Chapter 1

INTRODUCTION

"Give me Vesuvius' crater for an inkstand! Friends, hold my arms! For in the mere act of penning my thoughts of this [dissertation], they weary me, and make me faint with their outreaching comprehensiveness of sweep, as if to include the whole circle of the sciences, and all the generations of [tidal models], and [orbiters], and [rovers], past, present, and to come, with all the revolving panoramas of empire on [Io and Mars], and throughout the whole universe, not excluding its suburbs."

Moby Dick, Chapter 104: The Fossil Whale

1.1 Our evolving understanding of the Solar System

Humans have long been fascinated by the heavens. Without today's light pollution blocking the fainter objects in the night sky, our ancestors marveled, charted, and sometimes feared the depths of the starfield above. Consistent observations of the sky will quickly reveal to the observer several points of light that do not conform to the motion of the stars: the planets, wanderers across the sky. While Venus, Jupiter, and Saturn can outshine it, the distinctive red hue of Mars makes it easily stand out in the sky.

Our ancestors did not look up at this bright, red object transiting the night sky and wonder if it was a basaltic world with many minerals in common with Earth (e.g., Bibring et al., 2005; Ehlmann and Edwards, 2014; Hazen et al., 2008); if it once had a rich hydrologic cycle, with rivers, lakes, and glaciers (e.g., Baker et al., 1991); if those waters could once have hosted life, in a familiar or alien form (Grotzinger et al., 2014). They did not consider how the smaller diameter led to faster interior cooling than on their home, locking the inner core and outer core together, ceasing magnetic field generation, and subsequently losing the surface water to space or subsurface freezing (Jakosky, 2021). They did not ask how long it took for Mars to dry up.

Instead, they charted the movements of Mars and asked, "how does this relate to *me*?" The Mayan Dresden Codex, one of the oldest surviving books from the Americas (dating to the 11th or 12th century), records not the 687-day Mars year, but rather the 780 day synodic cycle for how Mars appears in the sky to the observers (Bricker et al., 2001; Wilson, 1924). Ancient cultures from China to Australia were fascinated by how planets interacted with each other in the night sky, and the cultural implications of tracking these bodies were far-reaching.

When Galileo trained his telescope on Jupiter January 8, 1610, he recorded the motion of Jupiter's four largest moons (Galilei, 1610). He was not looking at these quickly moving points of light in his 20-power telescope and wondering if any of them might harbor an ice shell over a subsurface ocean that could potentially host life (Reynolds et al., 1983). He did not ponder the volcanic output of the innermost "star," and consider if the particles output by its massive plumes could deliver sulfur to the trailing hemisphere of its ocean-world neighbor (e.g., Becker et al., 2022; Eviatar et al., 1981). Rather, he again asked the age-old question, "how does this relate to *me*?" This time, that question became extremely consequential in progressing our understanding of Solar System dynamics, providing some of the first solid evidence for the Copernican Heliocentric model, with huge repercussions for human self-importance as our egos no longer seemed to keep the heavens dancing in a slow-bound circle around the Earth (Copernicus, 1543).

Though our questions about these bodies have evolved through the centuries, they still retain that fundamental connection to *us*. We explore outwards to understand inwards, and the more we see of the Solar System, the more we want to know. The last 50 years have seen a golden age of space exploration, and our understanding of both Mars and Jupiter's innermost moon Io have evolved tremendously. The 1970s saw the first detailed pictures of the dusty, red, topographically varied Mars with the *Mariner* and *Viking* missions (Arvidson et al, 1989; Masursky, 1973; Soffen, 1976). They also gave us a detailed portrait of the outer solar system, with *Voyager* capturing Io mid-eruption (Strom, 1981). The late nineties and early aughts ushered in a new era: the Mars Exploration Rovers (Spirit and Opportunity) examined sedimentary rocks, reshaped by wind and ancient water (Squyres et al., 2004a; 2004b; 2004c); the launch of the Mars Global Surveyor satellite marked the beginning of continual orbital observations of Mars (e.g., Albee et al., 2001); and the *Galileo* mission captured Io's surface in unprecedented detail, complementing the *Voyager* coverage and providing thermal measurements that have informed a long debate about how Io's magma reaches the surface (Lopes et al., 2007). Today, the Mars Science Laboratory (MSL) Curiosity rover and Mars 2020 Perseverance rover collect new observations daily that shift our understanding of the ancient climatic system on Mars (e.g., Grotzinger et al., 2014; 2015; Mangold et al., 2021), while the *Juno* spacecraft has imaged Io on several flybys, capturing the topography of the north pole for the first time and advancing our understanding of Io's thermal output (Davies et al., 2024; Perry et al., 2025; Seeger et al., 2025).

