse, denoted by the change of bearing from SE to SW, aligned with the fault axis (Fig.2.1 A). The deposition of its latest eruption materials is recorded with lithological units Qmi and are present across all of our study areas (Fig.2.1 B). The southeast oriented tributaries merge to form the Opak River downslope, whereas the southwest is oriented to form Progo River. Opak River was selected for this research due to its proximity to the Parangkusumo coastal dune, providing a comprehensive fluvio-coastal-aeolian system that permits the investigation of volcanoclastic mineral sorting for several depositional environments that have shaped the surface of Mars. Together, they form the Opak Estuary as the river meets the Indian Ocean. Slope angle from source to sink is divided into two values which are; (1) proximal – medial, and (2) medial – distal. This division is made to distinguish the steep slope of the volcano itself and the much gentler slope from which the river starts to change its flow pattern from v-shaped gully incision towards meandering river. The slope angle for proximal-medial is 8.27° (14.54%) with bearing of N 169.5° E and for medial – distal is 0.32° (0.52%), bearing N 219° E. The

change in bearing at the medial site can be attributed to the Opak Fault in which the river followed a contact between the upthrown and downthrown block associated with the normal fault throw.

2.1.3 Opak Estuary

According to its geomorphologic classification (Perillo, 1995), the Opak Estuary is a river-dominated estuary with tidal river influence since the saltwater front is not well-defined at its anterior, unlike delta-front estuaries (Fig. 2.2 A). The NE-SW motion of Opak river discharge creates a tidal inlet with its discharge flow motion perpendicular to Parangkusumo Coastline (Fig. 2.2 B). The motion of the Indian Ocean waves on the southern hemisphere moves counterclockwise towards a NE direction due to the Coriolis Effect (Ray et al., 2005). The wash over barrier sand seen in the Opak Estuary is formed by longshore current, which generates NW-SE swash and NE-SW backwash. Wave energy reduces where Opak River discharge flows into the ocean as seen in the tidal inlet (Fig. 2.2 C). Tidal range in Opak estuary and Parangkusumo coastal area were compiled from a decade of Topex/Poseidon satellite altimeter data which show a semidiurnal tidal range of 40 – 50 cm and diurnal tidal range 15 – 20 cm (Egbert and Erofeeva, 2002; Ray et al., 2005). Based on these values which are less than 2 m, the tidal range in the Opak Estuary and Parangkusumo Shoreface is categorized as micro-tidal (Masselink and Short, 1993).

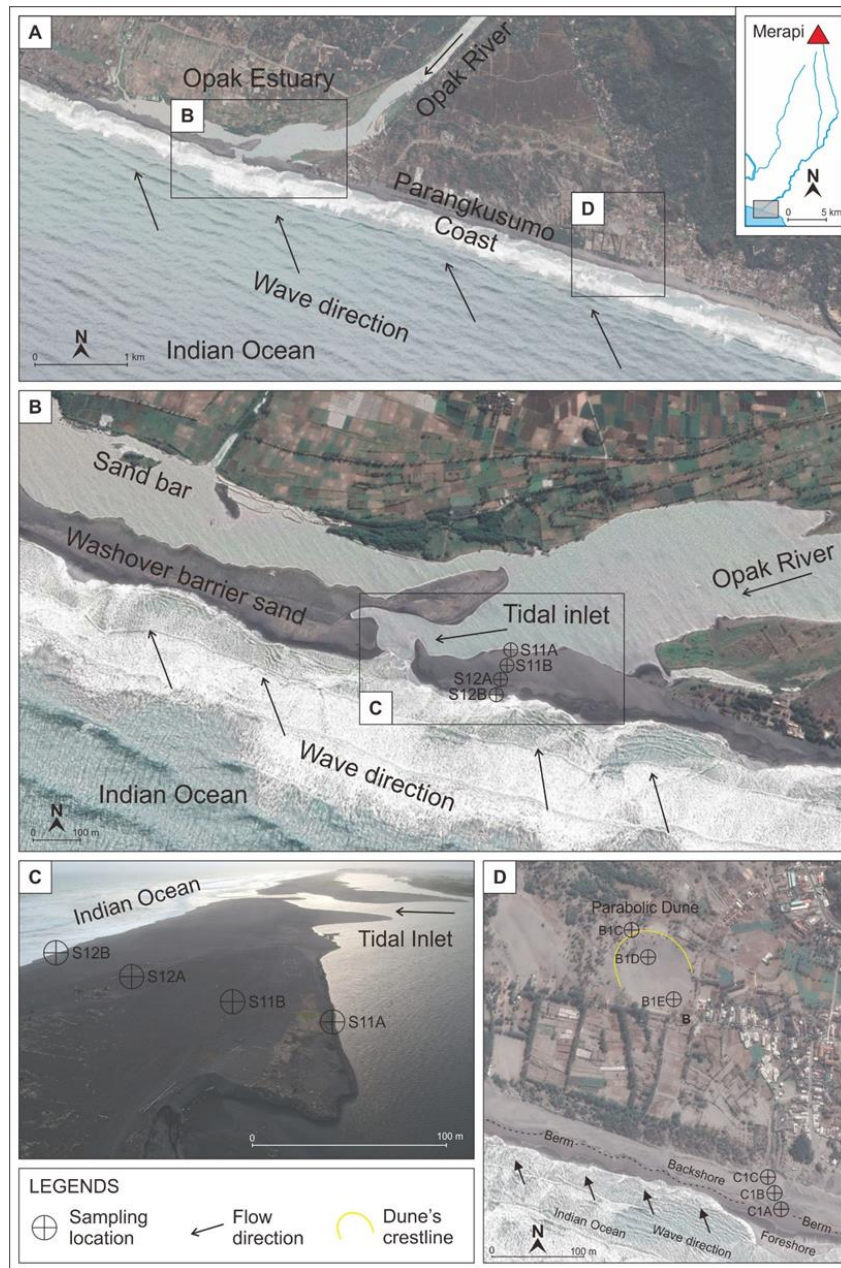


Figure 2.2 Distal part of this research showing Opak River, Opak Estuary, and the adjacent Parangkusumo Shoreface. Notice the bidirectional flow represented on the surface water between the river (A), estuary, and the ocean (B), interaction between tidal inlet and Indian Ocean (C) and the coastal parabolic sand dunes (D).

2.1.4 Parangkusumo Shoreface and Parabolic Sand Dune

Sediments deposited on the estuary are transported further by longshore current across Parangkusumo shoreface. The motion of the Indian Ocean wave with its eastward energy flux vector (Ray et al., 2005) results in swash and backwash motion, capable of supplying the sediments needed to initiate aeolian processes beyond the backshore, resulting in the formation and migration of parabolic sand dunes. Parabolic sand dunes are present approximately 3km southeast of Opak Estuary. These dunes are situated 300 m inland from the foreshore of Parangkusumo coast, with height reaching up to 6-7 m (Fig. 2.2 D). The NE wind flow patterns coming from the south have made a shallow, dish-shaped depression at the stoss side of these parabolic dunes, which is classified as a saucer-type blowout surface based on its geomorphological expression (Hesp, 2002). This type of blowout suggests that parabolic dunes situated in Parangkusumo are a result of ongoing aeolian processes, since an older foredune must exist before it migrates and formed the recent dune (Sloss et al., 2012a). Further on the lee side there is a presence of vegetation in form of shrubs.

2.2 PRECURSOR STUDIES OF MERAPI VOLCANICLASTICS

X-Ray Diffractometer by Aini et al. (2019) had shown the primary mineral composition from Merapi is pyroclastic materials composed of volcanic glass (50%), plagioclase (30%), hornblende (10%), quartz (6%), and opaque mineral including pyroxenes (4%). Plagioclase

was identified to bear 44% anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and 54% albite ($\text{NaAlSi}_3\text{O}_8$), thus confirming its classification as andesine. The pyroclastic flow of Merapi stratovolcano had been described previously as an amphibole-bearing pyroxene andesite (Surono et al., 2012) with pyroxenes, augite and hypersthene (Camus et al., 2000). In an attempt to determine the composition of the volcanic ash from a Merapi eruption, samples were analyzed using Atomic Absorption Spectroscopy (AAS) which revealed a distributive percentage of $\text{SiO}_2:\text{Al}_2\text{O}_3:\text{CaO}$ as 53:19:9 (Wahyuni et al., 2012) strengthening the calc-alkaline basalt-andesitic nature of Merapi volcanoclastics (Camus et al., 2000). Similarly, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used to determine the minor elemental composition of the volcanic ash. These two combined methodologies 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).

2.3 PRECURSOR STUDIES OF MARS VOLCANICLASTICS

Images returned from the Mariner 9 Mars fly-by mission in 1971 revealed the presence of outflow channels and valleys, similar to those formed by fluvial processes on the Earth, carved into the Martian surface (Alemanno, 2018). Since the Mariner mission, additional Mars orbiter, lander, and rover missions have shown the presence of aeolian, lacustrine, and potentially coastal deposits across the planet which have reworked volcanoclastic materials into sedimentary units (Carr and Head, 2003; McSween Jr. et al., 2009; Schmidt et al., 2014;

Treiman et al., 2016; Siebach et al., 2017; Morrison et al., 2018; Udry et al., 2018; Bedford et al., 2019; Bedford et al., 2020; Payré et al., 2020). Notable Mars geological activities are drawn from past and present Mars Mission (Fig. 2.3) which point to several documented surface processes (Carr, 2012). Martian crust is predominately basaltic with abundant plagioclase, pyroxenes, olivine and basaltic glass; However, more evolved mineral assemblages have been discovered such as major mineral phases detected by CheMin in Gale Crater to be composed of sanidine, pyroxenes, spinel, and alunite-jarosite group minerals (Morrison et al., 2018). This research serves as a mean to elucidate some Martian geological heterogeneity based on what observation from Merapi Stratovolcano, the extent of its analogous properties, and to revisit some Martian mineral sorting hypotheses in accordance to what this research could contribute upon.

Mars Odyssey Orbiter successfully mapped the crustal elemental composition of Mars, with a result of mineral assemblages ranging from basalt to basalt-andesitic origin (McSween Jr. et al., 2009). The first rock formation analyzed by Curiosity Rover was in Gale crater, performed by rover's instrument of Alpha Particle X-Ray Spectrometer (APXS) and ChemCam with a result of basaltic igneous origin (Schmidt et al., 2014). CheMin XRD from Curiosity Rover's instrument had identified mineralogical assemblages in the Windjana drilled sample of the Kimberley formation, Gale Crater (Treiman et al., 2016) composed of sanidine (21%), augite (20%), amorphous (15%), magnetite (12%), smectite (10%), and a possible detection of enstatite (marked with det? in Table 2 from Treiman et

al., 2016). Bradbury group consists of fluvial conglomerate, sandstone and lacustrine mudstone units (Grotzinger et al., 2014; 2015). Geochemical analyses by the Curiosity rover's APXS and ChemCam instruments of the Bradbury group showed that it contains a diverse geochemistry indicative of input from subalkaline basalt at the Yellowknife Bay locality, trachybasalt in the Darwin outcrop, and a trachytic source in the traverse from Darwin to the Kimberley formation (Schmidt et al., 2014; Anderson et al., 2015; Le Deit et al., 2016; Siebach et al., 2017; Bedford et al., 2019). Further along the rover's traverse in the foothills of Mt Sharp, Curiosity encountered the Murray formation which consisted of predominately lacustrine mudstone (Grotzinger et al., 2015). Geochemical data from the Murray formation shows further evidence for different sediment source regions that include a more silica-rich basalt such as a basalt-andesite with a SiO₂ concentration of 53.1 +/- 1.9 wt% (Bedford et al., 2019), and a possible rhyolite source at the Marias Pass locality (Morris et al., 2016; Bedford et al., 2019; Czarnecki et al., 2020). These evolved igneous assemblages are supported by mineralogical data provided by the CheMin XRD instrument which in particular showed high abundances of tridymite, a high temperature silica polymorph, present at the Marias Pass locality (Morris et al., 2016). These aforementioned precursor studies established the basis of our quantitative assessment to target specific minerals and elements, in conjunction of further expanding the sample collection of Merapi volcanoclastic from source to sink.

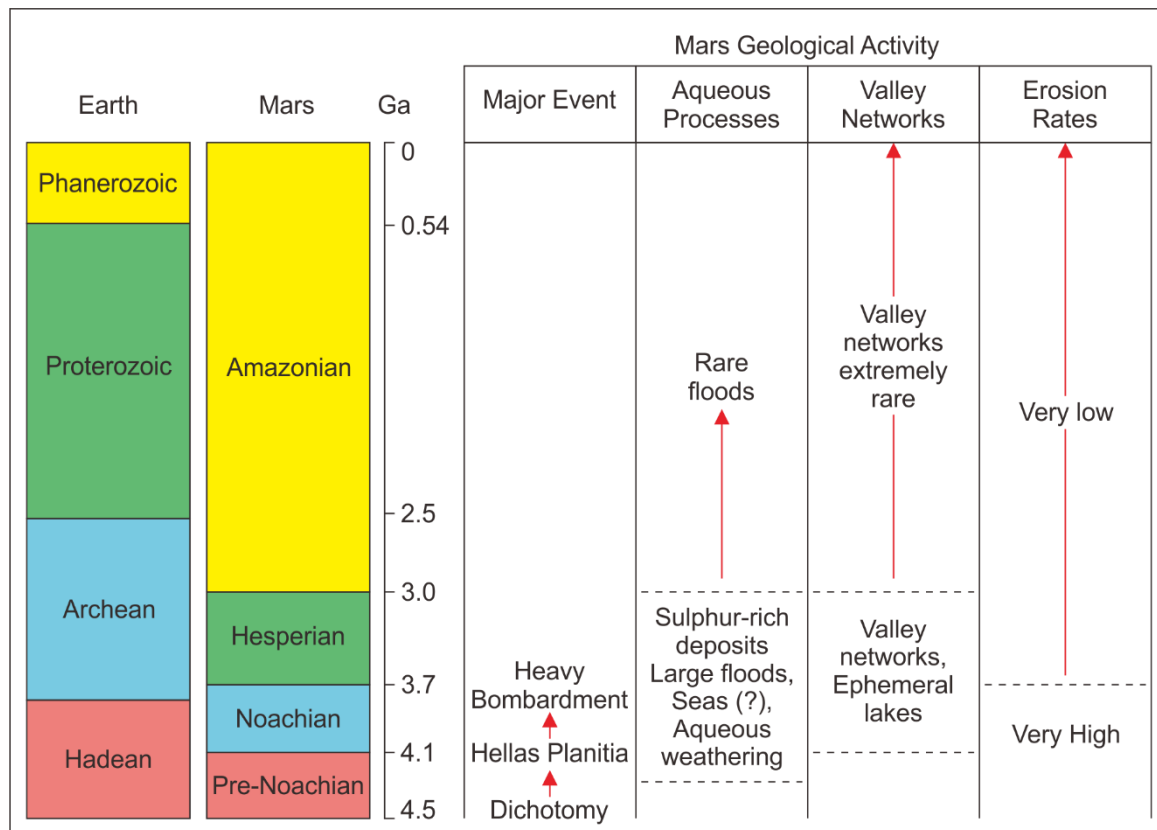


Figure 2.3 Mars geological activities and time-scale. Notice the comparison between Earth's and Mars' geological time scale. Most of aqueous surface processes which led to fluvial activity occurred during Noachian-Hesperian. The Amazonian is dominated with planet-scale aeolian processes. Modified after Carr, 2012.

2.4 SIGNIFICANCE OF STUDYING MARS-LIKE SEDIMENTARY SYSTEMS ON EARTH

Addressing martian hypotheses on Earth with a terrestrial analog study is beneficial since the samples can be collected primarily by in-situ fieldwork. This has been proven from previous research such as mineralogical identification from field observation and laboratory analysis in Ka'u Desert, Hawaii (Seelos et al., 2010) which established an analogous young basaltic material from ancient lava flows on Earth and Mars. Dyngjúsandur 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 (Sara, 2017). Previous Mars studies have focused solely on basaltic environments, however, missions in Gale crater (McSween Jr. et al., 2009; Schmidt et al., 2014; Sautter et al., 2015; Sautter et al., 2016; Treiman et al., 2016; Siebach et al., 2017; Bedford et al., 2019) shows that martian 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.

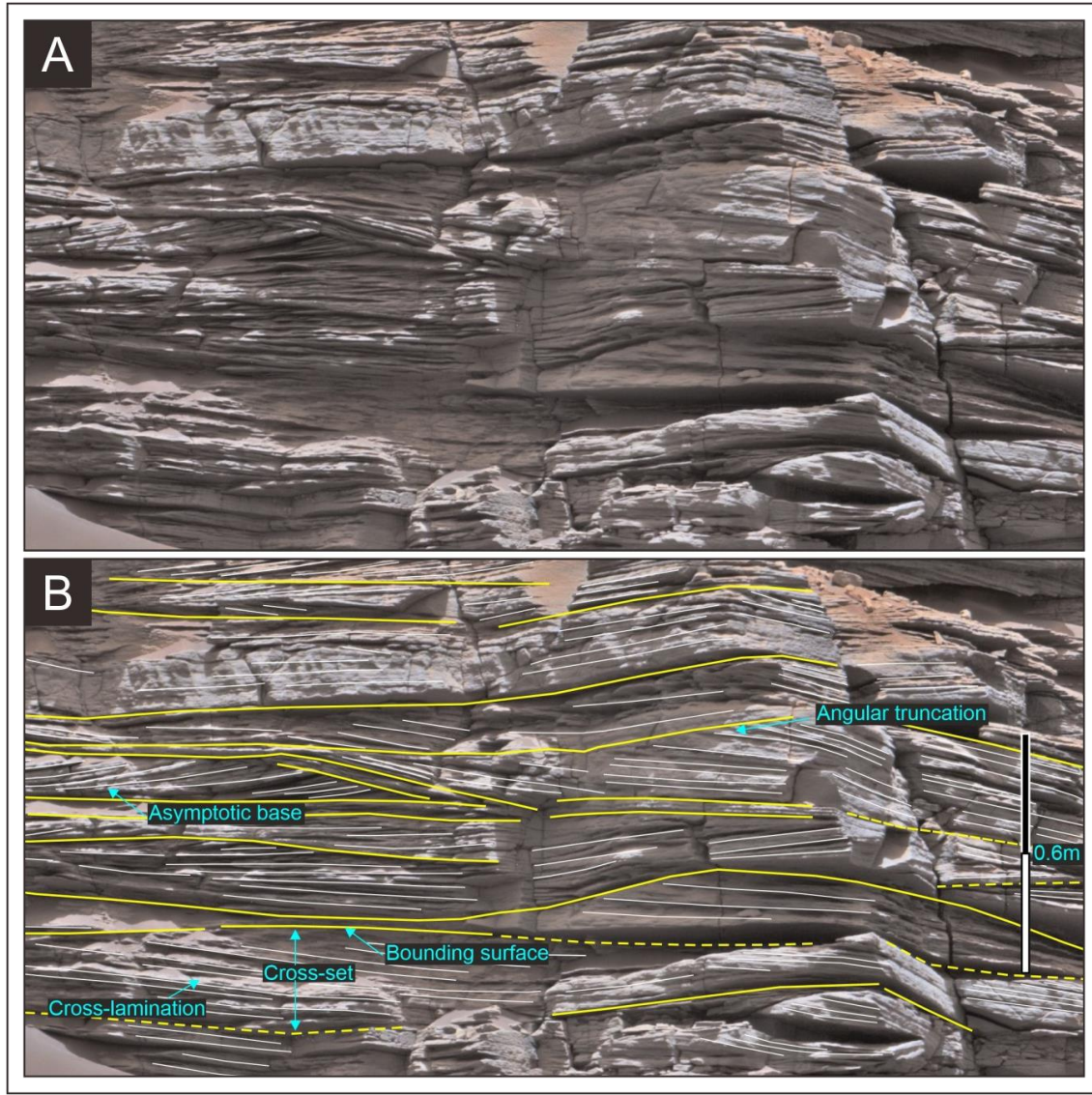


Figure 2.4 Stimson formation in Gale Crater taken by Curiosity’s Mastcam. The uninterpreted (A) and interpreted (B) strata show a distinctive ancient aeolian deposit, made of mafic grains of reworked volcanoclastic origin. Modified after Banham et al., 2021.

