Abstract

STUBBLEFIELD, RASHONDA KIAM. Extensional Tectonics at Alba Mons, Mars: A Case Study for Local versus Regional Stress Fields. (Under the direction of Dr. Paul K. Byrne).

Alba Mons is a large shield volcano on Mars, the development of which appears to be responsible for tectonic landforms oriented radially and circumferentially to the shield. These landforms include those interpreted as extensional structures, such as normal faults and systems of graben. These structures, however, may also be associated with broader, regional stress field emanating from the volcano-tectonic Tharsis Rise, to the south of Alba Mons and centered on the equator. In this study, I report on structural and statistical analyses for normal faults proximal to Alba Mons (in a region spanning 95–120° W and 14–50° N) and test for systematic changes in fault properties with distance from the volcano and from Tharsis. A total of 11,767 faults were mapped for this study, and these faults were all measured for strike, length, and distance from Alba Mons and Tharsis. Additional properties were qualitatively and quantitatively analyzed within a subset of 62 faults, and model ages were obtained for two areas with crater statistics. Distinguishing traits for each structure population include fault properties such as strike, vertical displacement (i.e., throw) distribution profiles, displacement–length ($D_{\text{max}}/L$) scaling, and spatial (i.e., cross-cutting) relationships with adjacent faults with different strikes. The only statistically significant correlation in these analyses was between study fault strike with distance from Tharsis. The lack of trends in the data suggest that one or more geological processes is obscuring the expected similarities in properties for these fault systems, such as volcanic resurfacing, mechanical restriction, or fault linkage. The correlation between fault strike and distance from Tharsis, however, paired with cross-cutting relationships and estimates for the timing of the last deformational events, allows for a spatiotemporal synthesis for the faults in the study
region. Faults that are circumferential and radial to Alba Mons are likely primarily associated with a local, volcano-related stress field. Faults that are radial to Tharsis are primarily associated with a regional stress field probably from that center. Lastly, faults that are radial to both Alba Mons and Tharsis likely reflect both local and regional stress fields. To first order, the effects of the Tharsis Rise become less prevalent with increasing distance from the center, and stresses associated with the volcano come to predominate in the very northern reaches of the study region.
Extensional Tectonics at Alba Mons, Mars: A Case Study for Local versus Regional Stress Fields

by
Rashonda Kiam Stubblefield

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science

Marine, Earth, and Atmospheric Sciences

Raleigh, North Carolina

2018

APPROVED BY:

________________________
Dr. Paul K. Byrne
Committee Chair

________________________
Dr. Karl W. Wegmann

________________________
Dr. Helena Mitasova
Dedication

I dedicate this work to my parents, who instilled and cultivated in me a sense of curiosity, wonderment, and respect for the natural world. To my mother, who took me to the library multiple times a week, enrolled me in Montessori preschool, and regularly took me to parks and museums. To my father, who held nightly chats with me to discuss the universe, taught me how to use computers at a very young age, and encouraged me during my many, many years of higher education.
Biography

Rashonda spent her first ten years in Hambden Township, Ohio, in a log cabin home on thirty acres of forested land with crystal-clear night skies. She attributes this upbringing to her respect and fascination with the natural world, especially the planets of the solar system. Her favorite place to visit was a nearby city park, where the cliffs of exposed, glacially-deposited bedrock gave her a sense of the mysterious subsurface of the planet. In 1999, she moved to California, where her curiosity about the forces and origin of materials that shape the landscape grew exponentially. In 2015, she graduated with honors from California State University Northridge, and began her search for a graduate program in Planetary Geology, to satisfy her lifelong interest in the uniqueness of the planets and their moons. When she received her acceptance letter from North Carolina State University, she cried so loudly that her roommates thought a family member had died. Moving across the country, away from her family, pets, and friends, was terrifying, but she knew the sacrifices would be worth it. Her time at NC State was a transformative experience, increasing her skills and confidence in herself. As a proud member of the inaugural Planetary Research Group cohort, she made lifelong friends and fulfilled her childhood dream to study the planets of the solar system.
Table of Contents