1.2 Mars and Io as geologic endmembers

Our current understanding of Mars and Io, informed by the aforementioned decades of observation, reflects two end members in geologic activity: one surface that has barely changed over the last 3.5 billion years (Mars), and one that changes daily (Io). Mars therefore contains an Earth-like rock record of deep time that has largely been erased on Earth due to plate tectonics, allowing us to peer back into a time of early Earth and Mars history. Io, on the other hand, is a dynamic and active body dominated by volcanism and tides—much like what Earth was like in the Hadean Eon. Volcanic activity is so prevalent on Io that impact craters are erased rapidly by new flows, leaving us with no record of them. Th extremely fresh surface is a foil to the ancient Martian one, though both offer a picture of the early Earth in their own way.

Earth, then, sits as an intermediate between these two endmember worlds. They provide the perfect backdrop to observe common terrestrial processes—like uplift, erosion, and alteration—but under wildly different gravity, atmospheric pressure, and temperature conditions. Therefore, we can once again look outward to understand ourselves, as our ancestors did. This work capitalizes on the active mission exploration of Mars by the Curiosity rover and Io by the *Juno* spacecraft to do just that.

1.3 Overview of Dissertation Chapters

1.3.1 Push and Pull

Chapter 2 of this work takes the most zoomed out view, examining Io as a complete body. Laplace orbital resonance between Io, Europa, and Ganymede (the innermost Galilean Satellites) pulls Io into an elliptical orbit, where the large but variable gravitational pull on the moon by Jupiter deforms it significantly, creating a tide up to 330 meters in the rocky body (as opposed to Earth's 1-meter tidal bulge in the open sea, or the 18-meter maximum tidal range recorded in the Bay of Fundy, Canada) (Figure 1). The tidal flexing heats the interior, resulting in near-constant volcanic eruptions on the surface in the form of long, thin lava flows and plumes of sulfur-dioxide rich gases that can stretch hundreds of meters above the surface. These eruptions leave behind (and sometime emanate from) depressed caldera-like features called paterae, of which there are over 400 on Io (Radebaugh et al., 2001). The gases blanket the surface in layers of sulfur-dioxide rich frost (with the variations in composition and alteration contributing to the colorful palette on Io's surface) (Carlson et al., 1997; Hapke, 1989; Geissler et la., 1999; Pearl et al., 1979; Spencer et al., 2000). Interlayered crust of basaltic to ultramafic lava flows and thin sulfur-rich deposits create a layered crust under compressional stress at depth due to subsidence, which is accommodated by the faulting that is hypothesized to uplift Io's impressive mountains, isolated tectonic blocks towering an average of 6 km above the surrounding plains but reaching heights of 16 km—nearly twice that of Mount Everest, on a body approximately the size of Earth's moon (McEwen et al., 2004; McKinnon et al., 2001; Schenk & Bulmer 1998; Schenk et al., 2001; Turtle et al., 2001). Paterae may form from magma exploiting the faulted subsurface to pool on the surface, or from hot-spot type volcanism exploiting crustal weaknesses to rise from the mantle or intermediate magma chambers (Davies et al., 2006; Jaeger et al., 2003; Keszthelyi et al., 2004; 2007; Kirchoff & McKinnon, 2009; McKinnon et al., 2001; O'Reilly & Davies, 1981; Spencer et al., 2020).

While the tidal stresses acting on Io contribute to deformation on a global scale, Bart et al. (2004) suggest the manifestation of these stresses on the surface may modify or create kilometer-scale wrinkled ridge textures visible in the highest resolution Galileo imagery, because the orientations of these features on the surface are orthogonal to the direction of maximum stress they experience during each orbit. Chapter 2 investigates whether tidal stresses could act on features of a much larger scale, influencing the formation of paterae or mountains on the surface; extensional stresses could contribute to paterae opening via rifting orthogonal to maximum stress, and/or compressional stresses could bias mountain uplift to occur orthogonal to maximum stress. The correlations between these surface features are an important component in understanding tidal controls on the eruptive episodes that have been observed to have some periodicity from Earth-based monitoring (de Kleer et al., 2019).