The geochemical composition of Wishstone class rocks indicates 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 infrared spectra 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 phreatic 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 (Scott & Tanaka, 1986; Greeley & Guest, 1987; Bradley et al., 2002), and at the Cerberus Fossae fissure system in Elysium Planitia which is a low-albedo, high-calcium pyroxene-rich unit (Horvath et al., 2021).

This thesis research aims not to compare an already established Mars analog such as Iceland and Hawaii with Merapi, but to give additional insights on Mars sedimentary systems based on our findings. The basaltic nature of Iceland's and Hawaii's magmatic composition is different from the Merapi's basaltic to basalt-andesitic magma. However, is it possible for Mars during its past to have volcanoes with a similar magmatic composition like Merapi? We might not be able to fully understand the provenance of this reworked igneous material

today on Mars; however, we can see the deposits of basaltic to andesitic minerals (Fig. 2.4) on Gale Crater (McSween Jr. et al., 2009; Schmidt et al., 2014; Treiman et al., 2016; Siebach et al., 2017; Bedford et al., 2019) and reworked pyroclastics on Home Plate, Gusev crater (Squyres et al., 2007). Indeed, magmatic and mineralogical fractionation are active scientific frontiers on Mars geology. The latest rover for Mars 2020 Mission, Perseverance, is even set to explore a more diverse geological complex in Jezero Crater (Fig. 2.5), with strong indication of ancient fluvial and coastal sedimentary systems. In Gale crater, Curiosity rover has delivered over 30 drilled samples of sedimentary material into its XRD instrument, CheMin, and found abundant plagioclase feldspar and pyroxene minerals. In addition, evolved igneous minerals such as sanidine, tridymite, and cristobalite are present at certain locations along its traverse indicative that basalt is not the only sediment source (Vaniman et al., 2014; Treiman et al., 2016; Morris et al., 2016; Rampe et al., 2020).

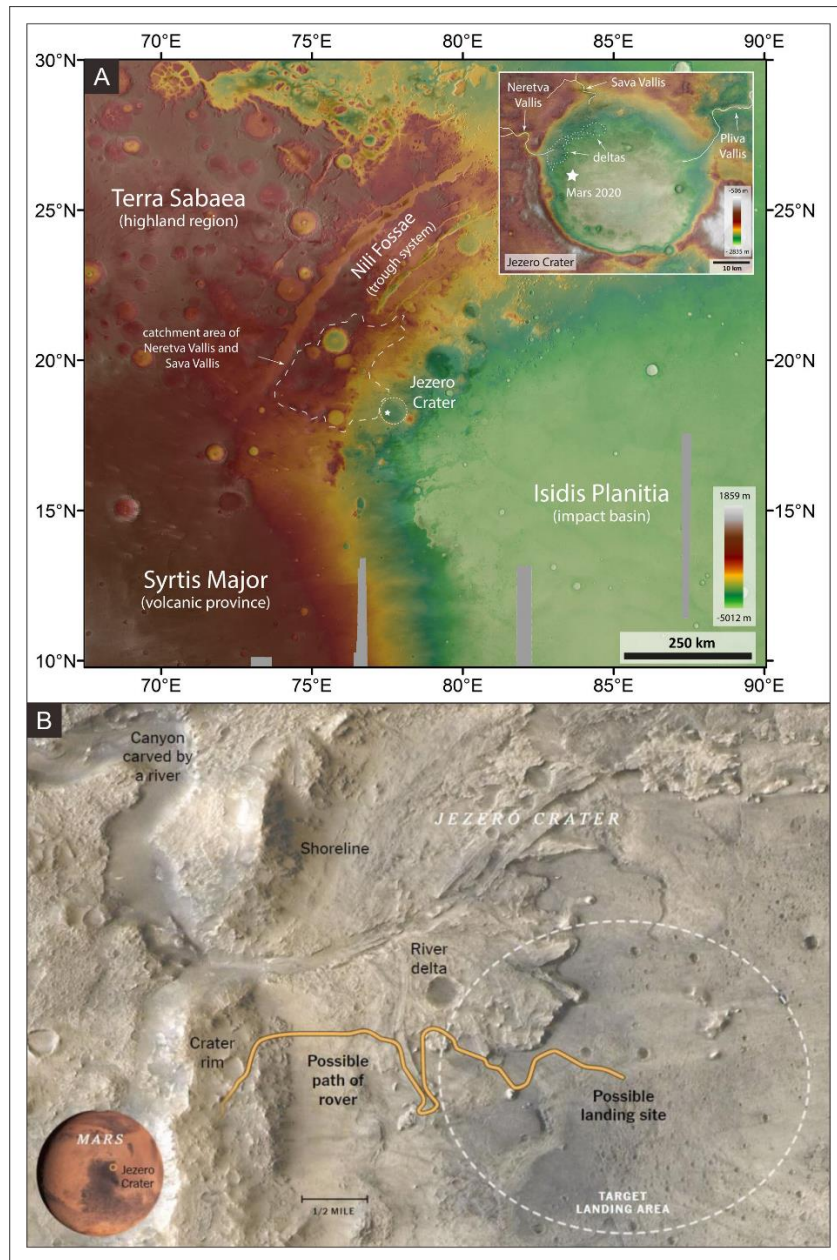


Figure 2.5 Jezero Crater and its surrounding geological provinces. Notice the proximity of the crater with Syrtis Major volcanic province (A). The landing site and trajectory of Perseverance Rover (B) are highlighted along with geomorphology of the surrounding area. After ESA Mars Express (A) and NASA/JPL-Caltech (B).

CHAPTER 3

METHODOLOGY

The methodology of this research consists of a geological expedition (sample collection and field work), laboratories analysis (grain size separation, digital petrography, XRD, and XRF), statistical analysis (Px/PF Ratio, Chemical Index of Alteration, A-CN-K ternary diagram, and multivariate statistical analysis), non-destructive geophysical acquisition, and the detection of bedform migration through remote sensing (COSI-Corr). Therefore, the methodological workflow is described in general (Fig. 3.1) and later divided into more detailed aspects.

3.1 SAMPLE COLLECTION AND FIELD WORK

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 (Fig. 3.2 A). Every stop-sites were aerially documented using a drone. Sampling locations are plotted with elevation and distance from source to sink in order to show their spatial variability (Fig. 3.2 B). The samples were then dried in a vacuum oven at a temperature of 60°C for 24 hours to remove any fluid such as water and brine.

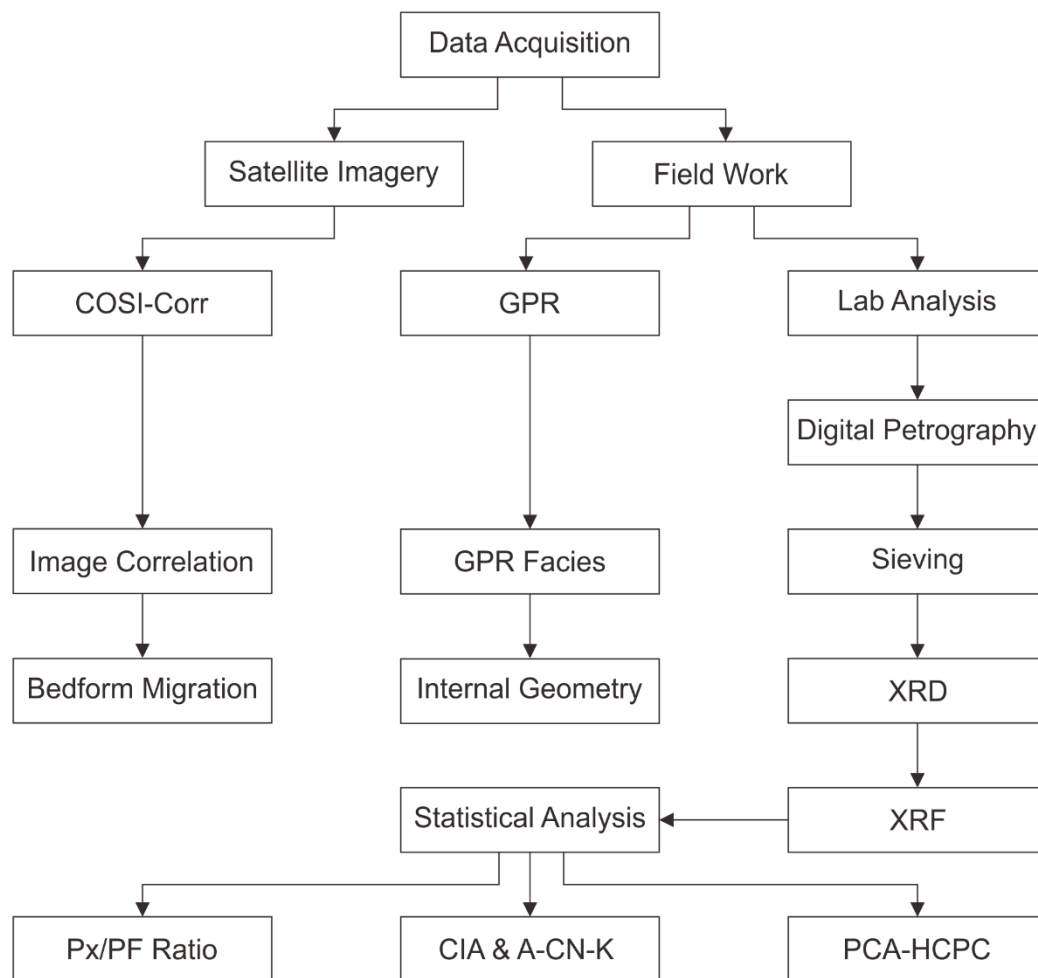


Figure 3.1 Generalized methodology of this thesis research. The methods are discussed further for each step along with each of their objectives.

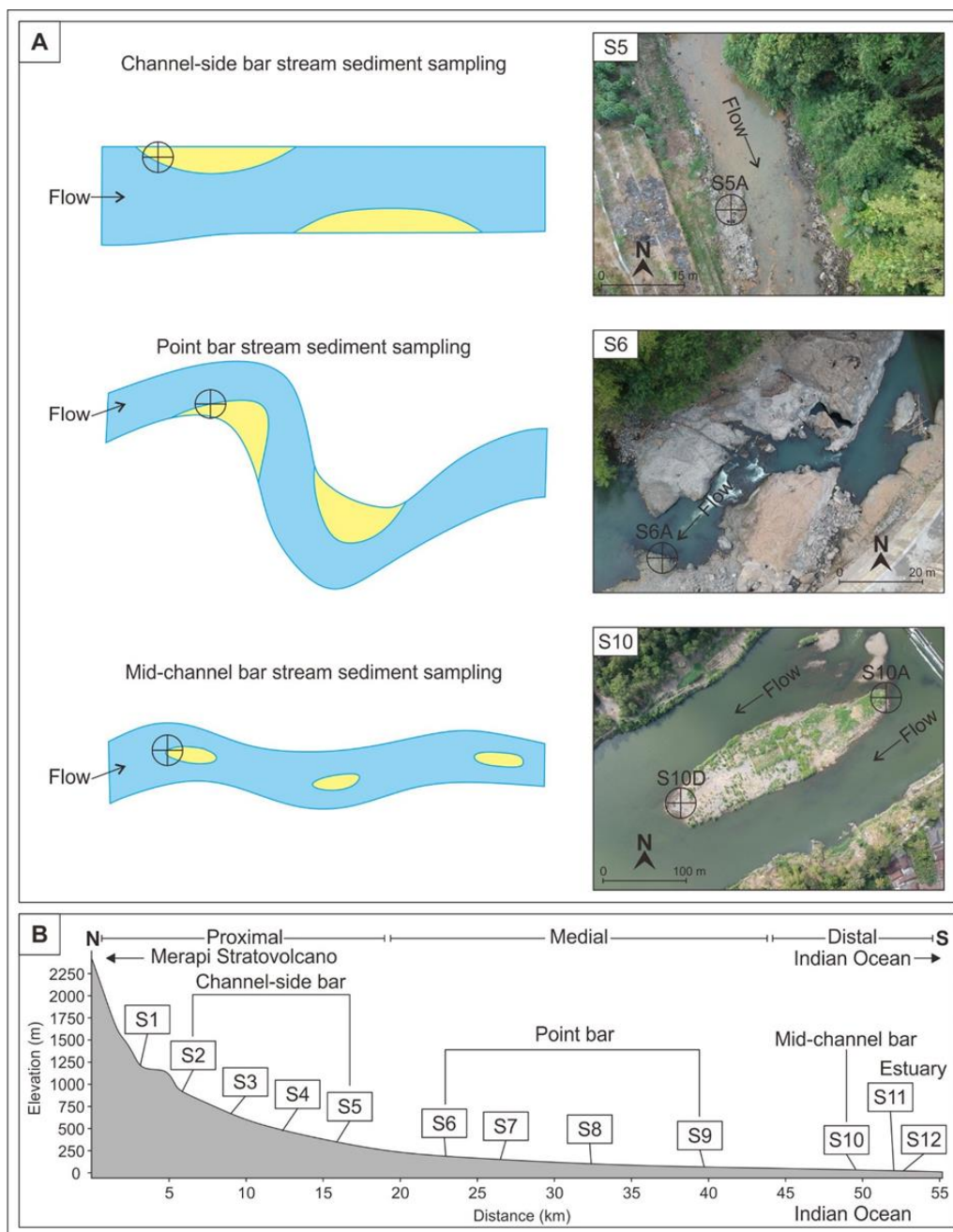


Figure 3.2 Sampling methodology according to their channel bar type. The sampling locations (A) are plotted with elevation and distance from source to sink (B). Notice the contrast of slope gradient between proximal – medial (S1 – S5) compared to medial – distal (S6 – S12).

3.2 LABORATORIES ANALYSIS

3.2.1 Grain Size Separation

To separate the grain size distribution, 25 g aliquots of each sample were sieved with a rotary shaker for 10 minutes. 6 sieving racks stacked with phi number (ϕ) ranging from 0 to +4 represent very coarse - very fine sand, whereas +5 and $\phi > 6$ represent coarse - medium and medium - fine silt, respectively. Average grain size is estimated by multiplying the result from sieve analysis with the grain size category (phi number), which will give a function of grain size relative to each sample net weight percentage.

3.2.2 Digital Petrography

Thin sections were prepared from the dried samples with the help of GeoZentrum NordBayern (Germany). These thin sections were scanned using Zeiss AxioScan, which was later processed using Zen Blue software to create ROI (Region of Interests) for each scanned thin section. Mineral identification was performed manually, however, extraction of identified mineral imageries was done using FIJI ImageJ software (Fig. 3.3).

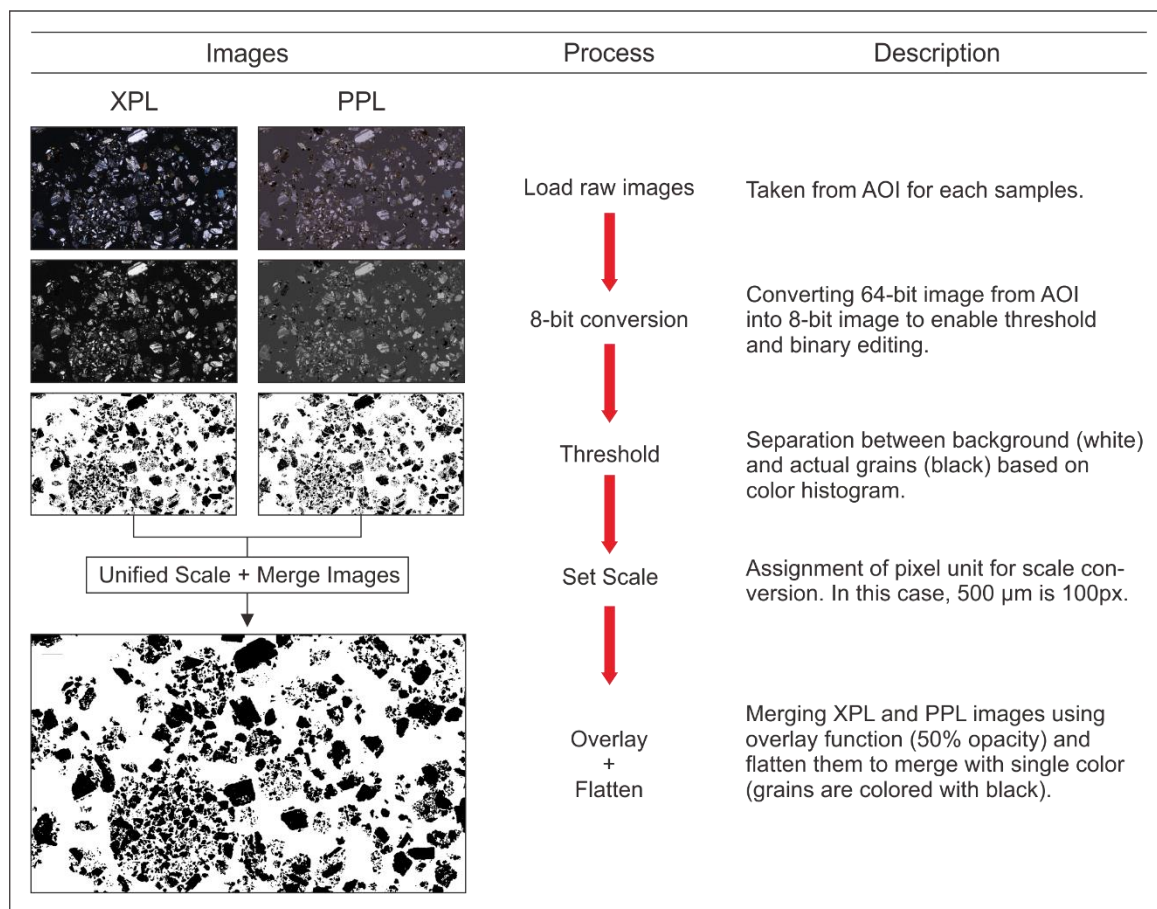


Figure 3.3 Workflow to isolate mineral grains from background image. The isolated mineral grains are used to analyze grain texture, in conjunction with manual identification of mineral.

3.2.3 X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF)

Bulk samples for XRD and XRF were pulverized prior to analyses using a rock crusher machine for 15 minutes. 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. For the determination of major and minor bulk elemental concentrations, samples were first pulverized into powder, loaded into special cups and the analysed 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 the results are reproduceable 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 concentrations 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.

3.3 STATISTICAL ANALYSIS

3.3.1 Pyroxene/Plagioclase Feldspar (Px/PF) Ratio

Hand specimen samples are selected as host rocks to calculate their average pyroxene /plagioclase feldspar (Px/PF) ratio as a cut-off value to determine the mineralogical sorting against their depositional environment. The average grain size value was then combined with the Px/PF ratio to identify the relationship between mineral sorting against the grain size function and its subsequent depositional distance. Subsequently, stream sediment samples were grouped as (1) pre-fault fluvial and (2) post-fault fluvial in order to understand the significance of Opak River in altering the mineralogical and grain size sorting. The average Px/PF ratio of parabolic sand dune was compared with Px/PF ratio of modern aeolian (Rocknest, Gobabeb, Ogunquit Beach) and ancient aeolian on Mars (Stimson formation's Big Sky, Okoruso, Greenhorn, and Lubango). The pyroxene of Stimson formation was summed up values from pigeonite and orthopyroxene (Rampe et al., 2020).

3.3.2 Chemical Index of Alteration and A-CN-K Ternary Diagram

Chemical Index of Alteration (CIA, in molar proportions) was calculated based on the measured oxides from the XRF. The wt% unit was converted into molar by dividing the weight percent by molecular weight (Goldberg and Humayun, 2010). We used the CIA ratio (Nesbitt and Young, 1982) as follows:

$$CIA = \left(\frac{Al_2O_3}{Al_2O_3 + CaO^* + Na_2O + K_2O} \right) \times 100$$

The result was plotted as an A-CN-K ternary diagram along with the findings from Gale Crater (Mangold et al., 2019), Stimson formation (Bedford et al., 2020), and Mars' crust (Taylor and McLennan, 2009).

