Chapter 1

INTRODUCTION

1 Introduction

Of the many methods that can be used to study the surface processes that were or are active on planetary surfaces, remote sensing has been an essential tool to examine these processes with a broad, regional- to global-scale view. Remote sensing is the process of gathering data about an environment from a distance, without the need to make physical contact. This includes data gathered by instruments on platforms like satellites, drones, and airplanes; and the various instruments can be used to collect visual, compositional, topographic, or thermal data. In this thesis, we apply these methods to examine the history of ancient aqueous alteration on Mars and the present conditions of water temperature in the Arctic here on Earth. We rely on satellite-based observations, which allow us insight into two locations that are challenging or nearly impossible to reach with in situ analysis. By combining the many types of data that can be gathered from orbit, we are able to delve deeply into the story of water on the surfaces of these two planets.

1.1 Phyllosilicates on Mars

Foundational questions about Mars that drive planetary science are about water: where and how much was present, over what distribution and time scales, and how it interacted with rock and the evolving climate. Early fly-by and orbital missions displayed geomorphology suggestive of a water-rich past for Mars. For example, channel and branching valley networks appear analogous to terrestrial river and drainage systems (Irwin et al., 2005; Carr, 1995), and there are sedimentological deposits comparable to terrestrial alluvial fans (Moore and Howard, 2005). These features have been found on some of the oldest surfaces on Mars, dating back to the Noachian period (>3.7 Gyr). The presence of past water was confirmed by geochemical data including the detection of aqueous alteration minerals by the Mars Exploration Rovers (Squyres et al., 2004).

One type of key alteration mineral is phyllosilicates, also known as clay minerals. They have been detected across Mars by two satellite-based visible–near-infrared hyperspectral imagers: OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) on board the Mars Express Orbiter and CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) on board the Mars Reconnaissance Orbiter (Poulet et al., 2005; Mustard et al., 2008). These phyllosilicates are predominantly Fe/Mg-phyllosilicates including smectites, chlorites, and serpentine, and their abundance across late Noachian – early Hesperian (~3.7 Ga) terrains indicates widespread aqueous alteration. Al-phyllosilicates including kaolinite ($Al_2Si_2O_5(OH)_4$) and montmorillonite ($(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot n(H_2O)$) have also been detected in more localized regions of the late Noachian surface stratigraphically overlying Fe/Mg-phyllosilicate.

Since their initial detection on Mars in 2005 (Poulet et al., 2005), Al-phyllosilicates have been used as an indicator for the nature of Mars' aqueous alteration. There have been numerous studies at both the regional and the global scale on these Al-phyllosilicates and their possible formation processes. Al-phyllosilicates have been detected locally by rovers including by Opportunity in Endeavor crater (Arvidson et al., 2014), Spirit in the Columbia Hills (Clark et al., 2007), and by Perseverance in float rocks in Jezero Crater (Royer et al., 2024). These small-scale deposits are not visible from orbit and may represent formation through cm–m-scale processes. They stand in contrast to the Al-phyllosilicate units detected from orbit, which are often the spectrally-dominant mineral over 1s–100s km^2.

Global, remote sensing-based studies tend to consider all of the large-scale Al-phyllosilicate-bearing units on Mars to have formed in a similar way: they argue that Al-phyllosilicate overlying Fe/Mg-phyllosilicate formed as part of a pedogenic leaching sequence from a basaltic protolith (e.g., Poulet et al., 2005; Carter et al., 2015; Moore et al., 2025; Klidaras et al., 2025). Notably, this process requires an extensive amount of aqueous alteration. However, region-specific studies have identified diversity between these Al-phyllosilicate bearing regions, and some studies have suggested alternative formation mechanisms beyond pedogenic leaching.

There are broadly two different endmember weathering scenarios that can produce Al-phyllosilicate overlying Fe/Mg-phyllosilicates at large-scale on Mars: (1) extensive alteration of a basaltic protolith or (2) alteration of a separate, more aluminous protolith overlying a basaltic protolith. Fe oxides are expected to form alongside Al-phyllosilicate (Nesbitt and Young, 1989; Gaudin et al., 2005; Greenberger et al., 2012) because Fe^{3+} is relatively immobile in weathering, at least under terrestrial conditions, and their absence can indicate reducing, acidic, or originally Fe-poor conditions (King and McSween, 2005; Tosca et al., 2004). In acidic alteration, sulfate hydroxides in the jarosite–alunite solid solution can form (Stoffregen, 1993). Each scenario produces characteristic mineral assemblages; thus, spectral and textural analysis of the present-day mineralogy can be used to help reverse-engineer the identity of the protolith and the geochemistry of the water that produced the weathering**.**

1.2 Summary of Chapters 2 and 3

In the first section of this thesis, we examine Al-phyllosilicate formation across Mars using remote sensing datasets. We combined hyperspectral visible–near-infrared imagery from the CRISM spectrometer with high-resolution imagery from HiRISE and the Mars Context Camera and with digital elevation models to understand the mineralogy of Al-phyllosilicate alteration assemblages as well as their stratigraphy and geomorphic contexts. In chapter 2, we examine in detail the Al-phyllosilicate in Nili Fossae, a region of ancient terrain west of Mars' Isidis impact basin. The Al-phyllosilicate in this region has previously been reported to have formed as part of a pedogenic leaching sequence (Ehlmann et al., 2009), but this analysis was performed without the most recent CRISM and HiRISE images and prior to the detection of jarosite alongside some of these Al-phyllosilicates (Ehlmann and Dundar, 2015). We developed a pipeline for using Gaussian fitting to automatically detect and map phases of interest including Al-phyllosilicate, Fe/Mg-phyllosilicate, jarosite, alunite, hydrated silica, and Fe oxide. By examining our mineral maps and the available high-resolution imagery, we conclude that the Al-phyllosilicate in this region is not consistent with formation from leaching of basalt but rather is more consistent with formation from a reworked aluminous volcanic ash deposit, with jarosite forming from local, likely volcanically-sourced sulfur.

