C h a p t e r 5

SUMMARY, IMPLICATIONS, AND OUTSTANDING QUESTIONS

In this work, we have demonstrated how the powerful tool of satellite-based remote sensing can be used to gain great insight into the processes that have shaped the surfaces of our planet and beyond. We use satellites to understand the record of water on Mars that existed ~3.7 billion years ago, or, with a small shift in the examined wavelengths, to understand the temperature of water that is present on the surface of Earth today. These projects have wide-ranging implications. In Chapters 2 and 3, our results provide further insight into the nature of Mars' chemical weathering history including the duration of water, pH, redox state, and protolith composition. In Chapter 4, our results demonstrate the efficacy of applying remote sensing to understand the spatial and seasonal patterns of river and wetlands water temperature in permafrost-rich environments like Alaska. In both applications, we use light transmitted to distant satellites to learn more about our Solar System.

5.1 Chapters 2 and 3

Since their initial detection on Mars in 2005 (Poulet et al., 2005), Al-phyllosilicates have been viewed as a window to understanding Mars' aqueous past. In Chapter 2, we examine the formation of Al-phyllosilicate in Mars' Nili Fossae region in light of the continued collection of CRISM and HiRISE imagery and the detection of associated jarosite (Ehlmann et al., 2009; Ehlmann and Dundar, 2015). Focusing on the relationships between the Al-phyllosilicate, jarosite, and Fe oxide, we found that the Al-phyllosilicate mineralogy and stratigraphy in Nili Fossae is not consistent with formation as part of a weathering sequence with Fe/Mg-phyllosilicate from basalt, as had been previously thought (Ehlmann et al., 2009). From our observations, we conclude that the Al-phyllosilicate in Nili Fossae most likely formed from a distinctly aluminous and sulfur-bearing protolith, most likely a volcanic ash. These observations change our known story of what happened in this key site for Mars' alteration history. Rather than recording among the most extensive histories of aqueous alteration on Mars, as had been presumed, we suggest that Nili Fossae instead records a combination of local volcanic processes and a history of more limited aqueous alteration. Our conclusions about the nature of Al-phyllosilicate formation in Nili Fossae serve to add to our understanding of the regional complexity of these Al-phyllosilicate bearing regions across Mars.

In Chapter 3, we performed a global survey of the six primary Al-phyllosilicate-bearing regions across Mars to reexamine, compare, and contrast their stratigraphy and formation processes with an eye towards understanding its localized complexity. We conclude that the Al-phyllosilicate-bearing regions across Mars are consistent with two distinct formation processes. In Hellas Planitia and the Eridania Basin region of Terra Sirenum, the Al-phyllosilicate indeed appears to be consistent with formation from pedogenic leaching of a basaltic protolith. In contrast, in Nili Fossae, Libya Montes, eastern Terra Sirenum, and Valles Marineris, we find that the mineralogy and stratigraphy of the Al-phyllosilicate is more consistent with formation from a volcaniclastic deposit like an ash. We observe jarosite only mixed with Al-phyllosilicate, never with Fe/Mg-phyllosilicate, which we argue indicates jarosite forming in the presence of locally sourced, likely volcanically derived, sulfur. Mawrth Vallis, we determine, has a mix of features consistent with pedogenic leaching and volcanic ash alteration and may represent a region shaped by both processes.

Our results have significant implications for our understanding of Mars' aqueous alteration as well as its volcanism. The formation of Al-phyllosilicate from basalt requires an extensive amount of water, likely an upper limit of tens of millions of years to form the thickest units observed (Bishop et al., 2018). However, because ashes weather far more readily to Al-phyllosilicate, we estimate that an order of magnitude less cumulative duration of water is required to produce much of the observed Al-phyllosilicate across Mars. Additionally, our conclusion that much of the Al-phyllosilicate formed from a volcanic ash suggests a more extensive record of explosive (ash-producing) volcanism than previously thought. We propose that much of the Al-phyllosilicate acts as a tracer for the extent of explosive volcanism, beyond what poorly preserved physical or structural evidence could indicate. We also conclude that this ash was likely generated from a more evolved, less basaltic volcanism. While Mars is dominantly basaltic (McSween, 2009), this and other evidence for localized evolved compositions (e.g. Christensen et al., 2005; Wray et al., 2013; Rogers and Farrand, 2022; Phillips et al., 2022) suggests the influence of fractional crystallization processes in Mars's interior and demonstrates that more felsic compositions may not be unique to planets with plate tectonics.