3.3.3 Multivariate Statistical Analysis

In order to reduce the relative effects of variables measured on different instruments, scales and ranges, the datasets 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). Two multivariate

statistical techniques were employed to find patterns in our high dimensional dataset and establish relationships. Firstly, Principal Component Analysis (PCA) using the singular value decomposition method. Second, Hierarchical Clustering of Principal Components (HCPC) based on Ward's method of agglomeration and Euclidean distance on the standardized dataset. Both PCA and HCPC 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 and Mundt, 2016), FactoInvestigate (Thureau and Husson, 2020), corrplot (Wei & Simko, 2017), Factoshiny (Vaissie et al., 2017), Performance Analytics (Peterson et al., 2014), and tidyverse (Wickham et al., 2019).

3.4 GROUND PENETRATING RADAR

Two GPR profiles were acquired to identify the internal structure of the shoreface and a parabolic sand dune using GSSI SIR 4000 installed with 100 Mhz antennae. A 110 m long GPR profile (Fig. 3.4 A) is acquired on our selected dune with surface sediment sampling along its blowout surface, stoss, and lee (Fig. 3.4 B). Similarly, a 90 m GPR profile on Parangkusumo Shoreface was acquired along with surface sediment sampling from the foreshore, berm, and backshore. Post-processing for both GPR lines includes global background removal, time-zero, first break estimation, predictive deconvolution, wavenumber filtering, amplitude and power gain, and topographic correction.

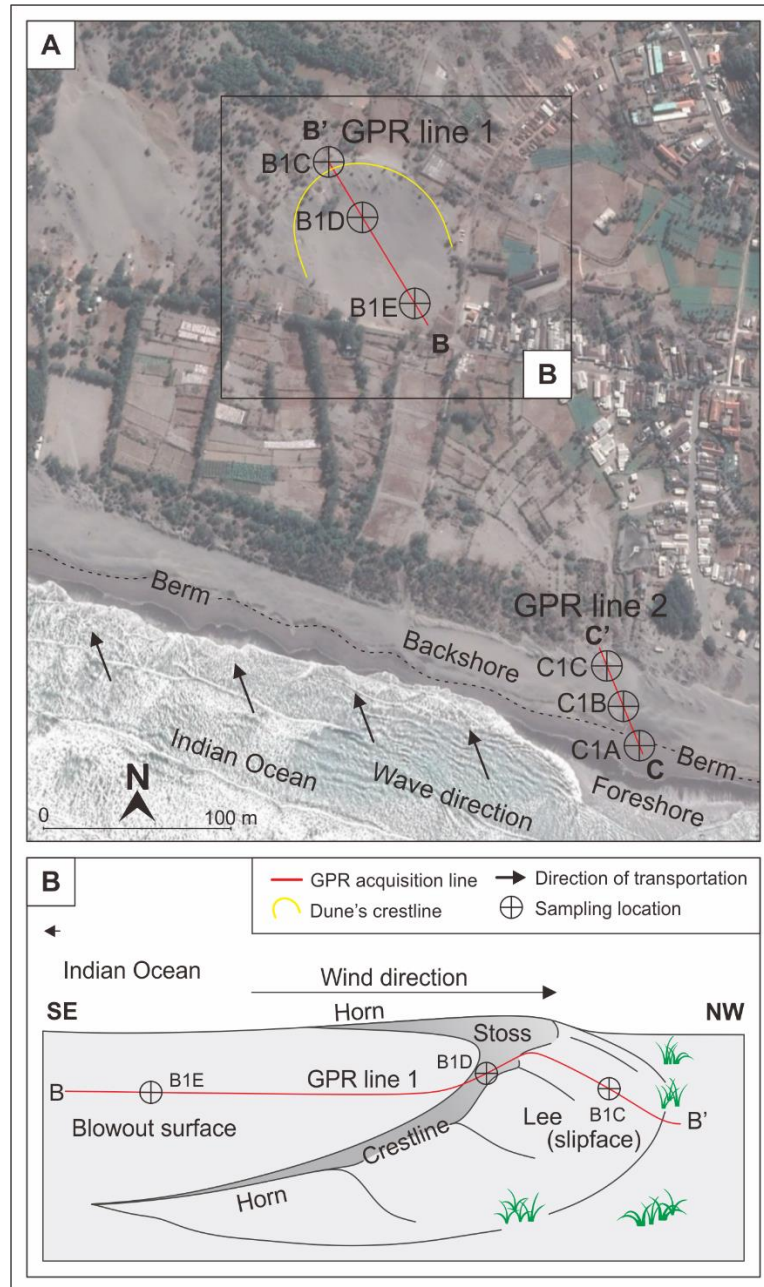


Figure 3.4 GPR acquisition profiles (A) and the illustration of dune morphology (B). Notice the second GPR line in the foreshore.

3.5 COSI-Corr

A total of 6 orthorectified Sentinel 2 satellite imageries with temporal variation from 2017, 2018, and 2019 each with wet and dry season were downloaded from United States Geological Survey (USGS) Earth Explorer website (<https://earthexplorer.usgs.gov>) as the inputs for image correlation and co-registration. Coordinate reference system was set using WGS 84 / UTM zone 49S. Details of each dataset can be seen in Table 2, and the available bands of each image are presented in Table 3. Image correlation workflow using COSI-Corr is presented in Fig. 3.5, and the parameters used to perform correlation are presented in Table 4. The NIR (Near Infra-Red) spectral band was chosen to conduct image correlation, as the NIR provides the clearest visual acuity while still retain the highest resolution of all available spectral bands. A comparison between RGB (Red-Green-Blue), NIR, and TCI (True Color Images) spectral bands is compiled in Fig. 3.6. Because each dataset has their own radiometric signature, a pre-processing step was needed to ensure that each data was normalized. The radiometric normalization was performed to reduce a time-series image variation (Hong and Zhang, 2008). Built-in *gdal_translate* command in QGIS was used to code for the radiometric band normalization into 0-255 values for the NIR band of each image. A pre-normalized and post-normalized image comparison is shown in Fig. 3.7. Image correlations were performed between wet and dry season for each year. The outputs from correlation step are 3 images, which are NS (North-South) Correlation, EW (East-West) Correlation, and SNR (Signal-to-Noise Ratio).

The results from NS and EW were used to calculate (1) average velocity map, to measure the rate of bedform migration, and (2) displacement map, to quantify the bedform migration using band math equation:

$$Velocity Map = \frac{Displacement Map_n + Displacement Map_{n+1} + \dots}{Time of Observation (in year)}$$

whereas the displacement map is derived from:

$$Displacement Map = \sqrt{EW^2 + NS^2}$$

Results from each year's displacement map were summed to calculate for cumulative displacement map. The cumulative displacement map was post-processed further using (1) Image detrending, to center the offset of histogram from the image correlation step, and (2) Masking by discard image values, to remove the artifact of water bodies and clouds. Finally, the post-processed image was taken into an input to create vector field which can be superimposed on each dataset, visualizing the direction and the magnitude of bedform migration.

Table 2 Sentinel 2 dataset information.

File	Year of Acquisition	Season	Available Bands	Spatial Resolution
L1C_2017_05_19	2017	Wet	14	Up to 10 m
L1C_2017_08_07		Dry	14	Up to 10 m
L1C_2018_05_04	2018	Wet	14	Up to 10 m
L1C_2018_10_11		Dry	14	Up to 10 m
L1C_2019_05_04	2019	Wet	14	Up to 10 m
L1C_2019_09_11		Dry	14	Up to 10 m

Table 3 Available bands from Sentinel 2 satellite imageries.

Band	Band Width (nm)	Central Wavelength (nm)	Resolution (m)	Remarks
B01	20	443	60	Aerosol detection
B02	65	490	10	Blue
B03	35	560	10	Green
B04	30	665	10	Red
B05	15	705	20	Vegetation Red Edge
B06	15	740	20	Vegetation Red Edge
B07	20	783	20	Vegetation Red Edge
B08	115	842	10	NIR
B08A	20	865	20	Vegetation Classification
B09	20	945	60	Water vapor
B10	30	1375	60	Cirrus
B11	90	1610	20	Snow/ice/cloud discrimination
B12	180	2190	20	Snow/ice/cloud discrimination
B13	-	-	-	TCI preprocessed from directly from USGS.

Table 4 Parameters implemented for image sub-pixel correlation using COSI-Corr.

Correlator	Frequency
Initial Window (pixel)	128 x 128
Final Window (pixel)	64 x 64
Step (pixel)	2 x 2
Mask Threshold	0.9
Robustness Iteration	2
Resampling Processes	No
Grided Output	Yes

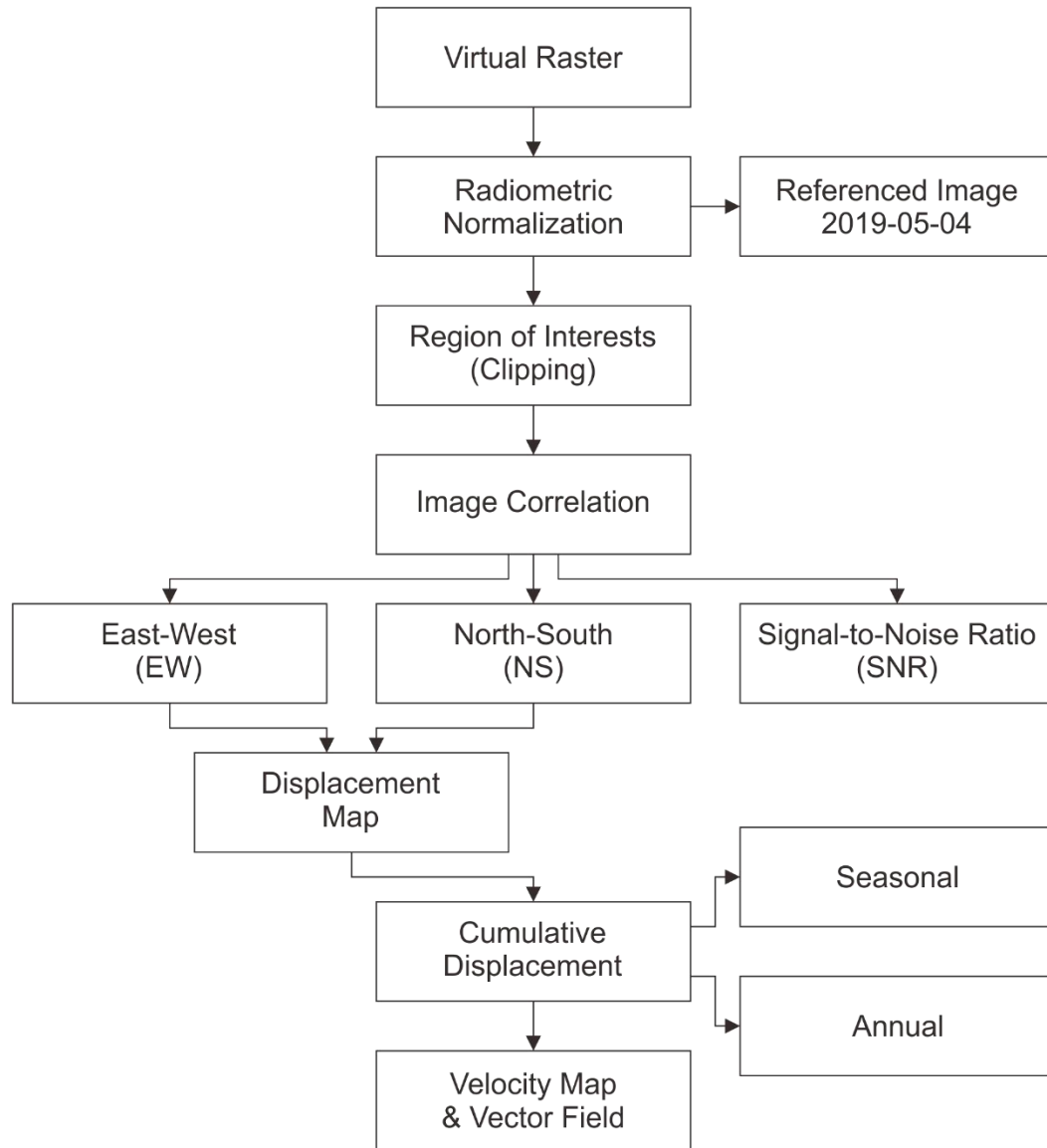


Figure 3.5 Workflow for COSI-Corr to generate displacements and velocity map. COSI-Corr was performed using build-in ENVI plugin, whereas map generation was carried out using QGIS.

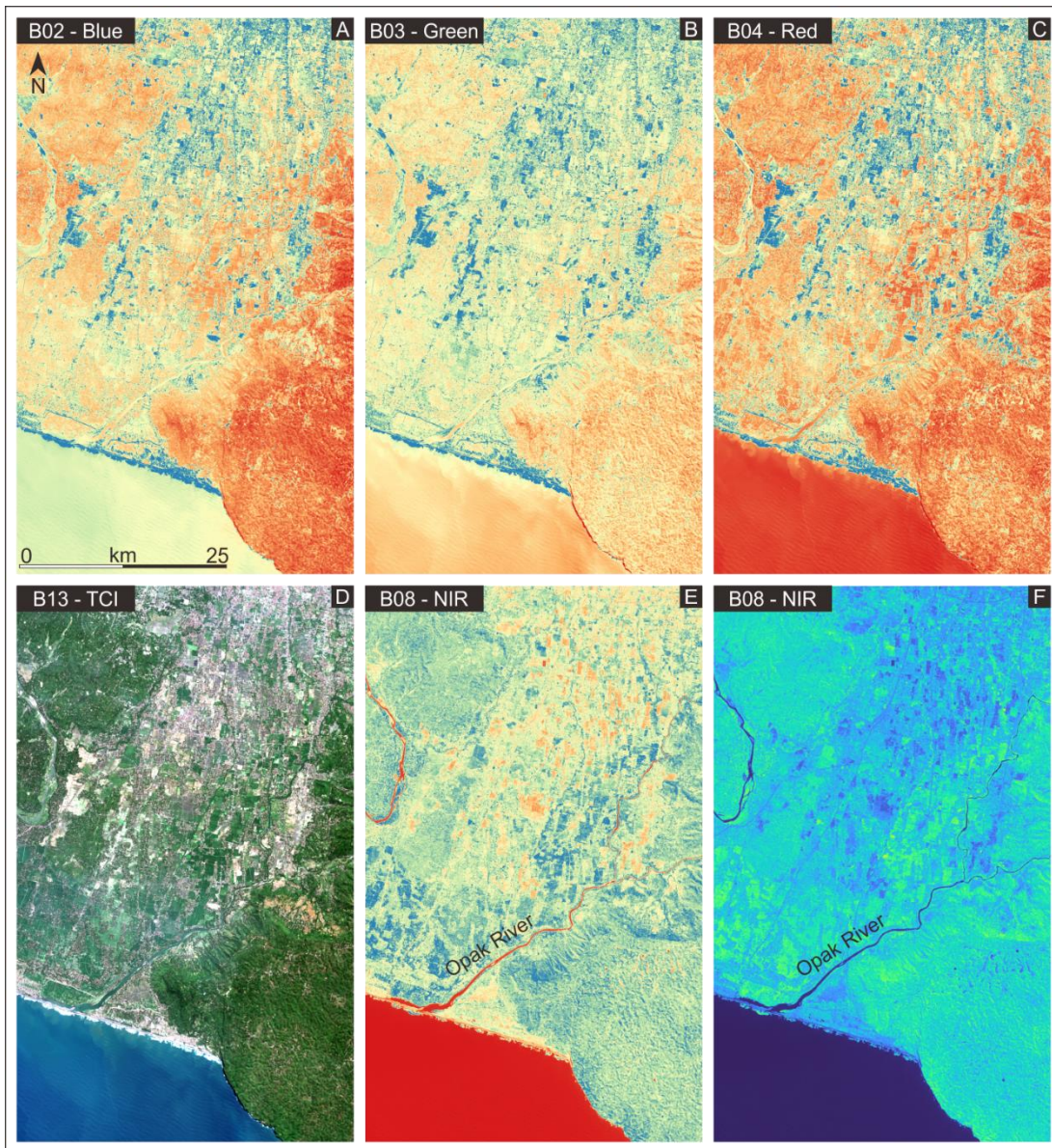


Figure 3.6 Band comparisons taken from 2018-05-04 Sentinel 2 Image. Blue (A), Green (B), and Red (C) are rendered in single band pseudo-color, which can be combined into a True Color Image (TCI) to show the visible light spectrum (D). Notice the better visual acuity for observing Opak River shown using Near Infra-Red (NIR) rendered in single band pseudo-color (E and F). The NIR images are colored in spectral color bar (E) and high-vis color bar (F).

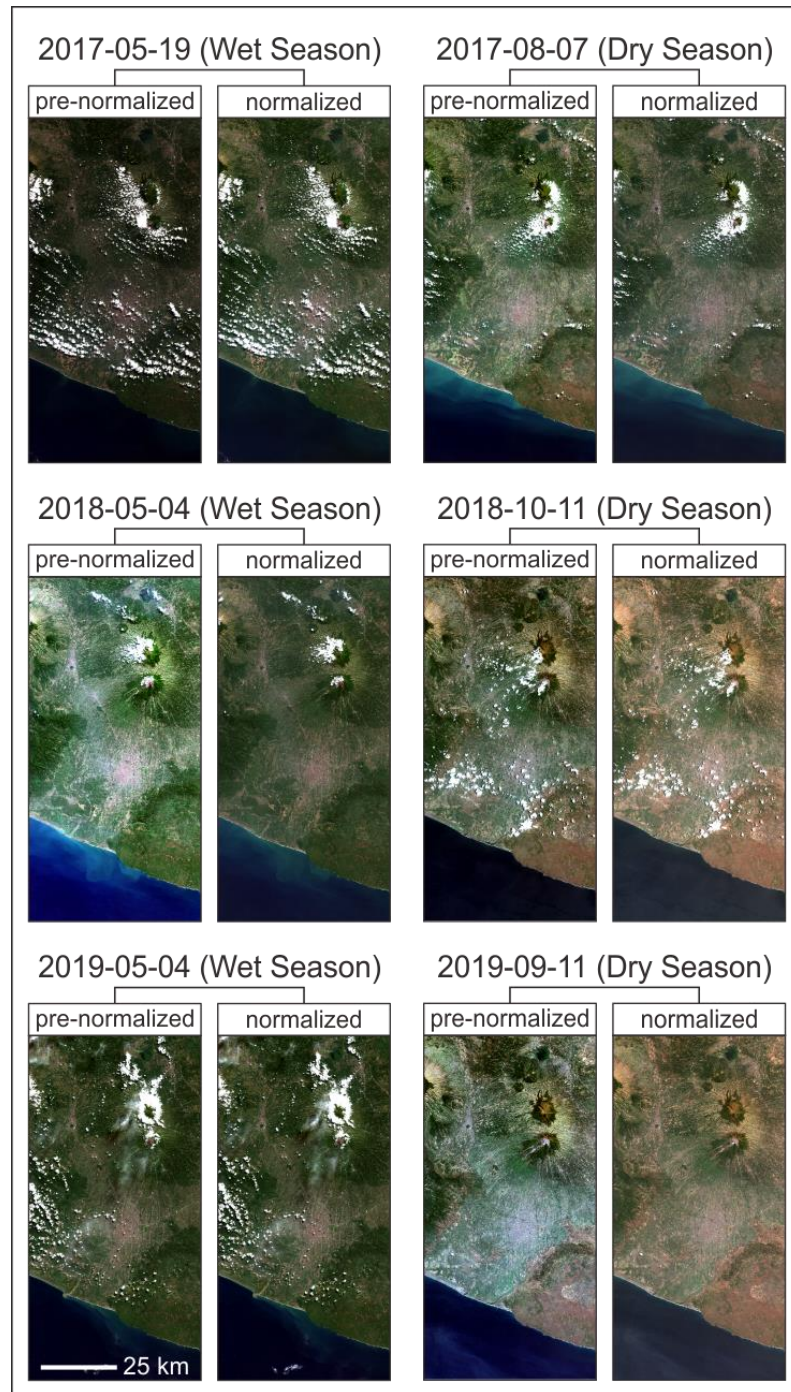


Figure 3.7 Comparison between pre- and normalized Sentinel 2 images. Notice the difference in cloud coverage and how the season affects radiometric reflectance on the vegetation.