List of Tables ................................................................................................................................. v
List of Figures ................................................................................................................................ vi

Chapter 1: Introduction, Background, and Overview ................................................................. 1
Geological setting ............................................................................................................................ 1
Normal faults and graben .............................................................................................................. 5
History of Mars data ...................................................................................................................... 6
Previous Alba Mons work ............................................................................................................ 7
Study rationale .............................................................................................................................. 14

Chapter 2: Methods ..................................................................................................................... 15
Data ............................................................................................................................................. 15
Study areas .................................................................................................................................. 16
Mapping methods and techniques ............................................................................................ 17
Analyses for all mapped faults .................................................................................................... 18
Fault analysis ............................................................................................................................... 19
Crater statistics analysis ............................................................................................................. 20

Chapter 3: Results ....................................................................................................................... 20
Study region results ..................................................................................................................... 21
Study area results ....................................................................................................................... 26
Study fault results by study area ............................................................................................... 37
Study fault results collectively ................................................................................................. 43
Crater statistics results ............................................................................................................. 44

Chapter 4: Discussion .................................................................................................................. 48
All faults ...................................................................................................................................... 48
Study faults ................................................................................................................................. 60
Cratering statistics .................................................................................................................... 67

Chapter 5: Conclusions ............................................................................................................... 69
References ................................................................................................................................. 71
List of Tables

Table 1  Study areas in this study. ......................................................................................16
Table 2  Number of faults, mean fault strike, and standard deviation for all structures mapped in this study. ............................................................................................22
Table 3  Total faults, mean fault strike, and standard deviation of fault strike by geological unit. ......................................................................................................23
Table 4  Results for selected faults in the “Tantalus North” study area. .........................34
Table 5  Results for selected faults in the “Tantalus South” study area. .........................36
Table 6  Results for selected faults in the “Ceraunius North” study area. .........................36
Table 7  Results for selected faults in the “Ceraunius South” study area. .........................37
Table 8  Results for selected faults in the “Tractus” study area. ........................................37
Table 9  Extensional strain estimate measurements for select study faults. ......................39
List of Figures

Figure 1  The Tharsis Rise on Mars, a broad, elevated dome situated at the planet’s equator and host to the largest volcanoes in the Solar System. ..............................2

Figure 2  The Alba Mons volcano. ..................................................................................4

Figure 3  A cartoon schematic of a graben in cross section. .............................................5

Figure 4  The relationship between vertical fault displacement \( D \) and fault length \( L \), shown here for an unrestricted normal fault. .................................................13

Figure 5  All faults mapped in this study, color-coded by mean elevation along strike.....21

Figure 6  All faults mapped in this study, color-coded by along strike. ............................22

Figure 7  All faults mapped in this study, color-coded by geological unit. .......................23

Figure 8  All faults mapped in this study, color-coded by length.................................25

Figure 9  All faults mapped in the “Tantalus North” study area, color-coded by strike. ....27

Figure 10 Trend of pit crater chains mapped with pits over 1 km in diameter mapped alongside all normal faults mapped in the “Tantalus North” study area. ..........28

Figure 11 All faults mapped in the “Tantalus South” study area, color-coded by strike. ....29

Figure 12 Trend of pit crater chains with pits over 1 km in diameter mapped alongside all normal faults in the “Tantalus North” study area. .............................30

Figure 13 All faults mapped in the “Ceraunius North” study area, color-coded by strike...31

Figure 14 Trend of pit crater chains with pits over 1 km in diameter mapped alongside all normal faults in the “Ceraunius North” study area.................................32

Figure 15 All mapped faults in “Ceraunius South” study area, color-coded by strike.......33

Figure 16 Trend of pit crater chains with pits over 1 km in diameter mapped alongside all normal faults in the “Ceraunius North” study area.................................34

Figure 17 All mapped faults in “Tractus” study area, color-coded by strike. ....................35

Figure 18 Trend of pit crater chains with pits over 1 km in diameter mapped alongside all normal faults in the “Tractus” study area............................................36

Figure 19 The 62 (31 graben-bounding pairs) study fault locations for this study.........37
Figure 20  Fault displacement profiles for all 14 study faults in “Tantalus North” .................39