In chapter 3, we apply our methods to a global survey of Al-phyllosilicate-bearing regions. There have been numerous regional-scale studies of Al-phyllosilicate-bearing regions (e.g. Ehlmann et al., 2009; Le Deit et al., 2012; Bishop et al., 2013; Leask et al., 2024; Wray et al., 2008; Michalski et al., 2013; Bishop et al., 2020), and they have identified diversity and complexity in the Al-phyllosilicate formation. However, most global-scale studies largely continue to consider Al-phyllosilicate an indicator of extensive pedogenic leaching of basalt (e.g. Carter et al., 2015; Klidaras et al., 2025; Moore et al., 2025). We perform a global analysis of these minerals, applying the same methods we used on a regional scale everywhere so that comparison can be rigorous and equitable. We examine six regions: Nili Fossae, Libya Montes, Hellas Planitia, Terra Sirenum, Valles Marineris, Mawrth Vallis. We use our Gaussian fitting pipeline to identify and map the same key minerals in all of these regions and examine their stratigraphy using high resolution imagery. We find that the Al-phyllosilicate in Hellas Planitia and Eridania Basin within Terra Sirenum are most consistent with formation from leaching of basalt. We find that Al-phyllosilicate in Nili Fossae, Libya Montes, Terra Sirenum, and Valles Marineris is instead more consistent with formation from alteration of an aluminous volcanic ash. Mawrth Vallis shows evidence of both processes. With this, we demonstrate that Al-phyllosilicate on Mars does not all form through the same process, nor does it always indicate extensive chemical alteration. Instead, our results suggest that limited weathering may have formed most of these deposits, and ash-producing volcanism may be more extensive than previously thought.

1.3 Arctic riverine corridor temperature

Today, Arctic environments exist in a precarious balance on the front lines of global climate change. Due to Arctic amplification, this region is experiencing more rapid warming than anywhere else on the planet, with an increase of up to 4°C predicted (Burn and Kokelj, 2009; Romanovsky et al., 2010; Post et al., 2019). This influence is felt everywhere in the region including by rivers and their surrounding wetlands. Rivers tie together numerous environments, processes, and water sources, all of which are influenced by the climate. In particular, the Arctic is a permafrost rich environment, but this permafrost is rapidly thawing due to climate change (Garnello et al., 2021; Schuur et al., 2022). As rivers navigate through permafrost-bearing terrain, they melt and erode it, so rivers influence the permafrost and in turn have their erosion style and speed stymied by it (Costard et al., 2003; Douglas et al., 2023; Geyman et al., 2024). Additionally, permafrost thaw and the formation of thermokarst lakes creates well-connected floodplains distinctive to these Arctic environments (Smith et al., 2005; Grosse et al., 2013).

Many of the questions about rivers and their riverine corridors in the Arctic, particularly in the changing climate, are tied to their temperature. This influences how they interact with permafrost during erosion (Costard et al., 2003; Douglas et al., 2023; Geyman et al., 2024), how inland waters release greenhouse gases (Striegl et al., 2012), and, critical to Arctic Indigenous communities, the health of salmon populations (Biela et al., 2022). While understanding the patterns of water temperature is essential to address these questions, the inland water temperature in these regions is not widely monitored. The United States Geological Survey (USGS) maintains a series of in situ temperature gauges in Alaska's rivers, but they are sparsely placed and cannot capture the diversity of water temperature across a river corridor (Krabbenhoft et al., 2022).

Thermal remote sensing can be used to address this gap. The Landsat satellites measure the radiance of energy emitted from the surface in the thermal infrared (~10–12 μm). This energy is proportional to temperature, and these data have been converted into the Land Surface Temperature (LST) dataset (Cook et al., 2014). This dataset and other satellite-based thermal imaging has been commonly used to measure sea surface temperature and lake surface temperature, but it has been infrequently applied to rivers. In particular, this data type has not been applied to high-latitude environments that are affected by permafrost and large seasonal temperature swings. LST provides complete spatial coverage with a high temporal frequency (repeat rate of 1–7 days) and could be used to help address questions of river and wetlands temperature in remote but critical regions like Alaska.

1.4 Summary of Chapter 4

In chapter 4, we examine the spatial and seasonal patterns of water temperature in riverine corridors in Alaska using LST. We ground truth the LST data set by comparing surface temperature values from this dataset to contemporaneous temperature measurements taken by the USGS's in situ temperature gauge at Pilot Station on the Yukon River. We find good agreement, with a mean LST offset of +0.73°C. We combine LST with visible–near infrared Landsat spectra to identify water, create masks of solely water temperature, and we remove 3 pixels from all water body borders to reduce the effects of land surface and water mixing. This creates a minimum size of water body that we were able to examine with this method, >210 meters in width. We examined 3 diverse locations in the Yukon River watershed: the meandering Koyukuk tributary, the confluence of the Yukon and Tanana rivers, and a typical anastomosing stretch of the Yukon River. For each location, we create and examine a water temperature map from just after ice break up in the spring, the height of summer, and just before refreezing in the fall. We compare these data to in situ air temperature and river discharge as well as in situ field temperature measurements taken at depth. We find that the surface temperature of rivers measured by LST is representative of the water temperature at depth, though this is not the case for thermally stratified oxbow lakes. We also find that water temperature largely traces air temperature, but it shows deviations from this due to mixing with other water bodies or internally. Finally, we discuss how remote sensing of water temperature can be applied to critical questions in Arctic environments including the survivability of salmon populations, riverbank erosion, and carbon cycling.

1.5 References

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