CHAPTER 4

RESULTS

The result of this research is presented systematically and spatially from map-scale (field investigation and COSI-Corr) to meso-scale (GPR and grain size distribution), the micro-scale (petrography, XRD, and XRF), and finally the statistical analysis (Px/PF ratio, A-CN-K ternary diagram, and multivariate statistical analysis).

4.1 FIELD INVESTIGATION AND SAMPLE COLLECTION

Reworked volcanoclastics from Merapi eruptions are transported by Opak River and deposited in channel-side bars during the proximal stage, followed by point bars on medial, and a mid-channel bar before eventually accumulate as estuary deposits in the distal part. Summary of sampling collection with each remark is tabulated in Table 5. 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 flows along the normal fault's axis (Fig. 2.1 A). Slope angle also affects Opak River's depositional environment (Fig. 2.1 B) which shows a contrast between (1) proximal – medial steep slope angle (8.27°, 14.54%, bearing N 169.5° E) and a gentler slope of (2) medial – distal (0.32°, 0.52%, bearing N 219° E).

Table 5 Sample identifications

Sample ID	Elevation (m)	Stream width (m)	Remarks
Stream sediment samples			
S2A	812	2	Channel-side bar
S3A	610	8	Channel-side bar
S4A	409	12	Channel-side bar
S5A	293	15	Channel-side bar
S6A	178	24	Point bar
S7A	124	26	Point bar
S8A	86	45	Point bar
S9A	48	50	Point bar
S10A	16	300	Mid-channel bar, NE tip
S10D	15	300	Mid-channel bar, SW tip, trenched and mined by the locals.
S11A	1	-	Estuary, washover barrier sand, facing the river.
S11B	2	-	Estuary, washover barrier sand, facing the river, located higher and less dark than S11A
S12A	2	-	Estuary, washover barrier sand, facing the ocean, located higher and less dark than S12B
S12B	1	-	Estuary, washover barrier sand, facing the ocean. Presence of shells along the shore.
Hand specimen samples			
S1A	1178	-	Dark grey mafic scoria
S1B	1167	-	Dark grey mafic diabase
S2C	812	-	Light grey porphyritic andesite
Shoreface samples			
C1A	1	-	Foreshore
C1B	2	-	Backshore
C1C	2	-	Backshore
Sand dune samples			
B1C	4	-	Lee side (slipface)
B1D	5	-	Stoss side (windward)
B1E	4	-	Blowout surface

A mid-channel bar is present in the distal site of Opak River, 5 km NE of the Opak Estuary (Fig. 4.1 A). The mid-channel bar is non-migrating and elongated, parallel to the flow of Opak River. Trenching is performed in the mid-channel bar since the unconsolidated nature of Merapi volcanoclastic sands were easily dug, and provides the visual identity of sedimentary structures formed within the mid-channel bar. This elongated, parallel to flow direction bar is non-migrating and situated in a low-sinuosity portion of the Opak River, 5km NE of the Opak Estuary. Trenching in the mid-channel bar shows a planar cross-bedding with stratified gravels embedded in the foresets (Fig. 4.1 C) 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 (Fig. 4.1 B).

4.2 MULTITEMPORAL REMOTE SENSING ANALYSIS

Initial result from image correlation using COSI-Corr (Fig. 4.2) shows 3 images of east-west (EW) correlation, north-south (NS) correlation, and Signal to Noise Ratio (SNR) for each dataset. All annual temporal image processing starts from wet season as the pre-event input and dry season as the post-event input. Overall, the result shows pixel displacement located at the proximal of Merapi stratovolcano and the distal part of Opak Estuary. Several artefacts of image correlation can be seen in the proximal and medial part of Opak River, notably from the clouds captured during the 2017 and 2018 events compared with the 2019 datasets.

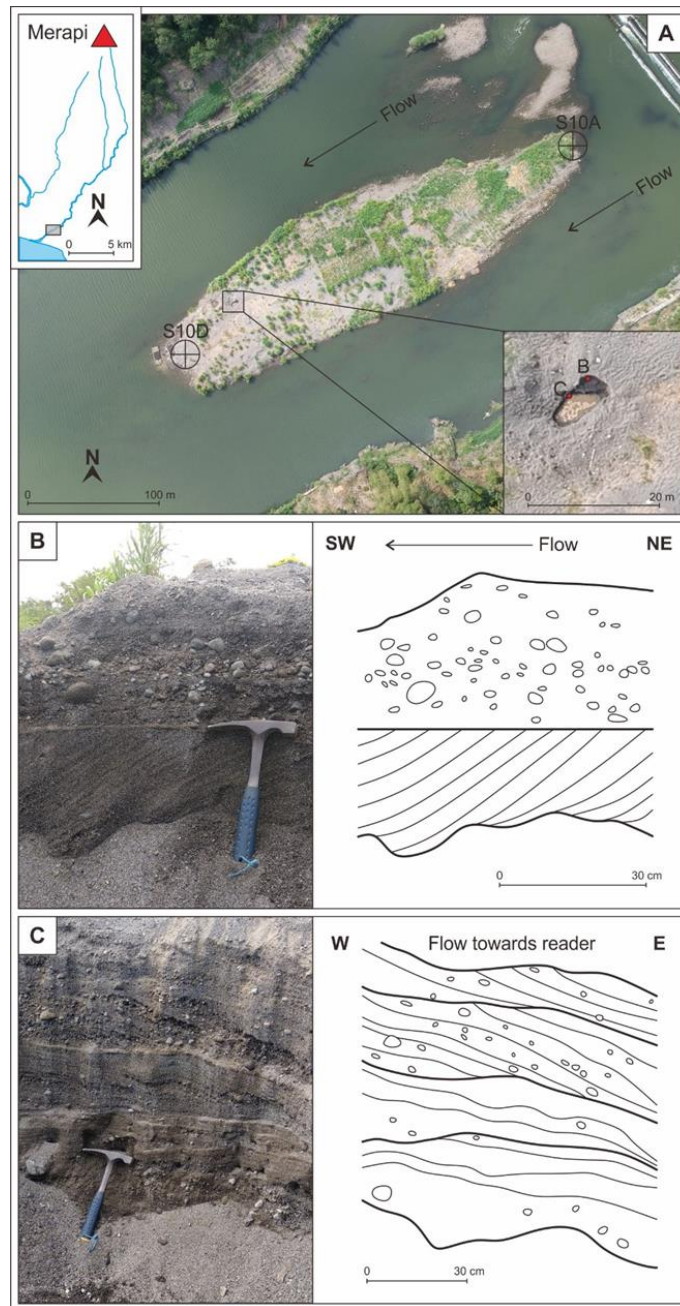


Figure 4.1 Mid-channel bar formed in S10 sampling location. Notice the sedimentary structure shown in the trench (A), formed by the unconsolidated black sands (B and C). This location is mined by the locals for their iron-rich sand used for construction materials.

Despite the contrast in cloud coverage, all of the results retain a similar noise in the interface between the estuary and Indian Ocean. This noise is due to wave currents radiometric signature captured by the satellite; therefore, it requires an additional step to mask the water bodies. The result from masking water bodies and clouds (Fig. 4.3) shows that within proximal part of Merapi is saturated with cloud coverage (most notably from 2017 and 2018 satellite image capture) which created de-correlation artefacts. However, the radiometric signal from the caldera of Merapi is still visible, which shows no bedform migration from pre-and post-2018 May eruption. In the medial part of Opak River, no deformation is detected prior and after the eruption event. Minor bedform migration detected in the southeast part of Opak River is in fact due to the difference in vegetation color reflectance between dry and wet season. Similarly, the rice fields in the southwest part of Opak River also created a pseudo bedform migration response due to luminosity reflectance created by seasonal variation, where these rice fields were drowned in irrigation during the wet season. The most notable bedform migration happens in Opak Estuary, which justifies the importance of calculating the bedform migration velocity specifically within that area.

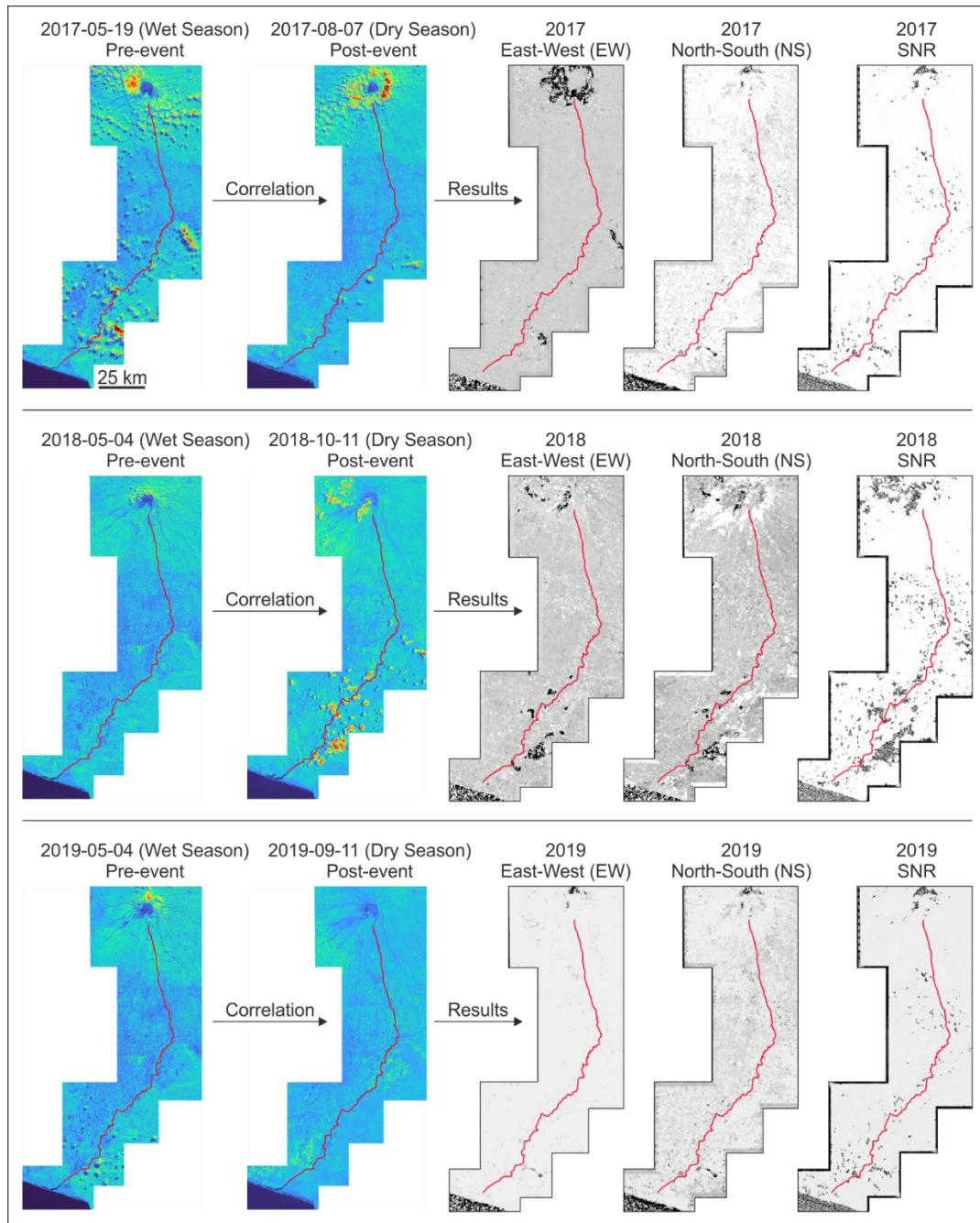


Figure 4.2 Initial results from COSI-Corr for each annual dataset. The imposed red line in each image denotes the trajectory of Opak River.

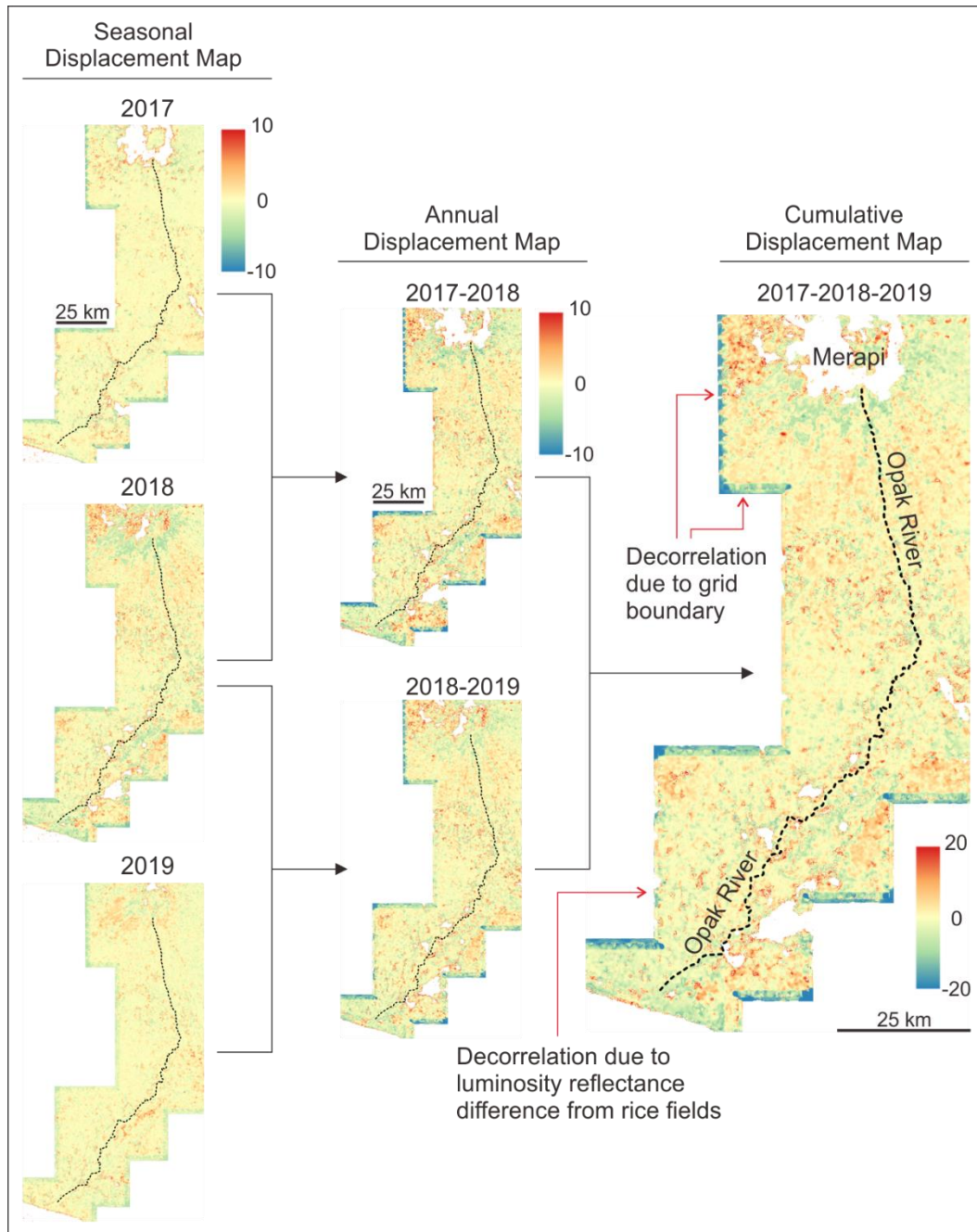


Figure 4.3 Seasonal, annual, and cumulative displacement maps of Merapi sedimentary systems.

Black dotted line denotes Opak River.

During the wet season of 2017, initially there were point bars attached within the meandering river bank (Fig. 4.4 A). Overtime, during the dry season, these point bars are detached at a rate of 0.5 m/year, migrating northeastward and eastward as shown by the vector field (Fig. 4.4 G). Accompanying the point bars detachment is an increasing width of Opak River from 97 m (Fig. 4.4 A) to 102 m (Fig. 4.4 B). Within a year, the point bars had completely disappeared (Fig. 4.4 C and D), and Opak River's width is substantially increased to 163 m during wet (Fig. 4.4 C) and 172 m (Fig. 4.4 D) during dry season of 2018. The visible estuarine lagoon mud flats (Fig. 4.4 A) are completely drowned as well during the wet season of 2018. The vector field shows that estuarine lagoon is not drowned by Indian Ocean, but instead by smaller fluvial channels across the rice fields flowing southwest (Fig. 4.4 G and H) with a rate of 2 m/year. The vector field within the estuarine lagoon shows a shift in direction and magnitude from an average of 2 m/year southwestward (Fig. 4.4 H) to 1.5 m/year northeastward (Fig. 4.4 I). A summary of spatial change within the Opak Estuary geomorphology is tabulated in Table 6.

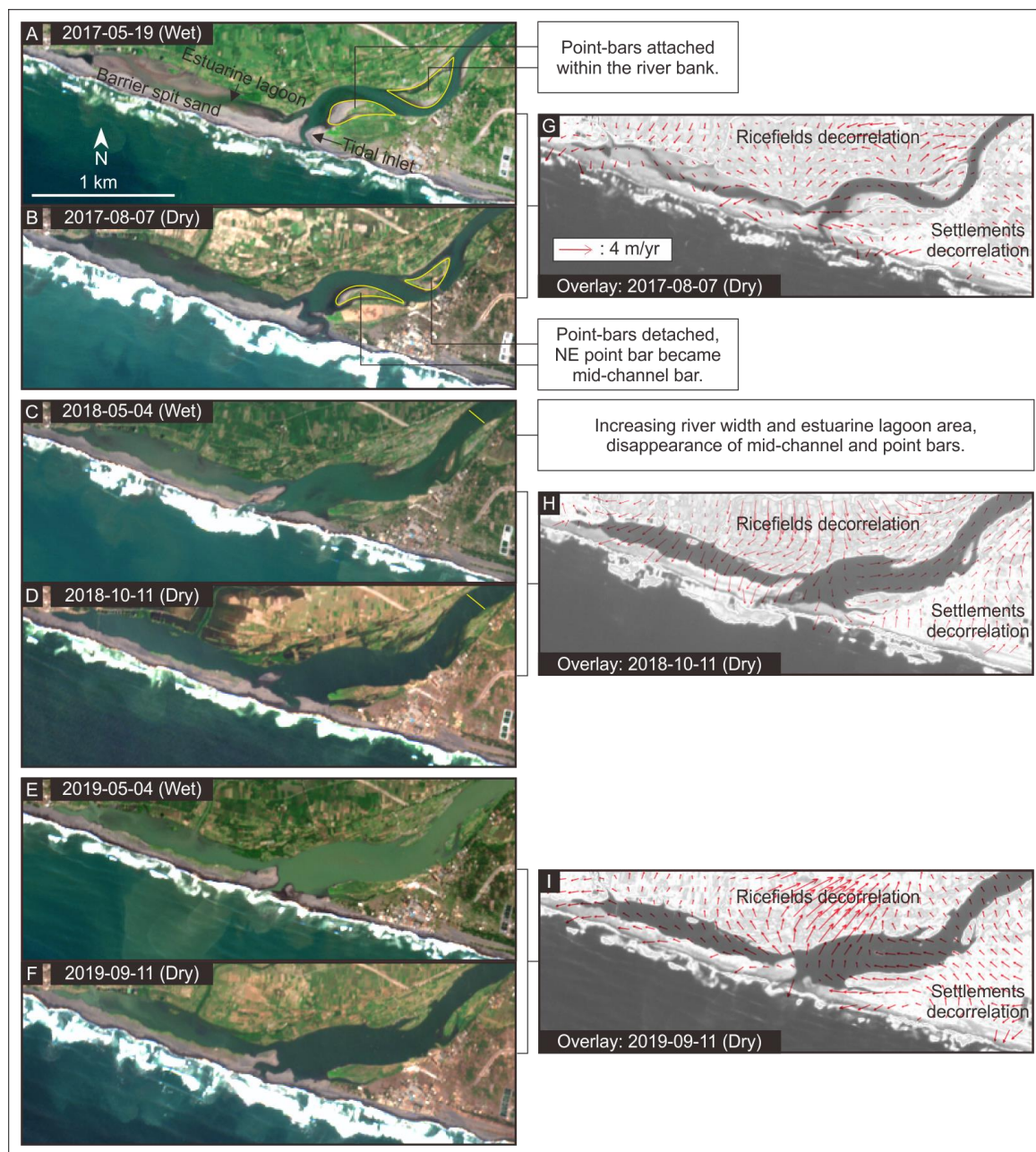


Figure 4.4 TCI images of Opak Estuary (A-F) and vector fields (G-I). Notice the change in river and tidal inlet width, along with area of estuarine lagoon. De-correlations are detected in the rice fields and settlements area.