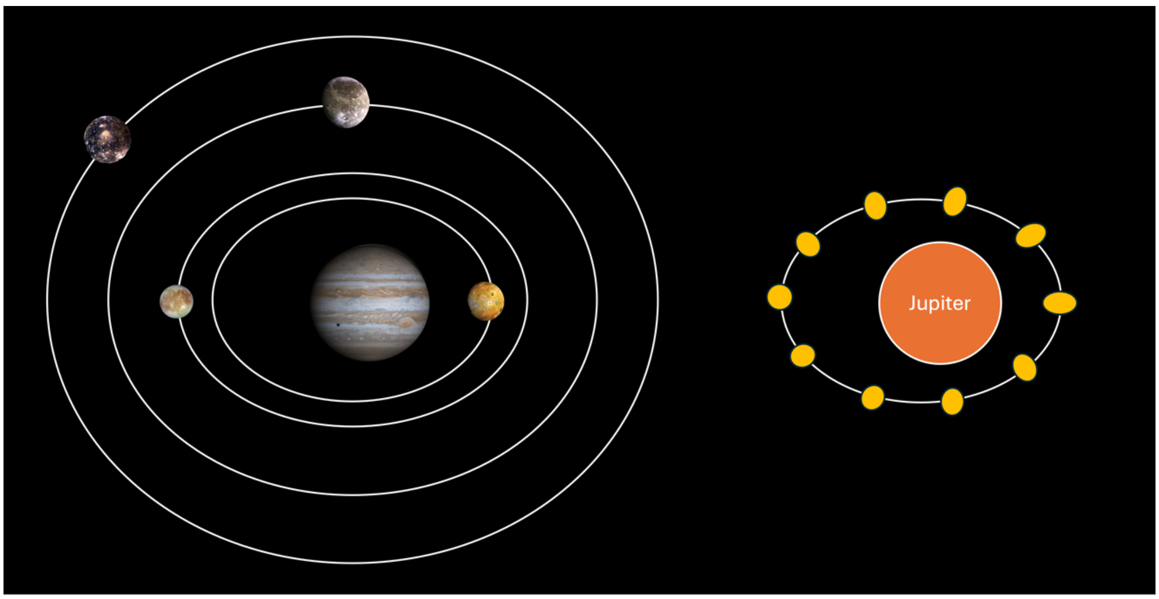

Figure 1. Schematic illustration of Galilean satellite orbital resonance (Io, Europa, Ganymede, and Callisto in increasing distance from Jupiter) creating (exaggerated) elliptical orbits (left) and resulting tidal deformation in Io (right).

1.3.2 Mountains Rise and Mountains Fall

The mountains on Io are dramatic, but require favorable sunset-like lighting conditions to easily discern them. Fortunately, the *Juno* spacecraft high-resolution imagery of Io's north polar region, collected by the *Junocam* instrument, delivered just that. For the first time, imagery has been obtained of a trio of mountains near the north pole, named Cocytus Montes after the three stone giant sentinels encountered by Dante and Virgil as they arrived at the frozen Cocytus, the river of wailing, in the ninth circle of the underworld (Alighieri, 1321/1982). These >5km tall massifs rise above the surrounding plains, with two edifices connected by a one- to three-kilometer high plateau. In Chapter 3, I present the first regional geologic map based on this new imagery and identify updates to the USGS global geologic map of Io (Williams et al., 2011). Previous work on the degradation of mountain structures and patera walls suggests that the main mechanisms for erosion are slumping, mass wasting, and sapping (Moore et al., 2001; Schenk & Bulmer, 1998). Through the new geologic map, I have identified a unique deposit of kilometer-scale, slab-shaped blocks of crust, dominantly distributed across the inter-mountain plateau, and consider the potential mechanisms for their formation and subsequent modification that are based more on terrestrial hillslope processes and regolith generation than has previously been considered for Io. As we get better and better data back from this distant, volcanic moon, we will sharpen our understanding of the large-scale features and their formation, but also will evolve our understanding of how these edifices break down in the absence of a water cycle, and what the near-surface cycling of material may look like on active airless bodies.