Figure 21  Fault displacement profiles, normalized by length and maximum displacement, for all 14 study faults in the “Tantalus North” study area. .................40

Figure 22  $D_{\text{max}}/L$ ratios for this study plotted with corresponding measurements for structures on Earth ........................................................................................................43

Figure 23  The “Tantalus South” study area is shown with a grey outline, and the area for which crater statistics were obtained is outlined in black. ........................................45

Figure 24  The “Tantalus South” CraterStats surface age estimates ........................................46

Figure 25  The “Ceraunius South” study area is shown with a grey outline, and the area for which crater statistics were obtained outlined in black ........................................47

Figure 26  The “Ceraunius South” CraterStats surface age estimates ........................................48

Figure 27  Fault strike plotted by elevation for all mapped faults...........................................50

Figure 28  Fault length plotted by distance from Alba Mons for all mapped faults.................52

Figure 29  Fault strike plotted by distance from Alba Mons for all mapped faults.................54

Figure 30  Fault strike plotted by latitude for all mapped faults.............................................55

Figure 31  Faults that are (Left) only radial to Alba Mons and (Right) only circumferential to the volcano.................................................................56

Figure 32  Faults that are radial both to Alba and Tharsis .....................................................57

Figure 33  Faults that are only radial to Tharsis that (Top) strike north–south, (Middle) strike northwesterly, and (Bottom) strike northeasterly ..............................60
1. Introduction, Background, and Overview

1.1. Geological Setting

Today, the planet Mars is in a phase of volcanic and tectonic quiescence (Cailleau et al., 2005). However, low erosion rates (Quantin et al., 2015) preserve billions-year-old volcanic and tectonic structures (Scott and Tanaka, 1986), which give us insight into processes that have taken place on the planet. A major site of geological activity on Mars has been the Tharsis Rise (*Figure 1*), a wide volcanic dome 8000 km wide with an average height of 11 km that is transected by giant tectonic features. Tharsis bears witness to intense crustal intrusion, surface deformation, and volcanic activity (Phillips et al., 2001; Cailleau et al., 2005). Wide uplift from a rising plume may have contributed to the topography of the region (Harder, 2000).
The tectonic activity in the Tharsis region predominantly occurred in the early history of Mars, before 3.7 billion years ago (Ga), decreasing until the middle-late Amazonian epoch, 1.4–0.3 Ga (Anderson et al., 2001; Cailleau et al., 2005). However, the basic lithospheric structure and stress
fields of the Tharsis Region have likely not changed since early Martian history (~4 Ga) (Anderson et al., 2001; Phillips et al., 2001; Williams et al., 2008; Golombek and Phillips, 2010). The entire region is characterized by a giant system of landforms interpreted as normal faults, formed by large-scale extensional stresses (Cailleau et al., 2005). The complexity of these faults renders Tharsis one of the most tectonically deformed and complicated regions on Mars.

The Tharsis Rise boasts pronounced radial-to-arcuate faults (Figure 1), which may reflect isostatic or flexural stresses due to volcanic loading (Turcotte et al., 1981; Sleep and Phillips, 1985; Banerdt et al., 1992; Cailleau et al., 2005). At a greater distance from the Tharsis center, the orientation of fractures is not constant. At the northern margin of the Tharsis Rise, in the vicinity of the highly-faulted shield volcano Alba Mons, the orientation of tectonic landforms change from E–W to NW–SE (Cailleau et al., 2005) (Figure 1).
The Alba Mons volcano itself (Figure 2), located at 20–60°N and 90–130°W (Ivanov and Head, 2006), is the largest edifice on Mars in terms of surface area. As a shield volcano, it is a broad, gently sloped (i.e., ~1°) construct (Plescia, 2004). The volcano and its environment are intensely deformed by faults (Raitala, 1988; Cailleau et al., 2005). Alba Mons has been a location of persistent volcanic activity during several 100-Myr time spans (Tanaka, 1990; Cailleau et al., 2003, 2005). Systems of normal faults cut across the volcano and the adjacent region, including circumferential faults that curve around the midflanks, and radial faults that extend from Tharsis highlands in the south to volcanic plains in the northeast (McGovern et al., 2001) (Figure 2).