Table 6 Spatial change of Opak River geomorphology.

Year	Season	Opak River width (m)	Tidal inlet width (m)	Estuarine lagoon area (km ²)
2017	Wet	97	40	0.226
	Dry	102	56	0.327
2018	Wet	163	111	0.253
	Dry	172	91	0.319
2019	Wet	181	87	0.263
	Dry	203	67	0.266

4.3 GPR FACIES INTERPRETATION

GPR profiles across the Parangkusumo shoreface and the parabolic sand dune show distinctive reflection patterns with several geometries and intensities (Fig. 4.5). An illustration of the parabolic dune transect is also shown (Fig. 4.5 A-i). GPR line B begins at the blowout surface and moves upwind to the lee in a SE-NW direction. The section reveals an internal geometry of the parabolic sand dune with different angularity of cross-strata and interdune surfaces (Fig. 4.5 B). The modern surface slope angle from the stoss side to the top of crestline is 4.5° while the lee side to top of crestline reaches 32.5° . Cross-strata surface and interdune surface reflection patterns are visible down to approximately 15 m effective depth from the surface of this dune. An interpreted established foredune is visible roughly 6 m beneath the modern lee surface with a steeper stoss-side slope of 13° and lee-side slope of 42° compared with the modern dune surface.

GPR line C with 90m length from the foreshore towards the backshore passed a substantial 4 m elevation height difference on the berm (Fig. 4.5 C). The effective depth of this GPR line reached approximately 6 m below the surface, shallower than the parabolic dune GPR line. A comparison between the uninterpreted and interpreted section is presented within the inset of GPR line C (Fig. 4.5 C-i and Fig. 4.5 C-ii), revealing upslope climbing clinoforms (red vector arrow) with angle of repose inclining towards NW, unidirectional with the swash motion of waves coming from Indian Ocean.

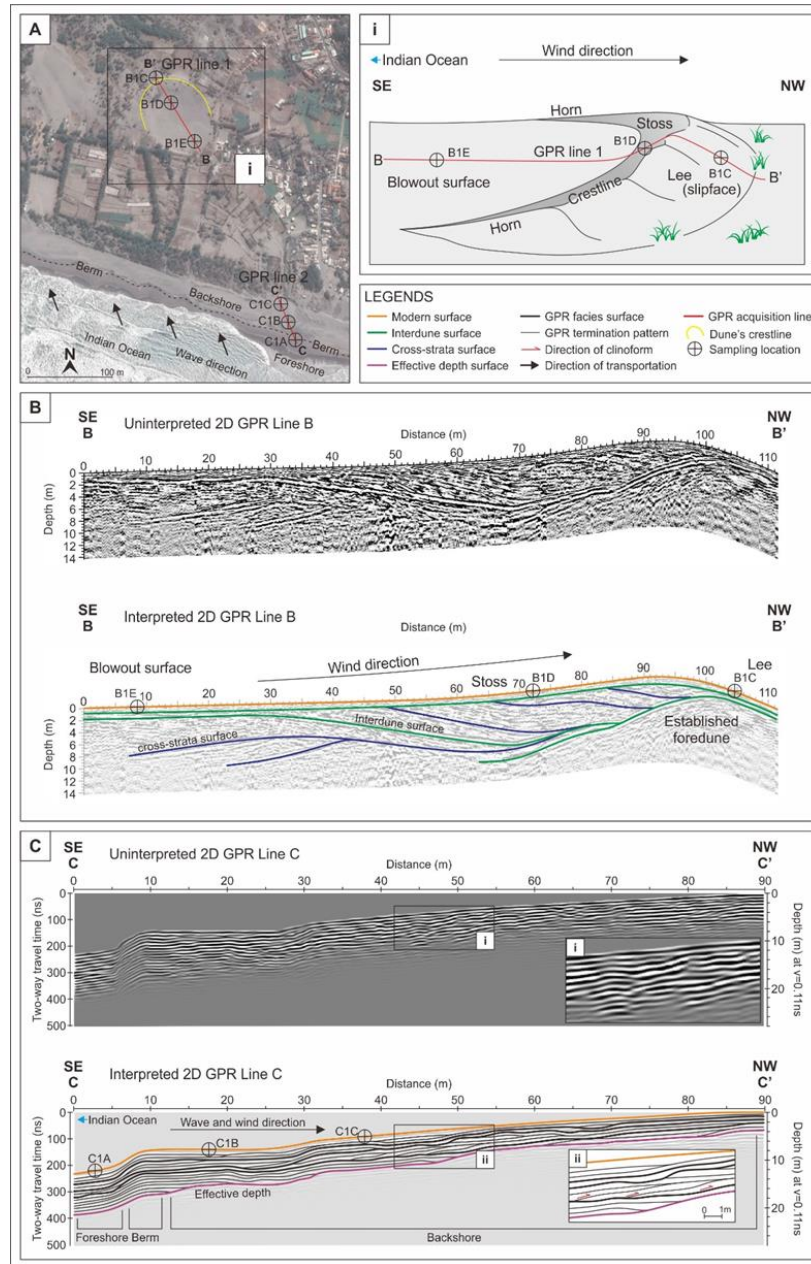


Figure 4.5 GPR acquisition profiles (A) and the illustration of dune morphology (A-i). Uninterpreted and interpreted GPR profiles are presented for each line (B and C). Notice the upslope climbing clinoforms (C-i and C-ii) formed within the shoreface profile as an indication of wave influence.

4.4 GRAIN SIZE DISTRIBUTION

Grain size distribution is plotted against the distance from source to sink and the depositional environment (Fig. 4.6). The proximal site has the average coarsest grains of all sites, with 24-40% of its grain size fraction consisting of very coarse and medium sand combined. The pre-fault sediment of S6A has 44% of its grain size fraction made of very coarse sand, while the post-fault sediments 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 fraction 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 Ocean has 28% of its average grain size consisting of medium to fine sand. Sample S12A, 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 consist of medium sand with an average of 40-56% of their grain size fractions across the blow-out surface, stoss, and lee. It is worth noting 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.

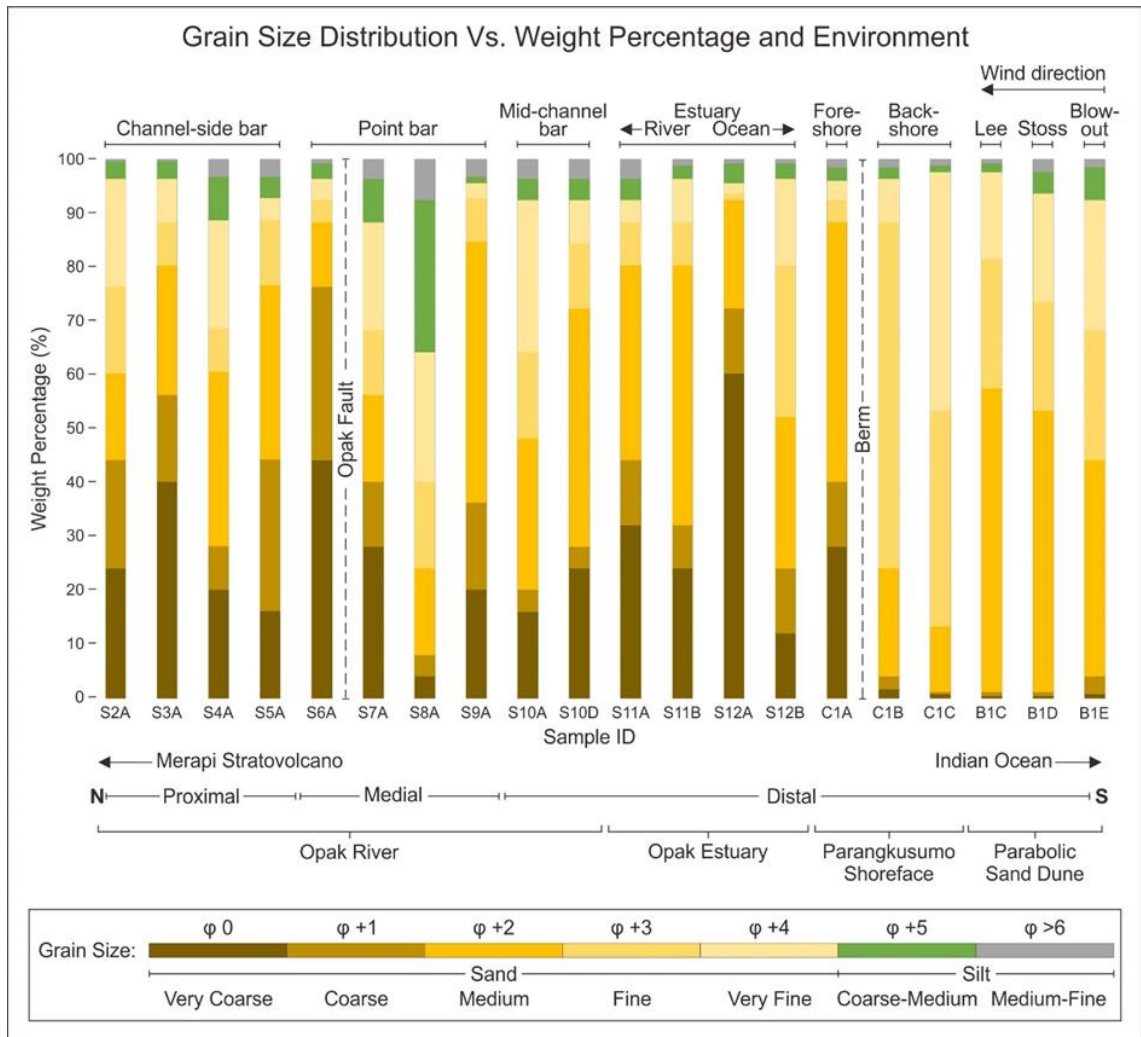


Figure 4.6 Grain size distribution from source to sink with its associated environments. Notice the inclusion of geomorphological expressions such as Opak Fault and Berm which affect the distribution of grain size, and the prevailing wind direction for sand dune samples.

4.5 DIGITAL PETROGRAPHIC ANALYSIS

Thin-section photomicrographs from hand specimen samples (Fig. 4.7) show the provenance rock for Merapi sedimentary system. The provenance rocks are porphyritic, meaning the size of each mineral is distinguishable from one another. In the thin section, plagioclase feldspar and pyroxene are the phenocrysts (very coarse to coarse sized), with smaller plagioclase feldspar as the groundmass (fine to very fine sized). This is common in andesitic rock where plagioclase feldspar is often found as phenocrysts as well as tiny laths in the groundmass (Best and Christiansen, 2001). Plagioclase feldspars are tabular and very angular, sometimes exhibiting a zoning when seen in XPL (Fig. 4.7, Sample S2C). Similarly, the pyroxenes are very angular, as expected in a provenance rock. The provenance hand specimen samples are all very poorly to poorly sorted. The trend in grain texture is retained in the proximal site until it reaches sample S5a (Fig. 4.8), where it becomes moderately sorted, with a presence of large plagioclase feldspar phenocryst. In the medial site (Fig. 4.9), sample S6A has a moderate to well sorted packing, and changes abruptly post Opak Fault into a very poorly sorted one in sample S7A with a pyroxene phenocryst. The presence of quartz emerges in sample S9A, with a well-sorted medium sized grain, at the end of medial site.

Within the distal part (Fig. 4.17), the upstream tip mid-channel bar has a poorly sorted grains and pyroxene phenocryst, contrasting the downstream tip which has a moderately sorted, rather homogenously-sized plagioclase feldspar and pyroxene. The estuarine samples show diminishing quartz presence, with very poorly to poorly sorted packing, and indistinguishable phenocryst and groundmass minerals.

The shoreface samples (Fig. 4.11) show a heterogeneous grain sorting within the interface of foreshore (C1A) with backshore samples (C1B, C1C). The foreshore sample has a moderately sorted medium-sized grain, whereas the backshore samples are well-sorted fine-sized grains. Further inland in the parabolic sand dune, samples show a very well to well-sorted medium-sized grains. Across the sedimentary systems from proximal to distal, grain sphericity retains a very angular to angular texture.

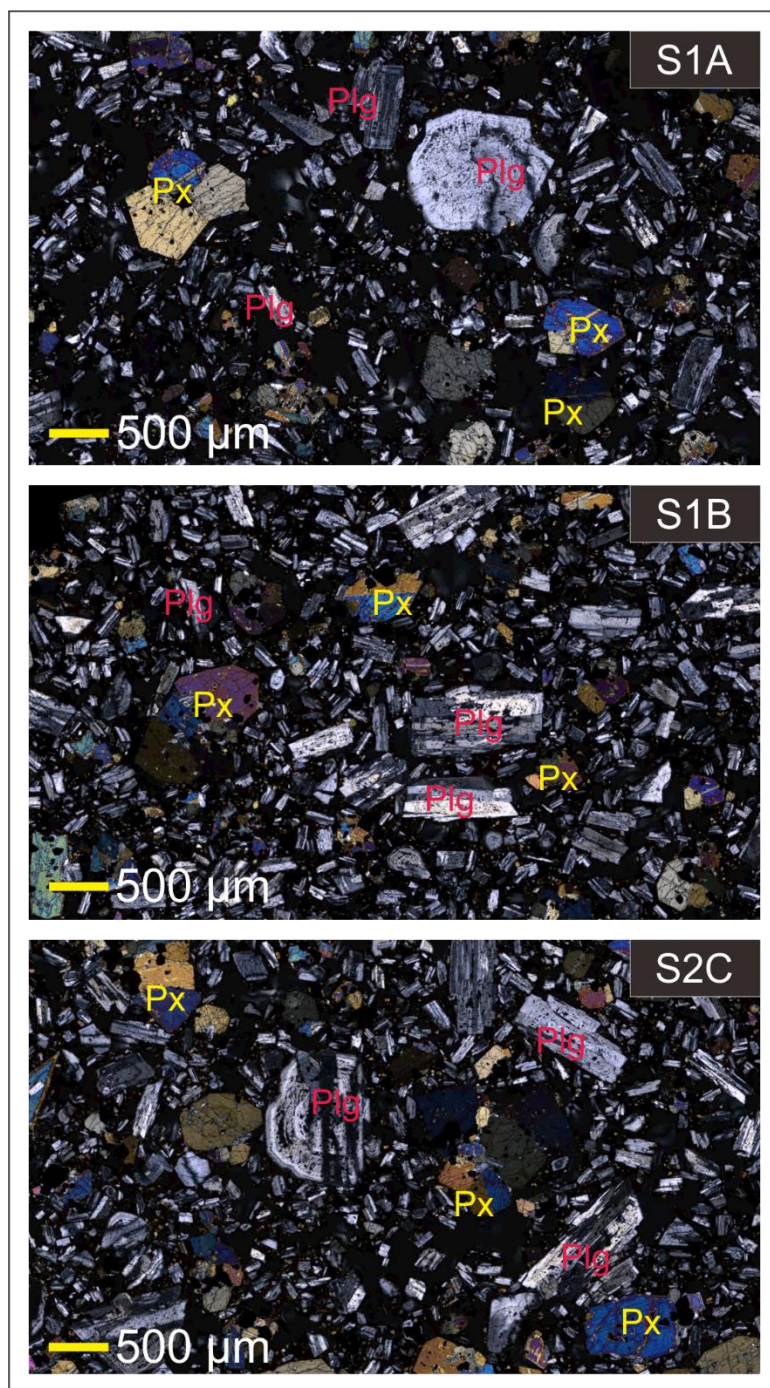


Figure 4.7 Hand specimen samples thin section photomicrographs in XPL view. Plg: Plagioclase Feldspar, Px: Pyroxene.

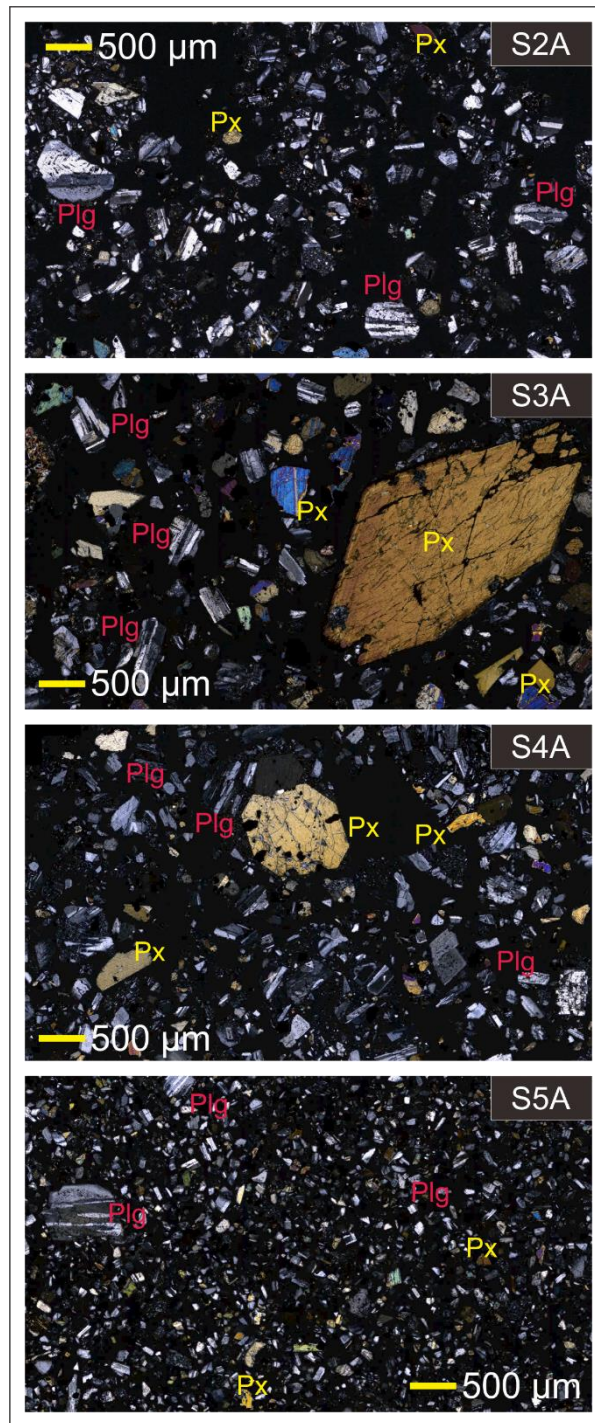


Figure 4.8 Proximal samples thin section photomicrographs in XPL view. All samples were taken from channel-side bar. Plg: Plagioclase Feldspar, Px: Pyroxene.