1.3.3 Top down or bottom up?

Chapter 4 shifts us to the inner Solar System and allows us to zoom from the orbital perspective on Mars all the way down to the cements filling pore spaces in the sedimentary rocks. While "good" resolutions for Io imagery are on the order of 1 km per pixel, the rovers on the surface of Mars can capture ∼150 μm/pixel imagery of the "workspace"—the rocks directly in front of the rover, accessible by the instruments on the rover's outstretched arm—and surrounding terrain, much more the cell phone photos we take of the rocks beneath our feet and surrounding landscapes while on a hike (Bell et al., 2017; Malin et al., 2017). The Curiosity rover has spent the last ~13 years driving across Gale crater, an impact crater situated at the precise point where Mars' southern highlands meet the northern lowlands in a global topographic crustal dichotomy (e.g., Watters et al., 2007). The rover has traversed

~34 km to date, climbing ~850 meters in elevation as it ascends the layered sedimentary mound, Aeolis Mons (or, informally, Mount Sharp), at the center of Gale crater. Each sol, or Martian day, of this journey is thoroughly documented with images, measurements of elemental abundances, occasional drill core analysis, and, when possible, the closest possible look at the rocks acquired by the Mars Hand Lens Imager (MAHLI) instrument, which can provide an average resolution of 100 microns/pixel for high standoff (25 cm above the rock surface) and 30 microns/ pixel for closer standoff (<5cm above the rock surface) (Edgett et al., 2012).

The suite of observations collected throughout the mission has transformed our understanding of Mars as sedimentary basaltic world with large-scale wind-blown sandstones and a robust groundwater system precipitating hematite spherules that was established through the groundbreaking work of the MER missions (e.g., Calvin et al., 2008; Grotzinger et al., 2005; McLennan et al., 2005). The sediments at Gale crater contain a fluvio-lacustrine deposits originating from the crater rim and flowing into a basin filling with a thick sequence of lacustrine mudstones, demonstrating that longstanding water bodies with neutral pH persisted for a minimum duration of hundreds to tens of thousands of years on early Mars, contributing to the prior OMEGA and CRISM orbital discoveries that Mars was once a habitable world (e.g., Grotzinger et al., 2014; 2015).

About 3.5 billion years ago, Mars experienced a climatic shift; after the core became coupled to the mantle and the magnetic dynamo shut off, atmospheric particles (and surface water) were more easily stripped away by solar wind and lost to space (e.g., Jakosky, 2021); more impactful, however, was the locking up of water in hydrated minerals in the crust, fated to remain sequestered away from the surface in the absence of plate tectonics-driven recycling (Scheller et al,. 2021). The timing and nature of this environmental transition is poorly constrained, but has major implications for how long Mars could have sustained life, and may even offer insight into the fluctuating conditions we are experiencing on Earth’s surface.

Mount Sharp, stretching ~5km above the crater floor, provides a record of the later phases of this transition, with the story written in the sedimentary rock record. Part way up its slopes, there is a distinct transition from clay-bearing strata deposited during the wet years to overlying sulfate-bearing strata, deposited in what was determined from orbit to be the succeeding dry years (Malin and Edgett, 2000; Milliken et al., 2010; Sheppard et al., 2021; Thomson et al., 2011). Observations made on the ground over the ~2 year period where the rover traversed through this clay-sulfate transition region became the basis for Chapter 4. Image and chemical analysis of the sedimentary sequence in this region quickly revealed that diagenetic fabrics, created by groundwater alterations of the rocks after lithification, greatly contributed to—and confounded—the story of Gale crater transitioning from a wet to dry depositional environment. The persistence of diagenetic fabrics like nodules, color variations, and veins disrupting the primary stratigraphy serve as an indicator that groundwater persisted long after the region became dominated by aeolian sandstones—and the appearance of rippled inter-dune lake deposits corroborates this persistent groundwater table (e.g., Caravaca et al., 2025; Gupta et al., 2023; Mondro et al., 2025). The increase in abundance of extremely soluble Mg-sulfate in the rock record moving upsection from the clay-bearing rocks is the clearest indication of aridification throughout this region. However, the formation mechanisms to emplace this Mg-sulfate are debated, and have lasting implications for the persistence of groundwater on Mars as it endured its aridification. Though there is evidence for localized periodic desiccation (Rapin et al., 2023), there is no record of evaporitic or near-surface crusts forming in the widespread, regional sedimentological record. How, then, did these Mg sulfates, which appear to be concentrated in nodules and pore-filling cements, form? Chapter 4 poses three alternative hypotheses for pathways in which groundwater may have remobilized pre-existing sulfates in higher or deeper stratigraphic units and reprecipitated them at depth within pore spaces. The top-down and bottom-up models presented here have implications for how long the groundwater table may have persisted once surface water ceased to flow on Mars, and provides a tidy framework to test over the coming years of rover exploration of an enigmatic web of boxwork-type raised ridges, potentially created by fracture fill (e.g., Siebach & Grotzinger, 2014).

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