Figure 2. The Alba Mons volcano (center), shown in equirectangular projection again with color-coded topography from the MOLA DEM. The five study areas in this project are also shown (black boxes).
1.2. Normal Faults and Graben

On the basis of image data returned for Mars (see Section 2.1), faults in the Alba Mons region are interpreted mainly as those with normal movement along the fault plane. Such faults form in an extensional tectonic regime, wherein the maximum compressive stress is oriented vertically, and the intermediate and minimum compressive stresses are horizontally oriented. If the yield strength of the crust is matched, shear failure along fault planes can occur (*Figure 3*). When two normal faults dip toward one another, such that the block of crust between them is down-dropped, the topographic low is termed a graben. Such a scenario occurs because the initial normal fault that forms (the primary fault) flexes the adjacent crust until a new (secondary) fault forms that dips toward (i.e., is antithetic to) the primary fault (Melosh and Williams, 1989).

*Figure 3.* A cartoon schematic of a graben in cross section. Credit: ASU/Smithsonian Institution.

Normal faults on Mars can form simple, long, narrow graben (Polit et al., 2009) as well as more complex, en échelon structures and even pull-apart graben (Bistacchi et al., 2004; Vaz, 2011). En échelon graben are composed of unconnected, discontinuous, yet overlapping faults (Ferrill et al., 1999) that form a “step-like” array on the surface. Pull-apart graben are rhombic (in map view), flat-bottomed structures bounded by steep, segmented oblique-extensional (i.e., transtensional) faults (McClay and Dooley, 1995). Sets of graben are characterized as radial when they emanate from a point, or circumferential when they curve around a landform. Due to the unique “wristwatch” pattern of faults in the Alba Mons region (van Wyk de Vries and
Matela, 1998) (Figure 2), the changes in graben orientation associated with the volcano, and the presence of distinct “patches” of graben at various distances to the volcanic edifice, it is clear that tectonic deformation in this region was far from straightforward.

Despite considerable focus on Alba Mons over the past several decades (see Section 1.3), several important questions remain. Did the graben in this region form solely from the stresses related to the Alba Mons volcano itself, are they part of a larger, Tharsis-related stress field, or might they even reflect the interaction between both local and regional stresses? Additionally, what was the nature of the faulting: a purely tectonic process, a process involving magmatism (such as dike intrusion), or, again, an interaction of both? These questions are much easier addressed for regions on Earth, where field studies and comprehensive geophysical measurements can test for the presence of tectonic versus volcanic activity, but for Mars we depend on observations returned by robotic spacecraft. Fortunately, substantial volumes of such data exist (see Section 2.1); moreover, that landforms are preserved on Mars for billions of years means that we are able to assess their morphology, and address these questions, long after tectonic activity has ended.

1.3. History of Mars Data
Viking 1 was the first spacecraft to provide global, high-resolution images of the surface of Mars. These images varied from 150–300 meters per pixel (m/px), and in some select areas of interest were at resolutions of up to 8 m/px. Several studies (e.g., Wise, 1976) and derived maps (e.g., Scott and Tanaka, 1986) used these images to investigate the pattern of faulting in the Tharsis region, including Alba Mons. In 1998, a global digital elevation model (DEM) became available thanks to the Mars Orbiter Laser Altimeter (MOLA) aboard the Mars Global Surveyor spacecraft (Smith et al., 2001). This new data set greatly facilitated the ability to study Martian tectonics. With the added third dimension (elevation), detailed structural studies could be performed. Analysis of the length, width, and depth of volcanic and tectonic structures associated with the volcano thus began in earnest (e.g., McGovern et al., 2001). More recently, even higher-resolution data have become available for the surface of Mars, and are used in this study. In particular, thermal infrared (IR) image data from the NASA Mars Odyssey Thermal Emission Imaging System (THEMIS) instrument, as well as visible-spectrum data from the ESA Mars Express High Resolution Stereo Camera (HRSC) and the NASA Mars Reconnaissance Orbiter
(MRO) Context Camera (CTX), are employed in this study of the tectonic characteristics and evolution of the Alba Mons volcano.