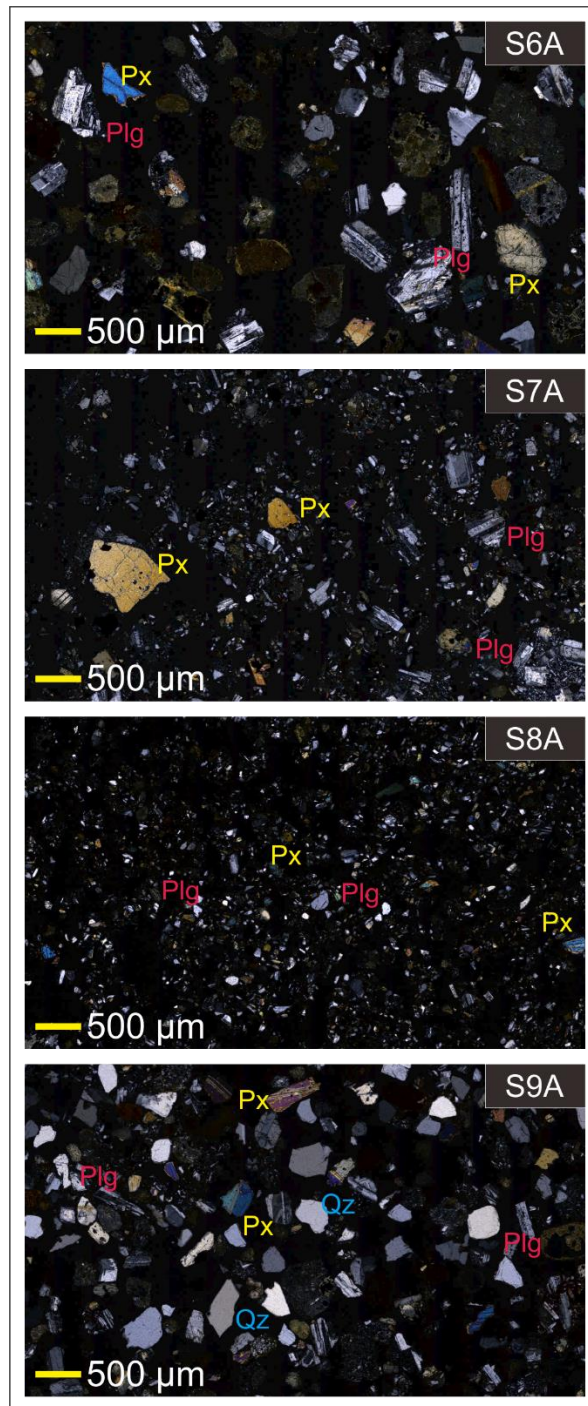


Figure 4.9 Medial samples thin section photomicrographs in XPL view. All samples were taken from point bar. Plg: Plagioclase Feldspar, Px: Pyroxene, Qz: Quartz.

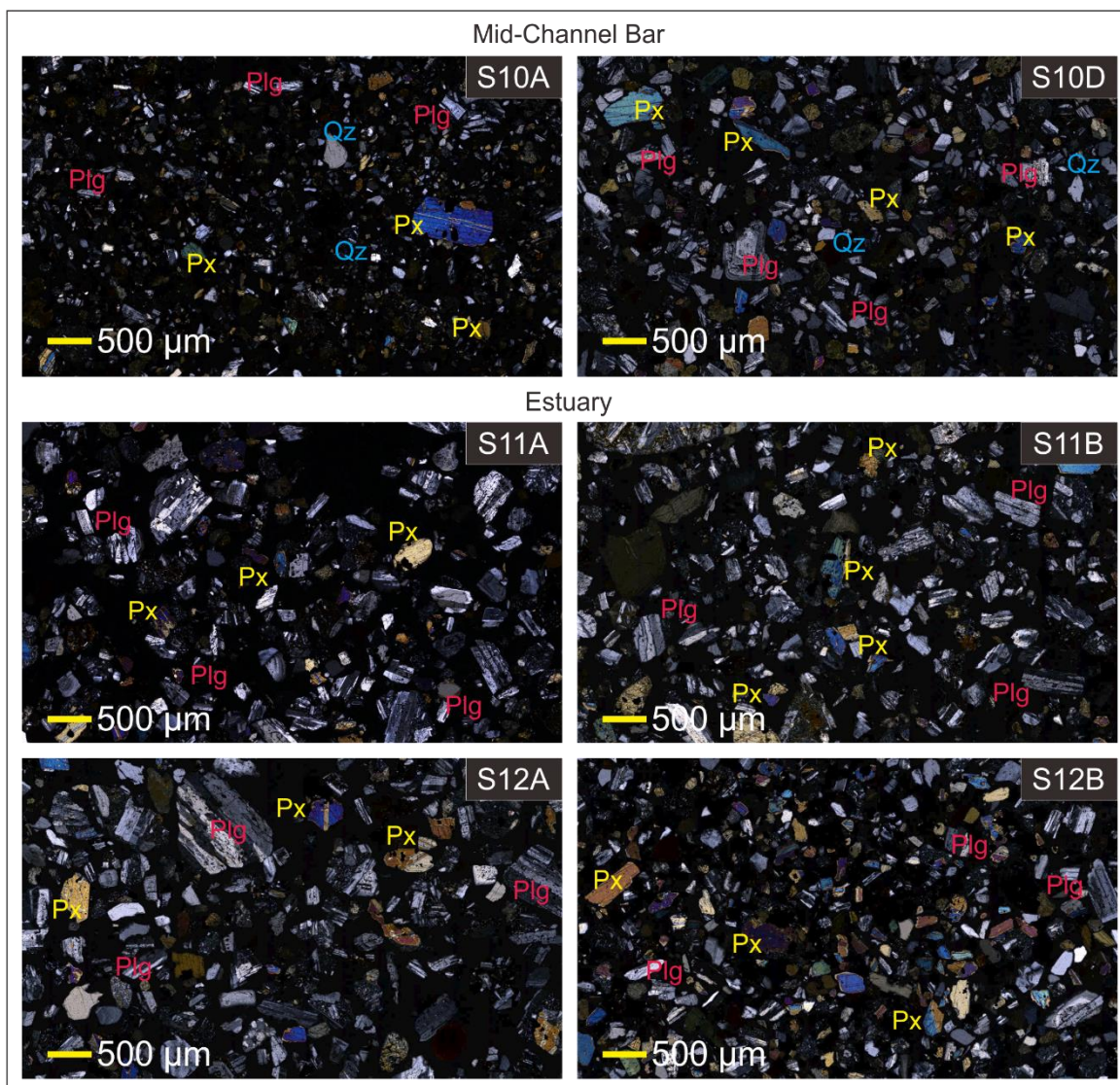


Figure 4.10 Distal samples (mid-channel bar and estuary) thin section photomicrographs in XPL view. Sample S10A and S10D were taken from mid-channel bar. Sample S11A – S12B were taken from Opak Estuary. Plg: Plagioclase Feldspar, Px: Pyroxene, Qz: Quartz.

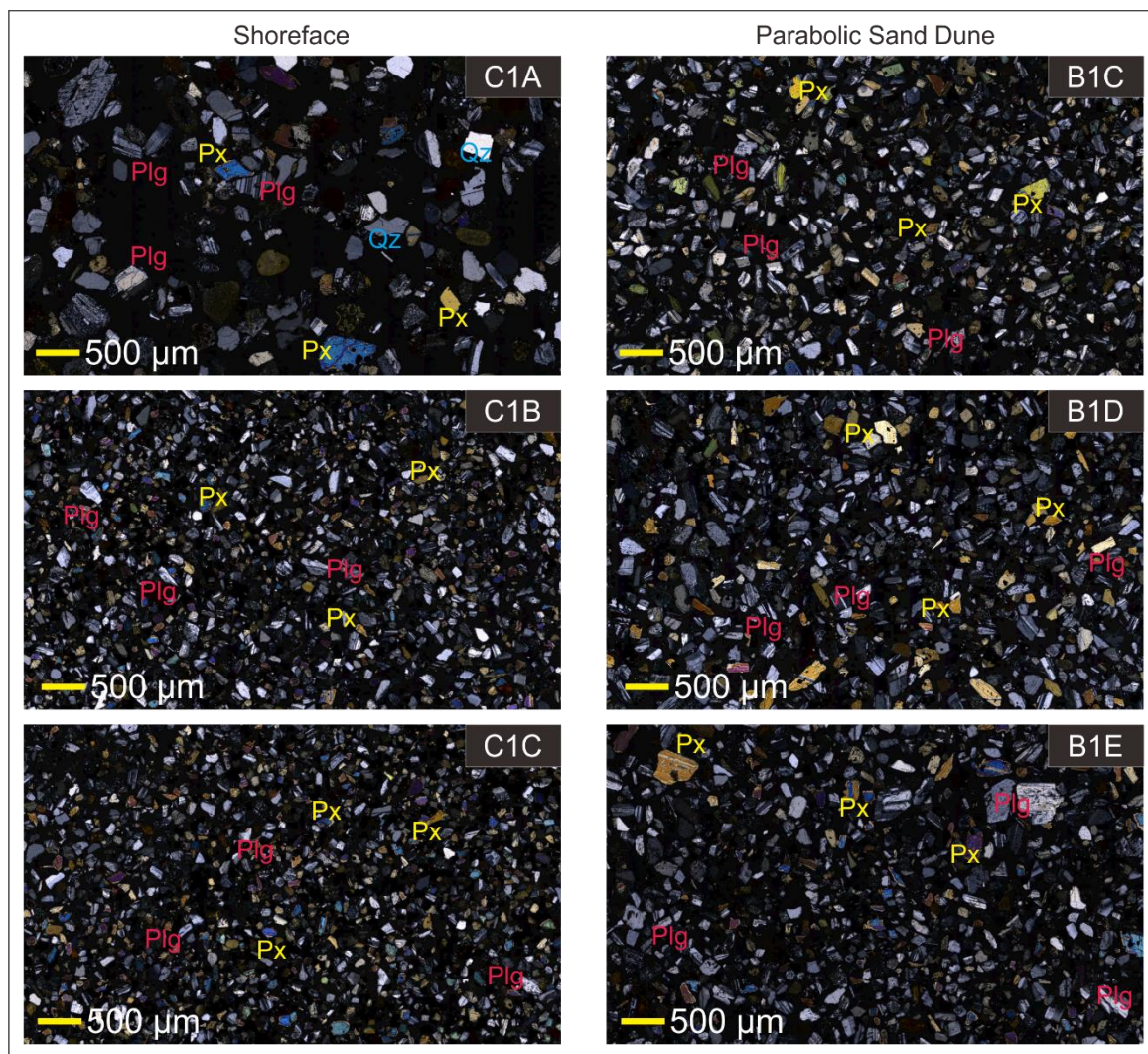


Figure 4.11 Distal samples (shoreface and dune) thin section photomicrographs in XPL view. Sample C1A-C1C were taken from Parangkusumo Shoreface. Sample B1C – B1E were taken from parabolic sand dune. Plg: Plagioclase Feldspar, Px: Pyroxene, Qz: Quartz.

4.6 XRD ANALYSIS

Minerals identified in the Merapi sediments based on their signature peak patterns from XRD analysis (Fig. 4.12 A) are anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$), albite ($\text{Na}(\text{Si}_3\text{Al})\text{O}_8$), augite ($\text{Ca}(\text{Fe}, \text{Mg})\text{Si}_2\text{O}_6$), enstatite ($(\text{Mg}, \text{Fe})\text{SiO}_3$), and calcite (CaCO_3). The quantification of bulk mineralogical composition is tabulated as averages for each sample (Table 7). A plot of mineralogical content with depositional distance (Fig. 4.12 B) shows an uneven distribution from proximal to distal. Anorthite and albite are grouped 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 (Rampe et al., 2020).

4.7 XRF ANALYSIS

Major elemental (Al, Si, Ca, Fe) and minor elemental compositions (K, Mg, Mn, Na, P, S, Ti; Fig. 4.13 A) are presented with distance and depositional environment. Abundance of oxides is also identified and plotted against depositional environment (Fig. 4.13 B). Prior to the interface of the fault (S6A), Fe and Fe_2O_3 are increasing. However, post-fault S7A shows a major decrease in those elemental and oxide abundances. Sample S12B also distinguishes itself from the rest of the measured samples because of the most abundant Fe and Fe_2O_3 .

Table 7 Identified Bulk Mineralogical Composition Based on XRD Spectra.

Sample ID	Albite (%)	Anorthite (%)	Augite (%)	Enstatite (%)	Calcite (%)
Hand specimen samples					
S1A	32.45	36.05	12.7	17.7	1
S1B	32.6	35.9	12.7	17.8	1
S2C	36.25	34.65	12.85	15.4	0.85
Stream sediment samples					
S2A	41.2	31.1	9.15	17.15	1.45
S3A	30.35	29.45	24.75	14.8	0.6
S4A	40.1	31.65	10.85	16.65	0.85
S5A	48.35	26.8	4.6	19.45	0.75
S6A	31.05	44.3	9.45	13.8	1.4
S7A	38.5	29.75	13.55	17.15	1
S8A	39.6	31.55	10.75	17.15	1
S9A	24	33.8	12.5	28.15	1.6
S10A	28.9	38.8	13.35	16.9	2.1
S10D	27.1	36.15	16.7	19.05	1.05
S11A	32.2	35.35	16.7	15.05	0.75
S11B	22.5	39	28.6	9	0.9
S12A	33.2	28.9	22.6	14.6	0.75
S12B	7.15	59.05	26.35	7	0.4

Table 7 (continued).

Shoreface samples					
C1A	26.85	37.55	15.7	18.75	1.1
C1B	23.4	38.9	26.35	11.3	0.05
C1C	24.7	37.6	22.35	14.95	0.5
Sand dune samples					
B1C	28.35	35.5	23.65	12.1	0.45
B1D	32.9	36.05	16.05	14.35	0.7
B1E	34.8	35.25	15.95	13.5	0.5

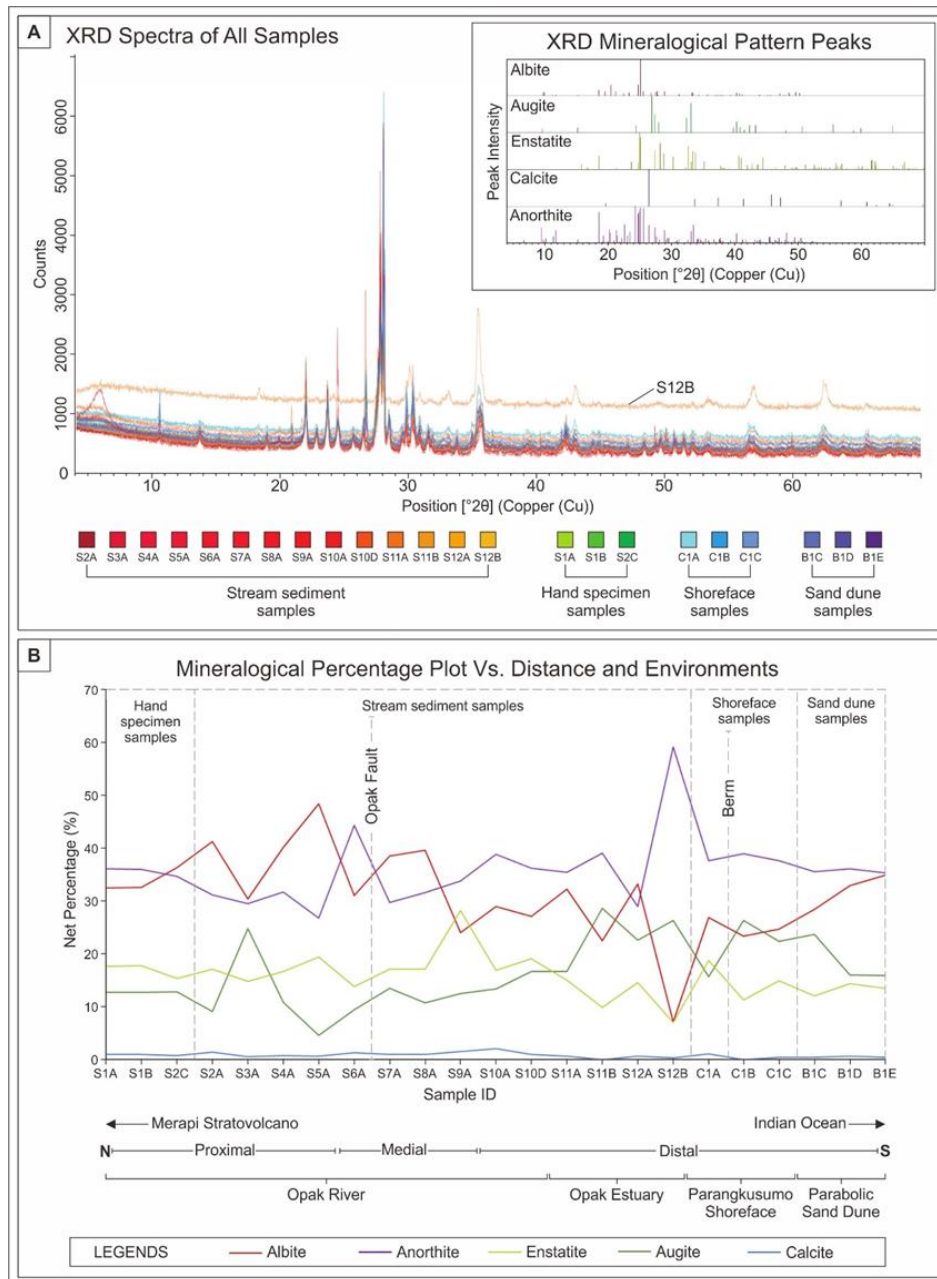


Figure 4.12 XRD spectra of all samples and the identified peaks for each mineral. The mineralogical pattern peaks show 5 distinct minerals, which are albite, augite, enstatite, calcite, and anorthite (A). Plotting of mineralogical net percentage value in accordance with distance of sedimentation and the associated environments (B).

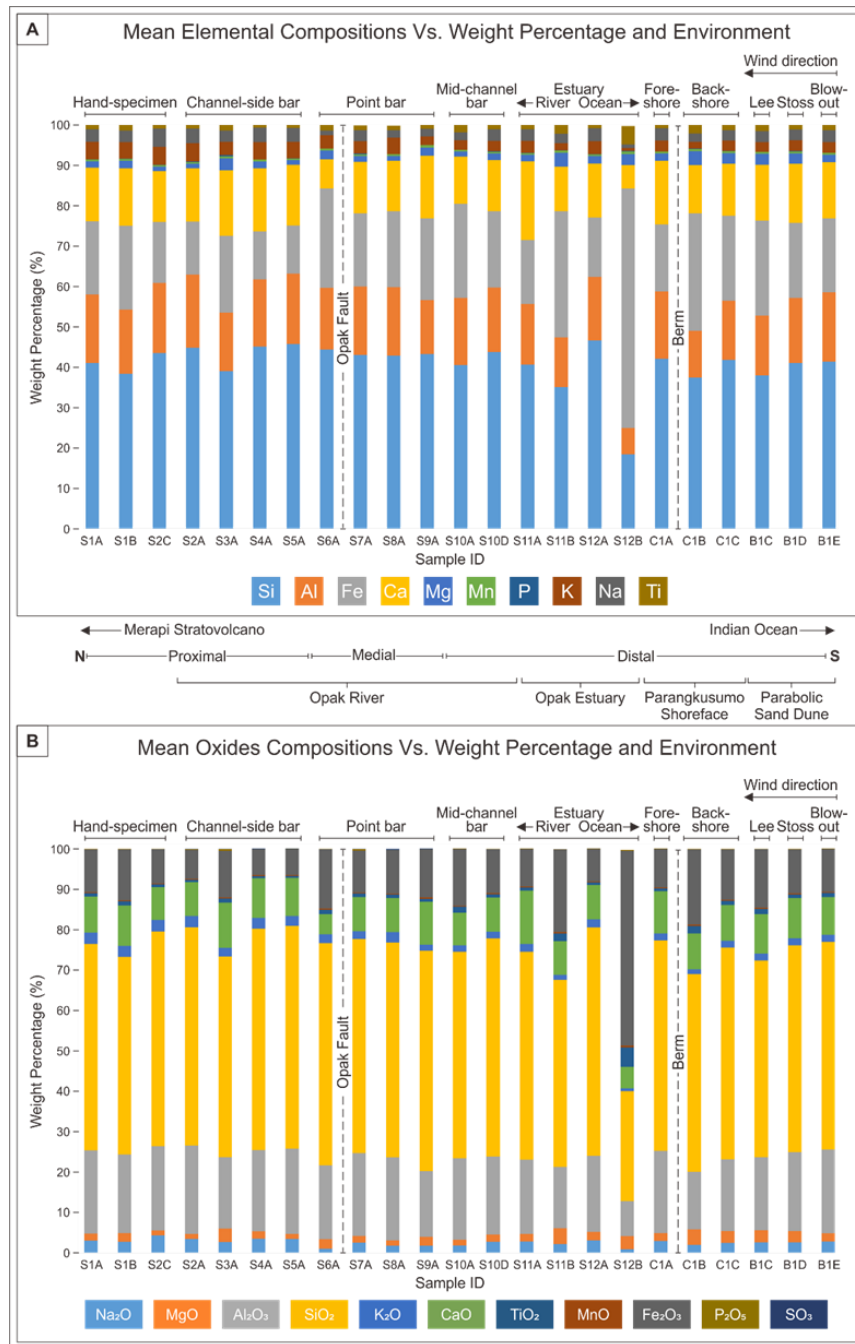


Figure 4.13 Mean elemental (A) and oxides (B) plot with distance and environments derived from XRF. Notice the abundance for Fe and Fe₂O₃ in the sample S12B compared to the others.