While regional studies of Al-phyllosilicate, including our Chapter 2, identify diversity in its formation, global-scale analyses largely lump the Al-phyllosilicate into one consistent formation story, one that requires an extensive amount of water. Where this mineral is found, it is often interpreted to indicate extensive alteration from a basalt or otherwise mafic protolith (e.g. Carter et al., 2015; Moore et al., 2025; Broz et al., 2025). While that may indeed be accurate in some cases, it is likely not the case globally. We conclude that Al-phyllosilicate on Mars should not be automatically synonymous with the highest levels of aqueous alteration, but instead interpretation of its formation process should be grounded in the geology of the region where it occurs, and we have identified which processes dominate in Mars' most significant Al-phyllosilicate-bearing regions.

Our results on the nature of Al-phyllosilicate formation on Mars in Chapter 2 and Chapter 3 prompt several questions for future analysis. In our work, we show that the extensive pedogenic leaching of basalt that had previously been thought to have occurred globally was instead likely isolated to a few key regions: Hellas Planitia, Eridania Basin, and Mawrth Vallis. Of the exposed surfaces of Mars, these three regions may represent the terrain that is the most altered by low-temperature aqueous alteration. The nature of Mars' ancient climate and the amount of liquid water it would need to have supported in the late Noachian–early Hesperian is a subject of continual debate. These extensively altered regions we identified provide valuable constraints on the extent and duration of liquid water that must have existed in Mars' past. Future work should examine the geologic context of these three sites to understand why they are so altered. What was the nature of water's interaction with them? Were similar processes active in all three regions, and if so, why in those specific locations? Understanding the behavior of water in the regions of Mars perhaps most chemically impacted by its presence will clarify the extent and duration of liquid water that Mars' ancient climate must have supported.

Additionally, in the regions of Mars where we concluded that volcanic ash deposits were the Al-phyllosilicate protolith, we often find jarosite in association with the Al-phyllosilicate. In

Chapter 2 and 3, we conclude that this jarosite likely formed from a contemporaneous or later stage of fluid interaction that leached iron from the surrounding rock and reacted with local ash-sourced sulfur. Future work should look to differentiate between a groundwater and a surface water source for that later stage of fluid, including a detailed examination of jarosite's positioning relative to local topography. Distinguishing between groundwater and surface water processes expands our understanding of the nature of Mars' water at the transition from the predominantly wetter Noachian to the predominantly drier Hesperian period.

While our results demonstrate the power of remote sensing to address in detail questions about Mars' chemical weathering history by relating its composition to its stratigraphy and geomorphic context, we also recognize where the resolution of orbital data is insufficient to fully address these questions. Everywhere we have sent landed missions on Mars has revealed complexity far beyond what can be seen from even the highest-resolution satellite imagery including unexpected stratigraphic relationships and minerals. Therefore, we argue that our results and those of other remote sensing studies support the need for further rover-based observations of Mars. The European Space Agency's ExoMars mission is planned to land in 2030 in Oxia Planum, which likely has laterally continuous phyllosilicates from Mawrth Vallis (Quantin-Nataf et al., 2021; Auré et al., 2026), and may provide our first chance to see these ancient phyllosilicates units up close. Additionally, the return of Al-phyllosilicate samples to Earth for laboratory analysis would be a tremendous boon to verifying their formation mechanism and gaining great insight into Mars' aqueous history. The Perseverance rover may have the opportunity to sample the kaolinite that is observed in Jezero Crater's rim for return to Earth. I argue that such sampling and sample return more broadly should be a priority.

5.2 Chapter 4

River water temperature plays a significant role in almost every process of interest to scientists and the communities that rely on them, but in situ measurements even on Earth are limited, particularly in the Arctic. In Chapter 4, we use remote sensing from Landsat satellites (LST) to generate water temperature maps of three diverse riverine environments in the Yukon River watershed of Alaska, examine the patterns that emerge from these maps, and compare these results to in situ data where available. We conclude that for sufficiently wide rivers, > 210 meters in width, the LST data set provides accurate water surface temperature measurements (mean error ±0.46°C). By comparing surface temperature measured by LST to the temperature measured in situ at depth in the meandering Koyukuk River and an adjacent oxbow lake, we corroborate expectations that remote sensing of river surface temperature is an accurate representation of the temperature throughout the river water column, although it is not for lakes due to their thermal stratification. We examine the spatial and seasonal patterns that emerge in our remotely sensed temperature maps and find that water temperature closely matches local air temperature, but with a lag due to higher thermal inertia. We also identify deviations in water temperature from air temperature due to other forces that influence water temperature, including mixing with intersecting water bodies, upstream watershed temperature, and mixing within individual bodies. These forces can create large (~5°C) variations in contemporaneous surface water temperature across a floodplain, a significant magnitude of variation for environmental processes that are modulated by temperature, but a variation that is challenging to capture with other methods besides remote sensing.