1.4. Previous Alba Mons Work
The first model to explain the complex fault pattern at Alba Mons was proposed by Wise (1976). In that study, Wise interpreted the faults of Alba and Tantalus Fossae (Figure 2) to be an expression of lithospheric stresses produced by the crustal loading by the volcano itself. Indeed, he was the first to suggest that the fault patterns at the Alba Mons region resulted from a combination of local, volcanic loading and a regional stress field. Numerical modeling by Wise (1976) reproduced circumferential faults by combining regional extension with a volcanic load on a thick plate, and predicted stresses to be generally E–W oriented, resulting in regional, Tharsis-originating faults with strikes that deviated from that trend in the vicinity of Alba Mons. This model, however, assumed that Alba Mons exerts only a surface load on the lithosphere, and so the results of Wise (1976) included only circumferential faults; the radial structures observed at the volcano were not replicated. Later studies (e.g., McGovern et al., 2001) determined that this incorporation of a surface load alone was the reason the model did not fully match observations. Moreover, the Wise (1976) model also utilized very low regional stress values that were insufficient to reorient principal stresses to produce the observed fault pattern. This issue may have arisen because knowledge of the topography of the Alba Mons region was poor at the time of this work.

Although no radial structures were produced in the model reported by Wise (1976), subsequent studies (e.g., McGovern et al., 2001; Cailleau et al., 2005; Ivanov and Head, 2006) expanded on the concept of treating Alba Mons as a lithospheric load, with the general view that both regional and local stress fields were involved in graben formation in the vicinity of the volcano (Raitala, 1988; Turtle and Melosh, 1997). The ultimate goal of these subsequent studies was to successfully account for both the circumferential and radial fault systems observed at Alba.

The publication of Scott and Tanaka's 1986 geologic map of the western hemisphere of Mars contributed greatly to these later efforts. The authors used the three Martian time-stratigraphic systems originally defined by Scott and Carr’s 1976 geologic map, in order from oldest to
youngest: Noachian, Hesperian, and Amazonian. These systems were divided based on physical characteristics and stratigraphic relations observed with data returned by the Mariner-9 mission, a NASA orbiting probe that took photos of the surface from 1971 to 1972 (Hartmann and Raper, 1974). The later map (Scott and Tanaka, 1986) divided the Alba Mons region into three units: a Hesperian lower member (Hal), composed primarily of flood lava sheets (Cattermole, 1987); an Amazonian middle member (Aam) that surrounds the summit region; and an Amazonian upper member (Aau) that includes the summit region and is generally within the bounds of the circumferential graben (Schneeberger and Pieri, 1991). This mapping revealed two interesting observations: that Alba Mons’ topography is asymmetric with respect to the geologic units present there, and that the summit is offset to the south and west of the circumferential normal faulting at the volcano (McGovern et al., 2001).

The Scott and Tanaka (1986) map also documented temporal relations between units associated with Alba Mons and the surrounding fault systems, indicating for instance that the radial graben of Tantalus Fossae (Figure 2) are generally of the same orientation as Tempe Terra graben, which cut into Hesperian and Noachian units. Further, some Ceraunius graben continue into the Amazonian-era “At5” unit (interrupted as lava flows from the Tharsis Montes volcanoes). And the lower Alba unit is largely superposed by the Arcadia Formation in the north, yet some radial graben propagate into these units. This additional information helped to shed light on the relative timing of faulting at Alba Mons, the possible driving formation mechanisms, and the resultant control over fault orientations. Scott and Tanaka (1986) also reported observations of the individual structures themselves, attempting to tie their formation into the volcanotectonic history of Alba Mons. For instance, these workers concluded that resurfacing by lava flows likely contributed to the current distribution of faults on the flanks of the volcano. The upper geologic unit (“Aau”)—that is, the youngest flows of Alba Mons—shows evidence of fault reactivation and/or continued tectonic movements, due to some older faults being partially buried by flows that are in turn displaced by younger faults (Scott and Tanaka, 1980; 1986). This combination of geological and tectonic mapping revealed a complex and multistage history of volcanism and faulting at Alba Mons.
Tanaka later narrowed his focus to a study on the tectonics of the Alba–Ceraunius region (Tanaka, 1990). With these observations, it became possible to construct a sequence of faulting in the area. Tanaka (1990) found that a first tectonic episode formed northeast-striking graben parallel to the Tharsis Montes (*Figure 1*), the Tantalus Fossae. A later and more widespread tectonic episode, probably related to Syria Planum- or Claritas Rise-centered radial faulting in the Noachian or in the early Hesperian (>3.6 Ga ago), formed the north-striking graben system, Ceraunius Fossae. The northern portion of Ceraunius Fossae that cuts across the main shield unit was reactivated—or was continuously active—until the early Amazonian (approximately 2.9–2.1 Ga). These Ceraunius Fossae structures imply an early E–W regional tensile stress field radial to Tharsis (Tanaka, 1990).