4.8 Px/PF RATIO ANALYSIS

Variability in the mineralogical sorting throughout the sedimentary systems by plotting a ratio of Px/PF against the depositional distance (Fig. 4.14), with host rock average Px/PF ratio of 0.43. Px/PF ratio is plotted against depositional distance with average grain size function (Fig. 4.15 A). 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, whereas the medial is deposited in point bars. Sample S3A is marked as the only proximal sample inclined towards pyroxene sorting, despite retaining similar average grain size to the remaining proximal samples (Fig. 4.15 A). The lowest Px/PF ratio (0.31) of all samples belongs to the point bar deposit of proximal-medial interface (S6A). The pre-fault medial site still follows the trend of plagioclase feldspar sorting from the proximal site, despite the depositional environment change from the channel-side bar to a point bar. The post-fault medial site shows a strong pyroxene sorting (Px/PF ratio of 0.45-0.70), entirely deposited in point bars, with average grain size function of medium-to-very fine sand. Sample S8A is marked as the only post-fault medial sample inclined towards plagioclase feldspar sorting, while having the lowest average grain size (very fine sand) of all measured samples (Fig. 4.15 A). The estuary samples are dominant in pyroxene sorting (Px/PF ratio of 0.47-0.63), and their average grain size function is between coarse-to-fine sand, which includes the coarsest grain of all measured sample (S12A), a top surface deposit of estuary's washover barrier sand. The shoreface sediments 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). Aeolian process shows that sorting occurred both in mineralogical and average grain size function, as the Px/PF ratio variability is accompanied by lesser concentration of coarse sand and more concentration of medium sand upwind. 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 study's modern aeolian dune has an average value of Px/PF ratio of 0.47, whereas the modern aeolian on Mars' Bagnold and Namib Dunes are between 0.55-0.75. The ancient aeolian units of Stimson formation have a Px/PF ratio are 0.29-0.70 (Fig. 4.15 B).

4.9 CIA AND A-CN-K TERNARY DIAGRAM

Results from the CIA and A-CN-K ternary diagram (Fig. 4.16) show that Merapi volcanoclastics 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 volcanoclastic samples (dashed blue line), whereas Eldborgir lava field samples are clustered shown clustered in dashed black line.

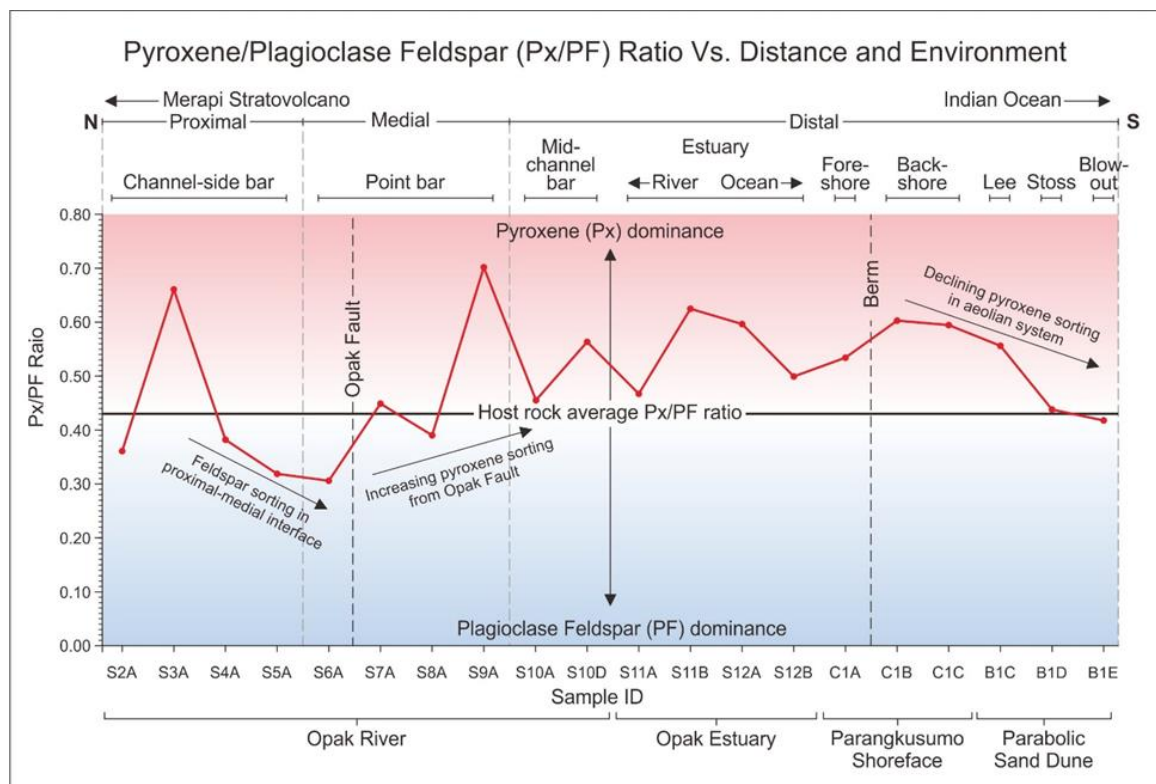


Figure 4.14 Pyroxene/Plagioclase Feldspar (Px/PF) ratio plot against depositional distance and environment. Note the presence of Opak Fault and Shoreface's berm in dashed line.

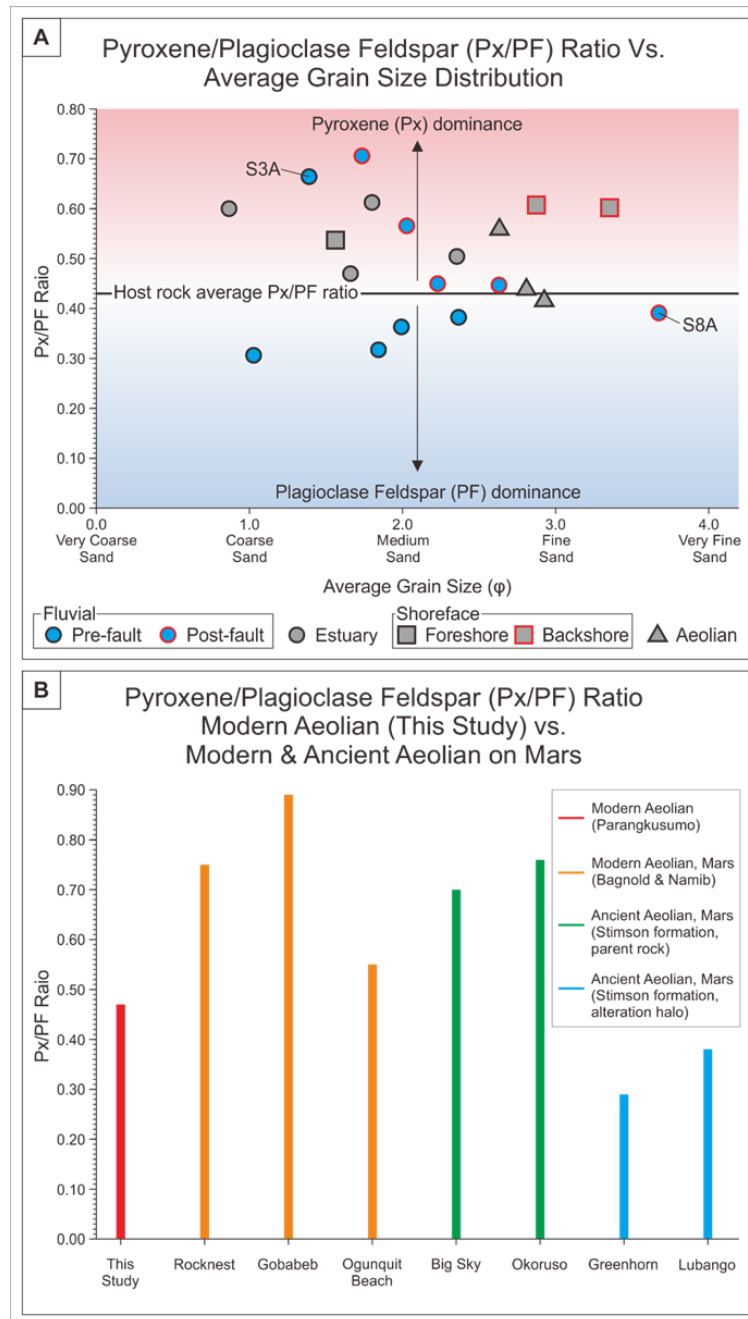


Figure 4.15 A plot of pyroxene/plagioclase feldspar (Px/PF) ratio against average grain size and depositional environment. Comparisons between this study’s modern aeolian Px/PF ratio (A) with modern and ancient aeolian found on Gale Crater (B).

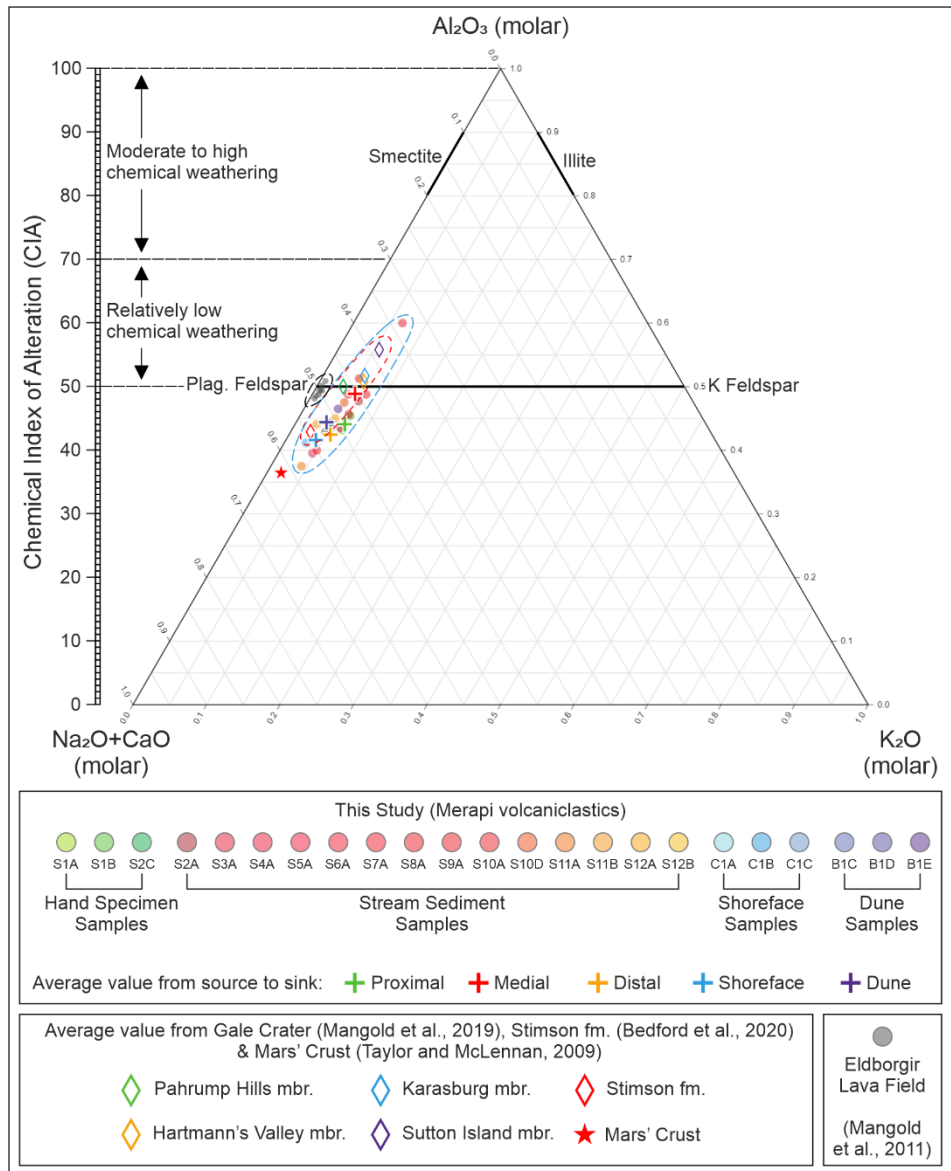


Figure 4.16 Ternary A-CN-K diagram of Merapi volcaniclastics in comparison with Gale Crater (Mangold et al., 2019), Stimson fm. (Bedford et al., 2020), Eldborgir lava field (Mangold et al., 2011) and Mars' crust (Taylor and McLennan, 2009). CIA value is plotted as a vertical axis within the A-CN-K diagram. Blue dashed line is Merapi cluster, red dashed line is Gale crater cluster, and black dashed line is Eldborgir cluster.

4.10 MULTIVARIATE STATISTICAL ANALYSIS

A hierarchical clustering (Fig. 4.17) 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 (Fig. 4.17 B). A total of 93.99% variability resemblance shown by PC-1 has established 3 clusters each with its own distinction, in particular sample S12B is compared to the rest (Cluster 1, Fig. 4.17). This distinction is a result of sample S12B 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 (Fig. 4.17 B), sharing a narrow range of albite (22.5% - 28.9%) and anorthite (35.5% - 39%), has the highest amount of iron (S10A and S11B) and all are in distal part. The last cluster (grey 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.

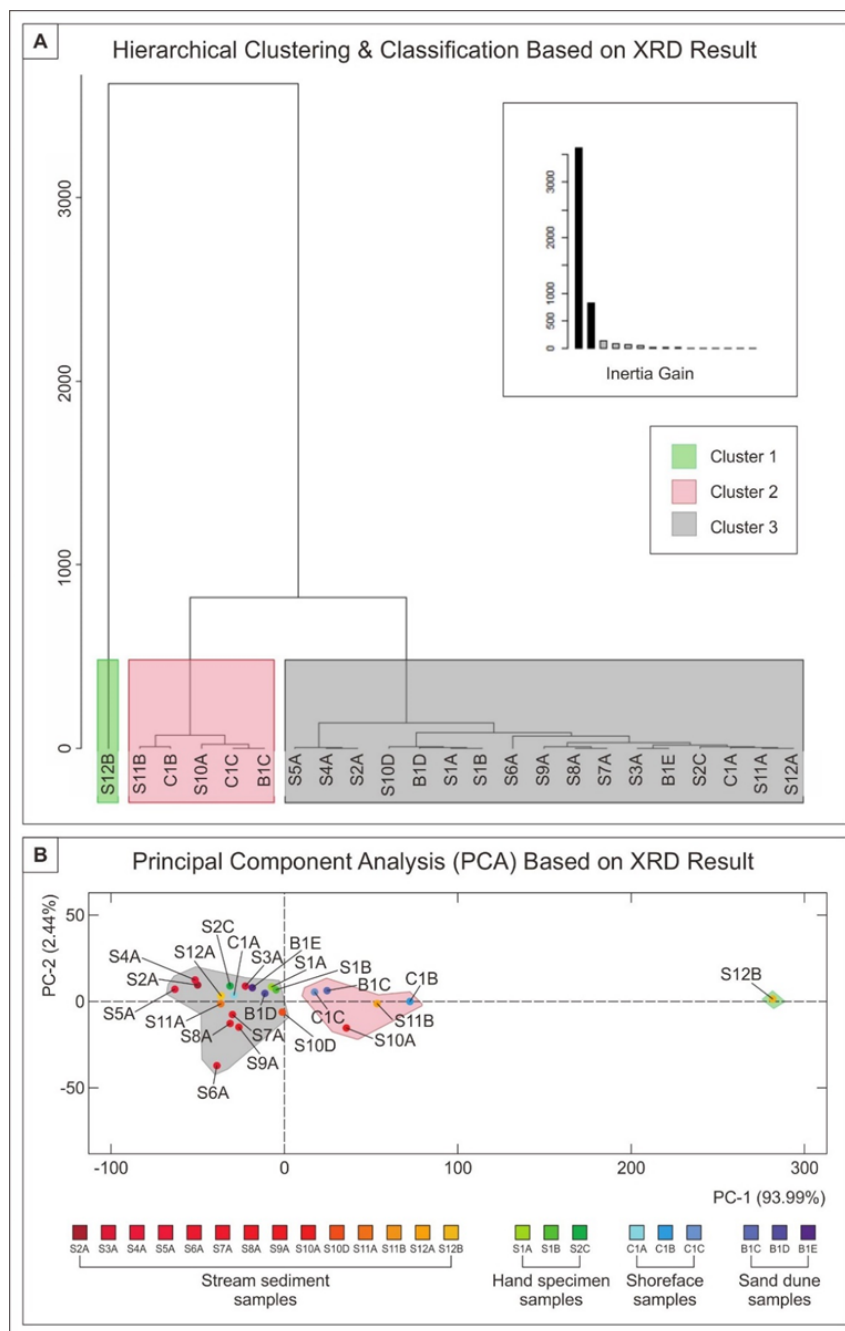


Figure 4.17 Hierarchical Clustering on Principal Components (HCPC) dendrogram and Principal Component Analysis (PCA) plot. Notice the three distinctive clusters in the dendrogram represented in green, red, and black (A), and PC-1 correlation value of 93.99% (B).

CHAPTER 5

DISCUSSION

Results from the Merapi fluvio-coastal-aeolian sedimentary system show that mineralogical sorting correlates with the depositional distance and the subsequent environments. Therefore, the discussion begins with the overall geomorphological aspect of Merapi sedimentary systems, followed by mineralogical, elemental, and spatial variability within each depositional environment on Merapi volcanoclastics. Insights on Mars sedimentary systems are presented based on the findings of this research by revisiting some of the Mars' hypotheses.

5.1 GEOMORPHOLOGICAL ASPECT OF MERAPI VOLCANIC-CLASTICS FROM SOURCE TO SINK

5.1.1 Geomorphology of the Proximal Site (Merapi Stratovolcano)

In the proximal site, Opak River geomorphology is affected by the lahar-carved subsidiaries (Fig. 2.1). The variability of fluvial depositional sub-environments along the Opak River is influenced by the geomorphology 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. Pre-

and post-2018 Merapi eruption shows no distinctive bedform migration from COSI-Corr image correlation, which elucidates the nature of phreatic eruption as a pyroclastic surge.

5.1.2 Geomorphology of the Medial Site (Opak River)

In the medial part, as the river runs along a much gentler slope, the trajectory of the river started to meander, thus providing the essential site for point bars to form. Further down system, the river geomorphology is able to form mid-channel bar. In the distal part, the river is substantially wider (Table 5) 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 (Fig. 4.1.4) 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.

5.1.3 Geomorphology of the Distal Site (Opak Estuary and Parang-kusumo Shoreface)

Chute cut-off bars are observed from COSI-Corr within the estuary during the dry season of 2017 (Fig. 4.4). As the river increases its sinuosity, meandering rivers with huge cross sections, significant curvature bends, and high discharges will have autogenic chute cutoffs

(Viero et al., 2018). Shortening the original meander loop through a bypassing channel results in a higher water-surface gradient, which boosts the reach's overall transport capacity and improves sediment delivery downstream. As a result, the mean channel width and planform shape of the meandering bends adjacent to those bypassed by the chute tend to readjust over time, separating the point bars from the river bank and forming the chute cut-off bars.

The parabolic dune formed along Parangkusumo coast is a product Merapi pyroclastics carried downstream by Opak River. The river formed Opak Estuary at its distal part, and longshore current transported the estuary's sediments to source Parangkusumo Shoreface's deposit through the motion of Indian Ocean wave with its 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 arc tilting to NW. The Parangkusumo Shoreface and the parabolic dune both shared similar mineralogical and elemental compositions, suggesting the dune is a product of aeolian transport from the same provenance. There might be an influence of Nglanggran Formation (Fig. 2.1A, Tmn) eroded materials within the dunes' composition, considering on the proximity of the outcrop to Opak River and Parangkusumo Shoreface. However, erosion from Nglanggran Formation is more likely derived from the faulting and transported down-system by fluvial process, rather than directly from the wind itself, considering the NW prevailing wind direction from Indian Ocean. Therefore, the materials introduced by Nglanggran Formation will be

deposited subsequently in the estuary before they enter the shoreface environment, which eventually sourced the dune sands.