We conclude that satellite-based remote sensing of water temperature can and should be applied to studies of Arctic riverine environments. Potential important applications include using LST to help predict the rates and processes of thermophysical riverbank erosion, as we find that LST-derived river surface temperature is demonstrative of the temperature of water in contact with permafrost-bearing riverbanks. Additionally, we demonstrate LST-derived river temperatures can be used to identify locations such as confluences that could act as lifesaving thermal refuges for migrating fish, especially crucial for declining salmon populations that are critical for Arctic communities (Jacob et al., 2010; Westley, 2020; Thorstad et al., 2021; Biela et al., 2022). Particularly in remote, data-poor environments, these remote sensing data sets can be key to understanding the thermal landscapes of riverine corridors and to examining their complex processes and implications.

In this study, we take advantage of the contiguous spatial coverage provided by remote sensing temperature data, but future work should also take advantage of its long temporal record. Many studies of river temperature's response to climate change have relied on in situ temperature gauges (e.g. Kaushal et al., 2010; Isaak et al., 2012), but the gauges present in Alaska were placed too recently (largely within the past 15 years) to record a climate change signal. Prior studies of climate change effects on Arctic rivers such as on salmon populations typically rely on air temperature as a proxy for water temperature (e.g. Biela et al., 2022), but it is unclear that both are responding the same to climate change. However, the LST data record goes back to 1982, long enough to record a climate change signal. Future work should use these remote sensing data to directly determine the effects of climate change on Arctic river temperature. By combining the long temporal record with the continuous spatial coverage, future work could also identify any effects of climate change on rivers' along-river thermal profiles. Finally, these datasets have global coverage and can be applied anywhere. The coverage, accuracy, and long temporal record of LST allow us to understand the effects of climate change on the temperature of sufficiently large rivers all over the world.

Future work to use remotely sensed thermal data to examine either the spatial or the temporal patterns of river temperature would benefit from higher spatial resolution and greater accuracy. While we have demonstrated the great potential of the Landsat LST dataset, we were limited to water bodies >210 m in width due to the low inherent spatial resolution of 100 m/pixel and the applied upsampling and interpolation to 30 m/pixel. If future Earth-orbiting missions were able to gather thermal data at higher resolution such as the 60 m/pixel of Landsat 7 or possibly even higher, this would greatly increase the number and diversity of water bodies whose temperature could be examined with this type of data. Additionally, for identifying subtle climate trends in water temperature and for understanding the thermal forces acting on watersheds in detail, temperature data with greater accuracy and smaller variation from measured in situ data would be beneficial. The greatest source of uncertainty is the atmospheric correction process, particularly due to atmospheric moisture (Hulley et al., 2012). Atmospheric correction pipelines are consistently evolving, so new, more rigorous algorithms may be able to improve data quality for applications across the globe.

5.3 Conclusions

The surfaces of planets tell the story of their natural history. From the minerals to the geomorphic features to the biosphere, these features record the planets' past. On Earth and throughout the solar system, water is one of the most important forces that has shaped and continues to shape planetary surfaces. From the active liquid water of our water-rich blue planet of Earth to the traces of ancient water long since disappeared on our red neighbor Mars, if we can understand the effects that water has had on shaping planetary surfaces, we can gain a great deal of insight into the history of these bodies. Remote sensing provides one of the most powerful tools we have to examine these processes and put together the story of their aqueous processes. Where it is difficult to conduct in situ field work (like the remote Arctic) or nigh impossible (like Mars), satellites provide us with eyes in the sky to examine aqueous processes on a detailed regional scale but also the ability to put those regions in a global context. Though this work has focused on water, it has led us to conclusions about volcanism, interior processes, environmental redox state, salmon ecology, greenhouse gas release, and more. Beyond our conclusions about Al-phyllosilicate formation on Mars or river temperature in Alaska, our results demonstrate the role that water plays as the lynchpin of connecting and understanding geologic and environmental processes throughout the Solar System.

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