Shoreface GPR profile (Fig 3.4 C) provides shallower depth than the parabolic dune GPR profile (Fig. 3.4 B) because saline water attenuates GPR signal. The parabolic dune GPR profile (Fig. 3.4 B) suggests an initial dune formed as a base of topographical height which became a catchment for aeolian sediment accumulation. This may have eventually led into the development of a secondary dune, initiated by continuous aeolian processes and excluded from beach processes (Sloss et al., 2012a, 2012b). Development of the parabolic dune over a period of time will form along axis oriented with the prevailing wind direction. The established foredune shown in the GPR section suggests an incipient foredune in the past that formed across an older blowout surface and reduced the flow of aeolian volcanoclastic sand coming from the shoreface (Carter et al., 1990; Hesp 1999). When the incipient foredune develops, sand inundation decreases while nutrient levels and vegetation cover increase, resulting in stable dunes and thus hindering further migration. The lee slope became a fertile ground for shrub plant species to grow, which prefer more stable conditions (Hesp 1999, 2002). Sand is gradually deposited on the seaward slope, and sometimes the crest of the dune which slowly becomes larger forming an established foredune. Due to the development of a recent, more stable dune on modern surface, continued aeolian transport will likely cause an increase in dune height, and with it a higher threshold for the volcanoclastic sands, making it less likely to migrate the dune further inland.

5.2 GRAIN SIZE AND GEOCHEMICAL VARIABILITY FROM SOURCE TO SINK

5.2.1 Grain Size and Geochemistry of the Proximal Site (Merapi Stratovolcano)

The grain size variability consists of decreasing particle size, starting from proximally very coarse-to-coarse grains deposited in channel-side bars, and the first point bar before it reaches the Opak Fault (Fig. 4.6). The interface between proximal to medial site of Opak River is essential as it provides the first evidence that mineral sorting occurs independent from the sedimentary bedforms. Despite having a different fluvial depositional sub-environment, the channel-side bar of S5A and point bar of S6A still retained plagioclase feldspar as its dominant mineral sorting preference. The preferred mineral sorting in the proximal site is plagioclase feldspar, whereas the medial and distal part is pyroxene (Fig. 4.14), 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 (Fig. 4.14), which might be the accumulation of a locally-eroded and transported pyroxene from a more recent Merapi eruption.

5.2.2 Grain Size and Geochemistry of the Medial Site (Opak River)

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 (Fig. 4.6). 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 (Fig. 2.1), consisting of an already 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 within the interface of pre- and post Opak Fault in CIA and A-CN-K ternary diagram (Fig. 4.16), which explained the contrast of sample S6A CIA value compared to the rest of the sample. The exposure and erosion of Semilir Formation might influence the sample S8A as the only post-fault medial sample with plagioclase sorting dominance instead of the pyroxene-dominant like the rest of the post-fault medial samples. The finer tuff-breccia material is also an indication to explain sample S8A as the sample with the lowest average grain size function across the sedimentary system (Fig. 4.15 A).

5.2.3 Grain Size and Geochemistry of the Distal Site (Opak Estuary and Parangkusumo Shoreface)

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 (Fig. 4.6) 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 (Fig. 4.6 and Fig. 4.15 A). The trend of grain size variability and Px/PF ratio on the dune site can be attributed to the parabolic sand dune geomorphology where the saucer-type blowout surface acts as a catchment area for sediments carried out by the wind from backshore. 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 additional force of gravity to move landward by settling in lee-ward side. Another notable result in this environment is the presence of a linear decreasing trend from medium, fine, very fine sand, and silt throughout blowout surface, stoss, and lee, which is parallel to the direction of prevailing wind (Fig. 2.2).

5.2.4 Minor Calcite (CaCO_3) Presence in Merapi Volcaniclastics

The minor presence of calcite in Merapi pyroclastic was a subject of a precursor research 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 materials are present as a contaminant melt in xenoliths

and Merapi feldspars (Deegan et al., 2010) thus their presence can be traced from the source towards 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 volcanoclastics whereas augite and enstatite as the phenocrysts from modern Merapi eruptive materials (Camus et al., 2000; Wahyuni et al., 2012; Preece et al., 2014).

5.2.5 Relationship between Geomorphology, Geochemistry and Grain Size Distribution

Observation from this thesis research 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 by the depositional environments in which the river flows and the complex interplay between estuary, shoreface, and backshore's aeolian activity. For example, ancient pyroclasts from previous Merapi eruptions might 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 compositionally enhanced from Opak fault to right before the Opak

Estuary, while no trend is observed before the fault. Additional sources can also influence sand dunes and samples from the coast, as materials are directly coming from the sea, presumably transporting pyroclastics from various volcanic sources (i.e., other Merapi tributaries or other volcanoes northward of Merapi). NW winds from Indian Ocean carried suspended materials not only from the local shoreface and Opak Estuary, but along the entire shoreface which encompasses another estuary from neighboring Progo River. This river is another drainage that flows from dendritic sources at the feet of Merapi Stratovolcano, with its anterior located 9 km NW of Opak River, also transporting Merapi volcaniclastics downstream (Fig. 2.1), possibly enriching elemental abundance of the aeolian deposits further windward.

5.3 INSIGHTS FOR MARS SEDIMENTARY SYSTEMS IMPACTED BY PYROCLASTIC MATERIALS

5.3.1 Bomb-Sag in Home Plate, Gusev Crater

Our data from the Merapi sedimentary systems show a high abundance of feldspar and pyroxene. Understanding how these minerals are sorted relative to each other as they are transported in different sedimentary systems will aid in the interpretation of sediment source and transportation on Mars. 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 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 (Fig. 5.1). The reworked materials in Home Plate shows the presence of albite, anorthite, and pyroxene from Alpha Particle X-ray Spectrometer (APXS) and CIPW normalization (Squyres et al., 2007), which are also identified in our samples from Merapi.

5.3.2 Pyroclastic Incised-Valley on Mars Volcanoes

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 and Baker, 1990), such as Alba Patera and Apollinaris Patera (Alemanno, 2018). In Merapi volcanoclastic sedimentary systems, our results show that explosive volcanism affects the sedimentary from source to sink as various fluvial depositional sub-environments are formed with definitive distance, (e.g. the channel- side bars in the proximal site, point bars in the medial, and mid-channel bar in the distal part of the river).

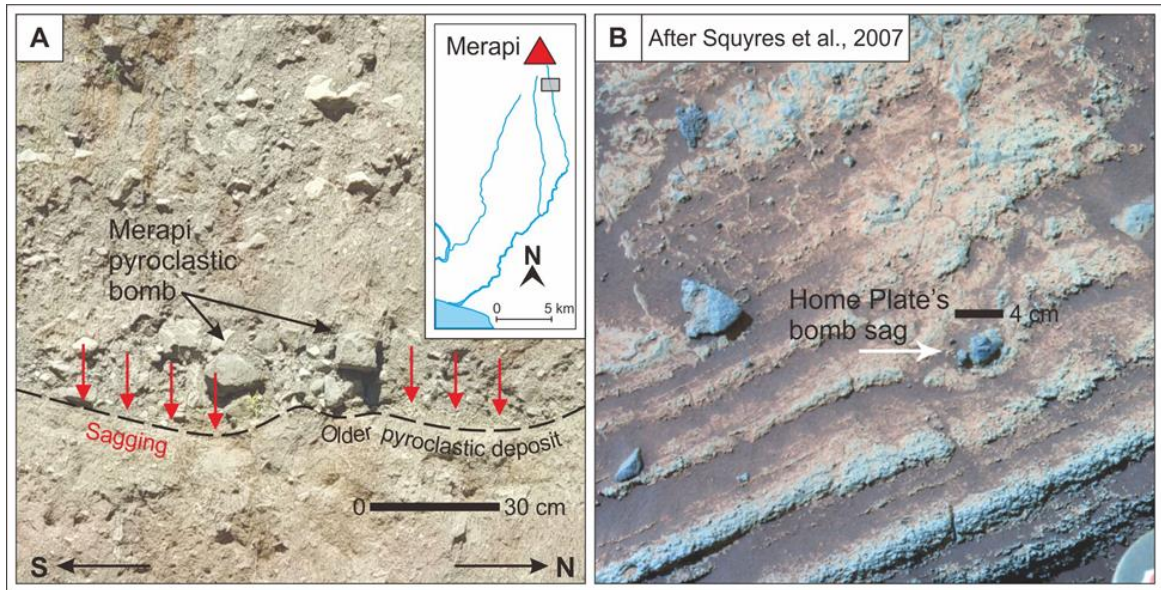


Figure 5.1 Comparison between Merapi's bomb sag in the proximal site (A) with Home Plate's bomb sag in Gusev Crater (B).

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.

5.3.3 Volcaniclastic Dunes on Mars

Volcanic eruption and aeolian processes impact the formation, migration, and evolution of volcaniclastic dunes (Edgett and Lancaster, 1993; Hooper et al., 2012; Grotzinger et al., 2014). The Parangkusumo coastal sand dune is a product of complex interaction between volcanic eruption and fluvio-coastal-aeolian sedimentary systems. The interplay between these sedimentary systems eventually provides the sediments' provenance for creating the parabolic sand dunes. Numerous studies of the martian surface have shown the volcaniclastic dunes on Mars (Greeley et al., 1992; Grotzinger et al., 2005; Schmidt et al., 2014; Lapotre and Rampe, 2018; Payré et al., 2020), their mobility (Bridges et al., 2012) and the presence of ancient fluvial channels (Carr, 2012) could be linked with transported volcaniclastics by the fluvial system on Mars in the past. A terrestrial analogous study at Sunset Crater, Arizona (Hooper et al., 2012) 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 igneous materials from fluvial sedimentation significantly aid in the incorporation of volcanoclastic materials from the source into distal aeolian deposits, as it is observed by the mineralogical and elemental similarity drawn from our multivariate statistical analysis with 93.99% PC-1 value. It implies that any pyroclastic ejecta from Merapi are transported further down-system by Opak River from proximal, medial, and distal part, before eventually deposited in the shoreface and carried landward with the introduction of aeolian processes. 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 volcanoclastics along the fluvial trajectory, and the interface between fluvial-aeolian sedimentary systems will become the site of aeolian deposits' provenance, as seen by the interaction between Opak River – Opak Estuary – Parangkusumo Shoreface.

5.3.4 Paleo-Coastal Environment on Mars

Whether or not the Northern lowlands of Mars held one or more oceans in the past is a hotly debated topic (e.g., Head et al., 1999; Malin and Edgett, 1999; Clifford and Parker, 2001; Carr and Head, 2003; Ghatan and Zimbelman, 2006). 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 (Head et al., 1999; Clifford and Parker, 2001). These contacts were visible from an orbiter since the geomorphological expression is distinctive from its surroundings with a topographically inverted terrain (Head et al., 1999; Clifford and Parker, 2001; Di Achille and Hynek, 2010; Hughes et al., 2019). Although the establishment of paleo-ocean hypothesis in the Northern lowlands of Mars is more viable through paleo-climate reconstruction, if such an ocean did exist on Mars in the past, results from this research suggests that the distal part of fluvial discharge into a large standing water body would result in the build-up of a coarse, sedimentary material, such as what is seen at the geomorphological expression of the volcanoclastic shoreface in Parangkusumo coastline. This requires additional exploration on Mars to justify, especially at the edge of Northern lowlands. If the sedimentary structure or stratigraphic features can be imaged on those locations by means of physical extraction (coring, trenching) or non-destructive geophysical approach (such as GPR), there might be a clue to discern about the nature of Martian volcanoclastic paleo-coastline.

5.3.5 Insights for Mineral Sorting on Mars

A key finding from this research is to identify whether the Gale crater's deposits (Bedford et al., 2020; Rampe et al., 2020) are transported by fluvial process during the past Mars surface condition. 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 being deposited within the crater itself (McSween Jr. et al., 2009; Schmidt et al., 2014; Sautter et al., 2015; Sautter et al., 2016; Treiman et al., 2016; Siebach et al., 2017; Bedford et al., 2019; Bedford et al., 2020; Rampe et al., 2020). To gain an insight into either of the hypothesis, in CIA and A-CN-K ternary diagram (Fig. 4.16) Merapi represents modern fluvial sediment, and lava field sediments from Eldsborgir in Iceland (Mangold et al., 2011), an already established analogous Mars site, represents sediment deposition solely by aeolian and gravitational settling. The site of Eldsborgir is chosen to represent the hypothesis of crater rim-derived transported sediments 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. This implies that Gale crater sediments had been affected by progressive (although not heavily, as CIA shows) chemical weathering of a river, e.g. increasing Al and reducing alkaline elements (i.e Na, K, Ca, Mg) downsystem (Nesbitt and Young, 1984).

Results from this thesis favor the interpretation of incongruent dissolution for plagioclase feldspar found within the Murray formation, Gale Crater (Mangold et al., 2019). Drilled samples in Murray formation are dominated by plagioclase feldspar, and there has been discussion regarding alteration versus provenance effects for the ChemCam-derived interpretation of the drilling samples. Our study reveals that plagioclase feldspar is the most abundant mineral from source to sink, thus making 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 decrease 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 (Fig. 4.12 B and Fig. 4.14) is followed with decreasing amount of Na (Fig. 4.13 A). The fluvially-transported S2A and S3A make it possible to assume that alteration occurred based on aqueous process.

Furthermore, this thesis research shows that pyroxene is in a higher abundance relative to feldspar in medial and distal sites, deposited in point 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 sediment 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 to the findings of CheMin measurement from barchanoidal dune (Bagnold and Namib 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 CheMin findings of Gobabeb and Ogunquit Beach samples (Fig. 9B), where the upwind margin has less concentration of plagioclase feldspar compared to the downwind margin (Rampe et al., 2020).

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Merapi volcanoclastics are a product of an active volcano that could provide insights to constrain Mars older and more recent volcanoclastics by focusing on unaltered anorthite, albite, and pyroxenes found on Mars' crust. Key findings from the thesis research are:

1. The interconnected surface processes of volcanic eruption, fluvial discharge, longshore current, and coastal volcanoclastic aeolian sand dunes are all inseparable from shaping the geomorphology of a reworked volcanoclastic terrain in Merapi sedimentary systems.
2. Image correlation shows that estuarine sedimentary system exhibits a more rapid bedform migration compared to the rest of the system.
3. The grain size and mineral sorting exhibit a distinctive signature for each depositional environment from source to sink. This grain size and mineral sorting can constrain several Mars hypotheses, especially to address the geological diversity of Mars rover landing sites.
4. Fluvial sedimentary system is capable to transport pyroxenes further into the distal site, despite pyroxenes having higher density than plagioclase feldspar.

5. Sediment recharge from Opak Fault shows pyroxene enrichment, and pyroxene sorting occurs from medial to distal, of which the river trajectory follows Opak Fault axis.
6. Wind-driven sorting in aeolian environment shows that both mineralogical and average grain size functions are gradually changing across the bedforms, parallel to the direction of prevailing wind, despite having similar average grain sizes.
7. 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.
8. Mineral sorting variability can be observed in bedforms regardless of their grain size distribution and the depositional environment of their sedimentary system. It is exhibited by 3 examples; (1) The proximal-medial interface of Opak River; (2) 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; (3) 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.

6.2 RECOMMENDATIONS

Improvements that can be done further for this research are as follows:

1. Implementing a tidal-gauge measurement in-situ within the estuary to add vertical dimension (river depth) of Opak sedimentary system, as this will provide a 3D data which later can be modeled into the evolution of the Opak Estuary.
2. Collect a longer interval of a high-resolution multitemporal satellite imagery to observe the bedform migration of parabolic sand dune prior to dune stabilization.

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VITAE

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I'm a graduate master's student in Geology with an undergraduate engineering degree in Geophysics. I strive to become a full-fledged geoscientist with utmost interest in integrating the physical Earth model with quantitative parameters to predict a particular geological phenomenon. I am obsessed with planetary geoscience as it provides a new challenging frontier for my geomodelling experience, and I believe that space is the next frontier of exploration. My research interest is planetary surface processes through geological, geophysical, and remote sensing approach. Through in-situ analysis and orbital spectrometry, I have worked on analogous sedimentary systems on Earth, which were analogous to Mars. I know how to perform planetary multi-temporal spatial analysis under

the mentorship of Prof. Jean-Philippe Avouac's research group (California Institute of Technology, Pasadena). The CPG laboratory mentors my experience performing geochemical laboratory analysis (XRD and XRF) under Dr. Abduljamiu Amao's (KFUPM, Dhahran) supervision. Some highlights of my master's study in KFUPM:

- A month-long (February-March, 2022) research visit to Caltech, trained by Dr. Saif Aati and Prof. Jean-Philippe Avouac to utilize COSI-Corr (Co-registration of Optically Sensed Images and Correlation). Datasets for training included multi-temporal glacier displacement, earthquake-induced ground displacement, and dune migration from Nili Patera, Mars. I utilized the method to detect bedform migration of my thesis study area, which was the dynamicity of volcanoclastics from source to sink in fluvial, coastal, and aeolian sedimentary systems. Currently, I am involved in an aeolian research group initiated by Caltech's Prof. Jean-Philippe Avouac group.
- A summer-long internship with Stanford School of Earth, Energy, and Environmental Science where I learned on how to perform stratigraphic forward modeling (SFM) through an open-source environment (Python). I studied Python during the CoVID-19 lockdown and managed to submit the result as an extended abstract for EAGE 2022 International Conference in St. Petersburg. My work revolves around coding the SFM (based on Basin and Land Dynamics written in Python, also known as BADLANDS) and interpreting stratigraphic sequence packages.

- Silver medalist in the American Association of Petroleum Geologists (AAPG) Imperial Barrel Award (IBA) 2020 and 1st place in the Middle East Region. I worked on the subsurface imaging and seismic data processing and interpretation, including spectral decomposition and multi-attribute, to unravel potential petroleum systems which were previously not discovered.

Journal Publications:

1. **Argadestya, I.**, Amao, A. O, Bedford, C., Soupios, P., and Al-Ramadan, K. (publication in progress). Mineralogical, Elemental, and Spatial Variability of Volcaniclastics in Fluvio-Coastal-Aeolian Sedimentary Systems and Their Insights for Mineral Sorting on Mars. Earth and Space Science. Pre-print ESSOAr DOI: 10.1002/essoar.10510527.1
2. Amao, A. O., Hallock, P., Kaminski, M., **Argadestya, I.**, and Frontalini, F. (under-review). Modelling climatically and ecologically suitable environment for benthic foraminiferal species. Pre-print DOI: 10.21203/rs.3.rs-1755000/v1
3. Hanafy, S., Soupios, P., Stampolidis, A., Bender-Koch, C., Al-Ramadan, K., Al-Shuhail, A., Solling, T., and **Argadestya, I.** (2021). Comprehensive Geophysical study at Wabar crater, Rub Al-Khali desert, Saudi Arabia. Earth and Space Science. DOI: 10.1029/2020EA001432
4. Chan, S. A., Hassan, A. M., Usman, M., Humphrey, J., Amao, A. O., **Argadestya, I.**, Alzayer, Y., and Duque, F. (2021). Total organic carbon (TOC) quantification

using artificial neural networks: Improved prediction by leveraging XRF data.

Journal of Petroleum Science and Engineering. DOI: 10.1016/j.petrol.2021.109389

Conference Papers and Presentations:

1. **Argadestya, I.**, Al-Dhukayl, Y., Koeshidayatullah, A., and Al-Ramadan, K. (2022). The Interplay Between Tectonics and Sea-level Fluctuations During the Development of Sedimentary System Tracts in a Mixed Carbonate-Siliciclastic System. 2022 EAGE 10th International Conference, Saint Petersburg, Russia.
2. **Argadestya, I.**, Al-Abyadh, A., Usman, M., Khan, P., Ahmed, S., Samudera, A., and Kaka, S. (2019). Surface and Subsurface Fault Correlation Using Outcrops, Gravity, and VLF Electromagnetic in West Jiwo Hill, Indonesia. 2019 EAGE 81st Annual Conference and Exhibition, London, United Kingdom. DOI: 10.3997/2214-4609.201901469