In a study of Tharsis rise-related structures, Tanaka et al. (1991) concluded that linear graben in the vicinity of Alba Mons (Fig. 2) could be generally attributed to regional extension arising from activity centered at Tharsis itself. These workers suggested that radial-to-arcuate graben on the flanks of Alba Mons may have been induced by spreading of the volcano (e.g., Borgia et al., 2000) enabled by a ductile layer between the upper crust and the strong upper mantle (Tanaka et al., 1991).

In contrast, Mège and Masson (1996) proposed a plume tectonics model for the formation of the entire Tharsis Region, including Alba Mons and its associated fault systems. These authors determined that the dominant NE–SW orientations of these faults (i.e., Tantalus Fossae and the northern segments of Alba Fossae) are controlled by a regional- or Tharsis-scale stress field (Wise, 1976; Mège and Masson, 1996). Some workers, including Mège and Masson (1996), suggested that some portions of the graben systems associated with the Tharsis Rise in general, and Alba Patera in particular, may have been formed by subsurface dike swarms (Plescia, 1991; Davis and Tanaka, 1995). Mège and Masson (1996) also suggested that the circumferential graben of Alba and Tantalus Fossae resulted from a purely regional tectonic process, whereas graben to the northeast show evidence for a magmatic component (i.e., dike propagation, as evidenced by U-shaped depressions of the graben, spatter cone chains, and en echelon segments)—and so these authors regarded the graben in this area as the outliers of a regional dike swarm.
Turtle and Melosh (1997) regarded Alba Mons’ circumferential faults as a manifestation of volcanic surface-load stresses. These authors built on the model proposed by Wise (1976) by starting with a surface load emplaced on an elastic plate overlying an inviscid substrate. Turtle and Melosh (1997) varied in their numerical model load dimensions and elastic lithosphere thickness to fit the then-available topography and gravity data, and calculated a thickness of the lithosphere of 10–50 km. To match the observed fault trends, these workers superposed a regional stress field onto the volcano-driven flexural stress. They found that extensional stresses with magnitudes of 150–200 MPa, combined with the local axisymmetric stress field arising from the loading of the lithosphere by Alba Mons, could create the observed pattern of strain. However, such a stress magnitude is beyond the highest recorded strength of intact basalt (tensile strength, −14 MPa), and so the prospect for stresses this high acting on the Martian lithosphere is unlikely (Schultz, 1993).

The acquisition in the early 2000s of the MOLA global topographic dataset by the Mars Global Survey mission (Smith et al., 2001) revealed a key observation: that Alba Mons is a much larger volcano than previously assumed. In Viking images, it appeared that the volcano was almost entirely situated between Alba Fossae, to the west, and Tantalus Fossae, to the east (Mouginis-Mark et al., 1988; Cattermole, 1990; Turtle and Melosh, 1997) (Figure 2). However, MOLA indicated that the shield actually extends from 20–60°N and 90–130°W (Ivanov and Head, 2006). With these new elevation data, workers were able to study the graben of Alba Mons region in much greater detail. For example, it became apparent that the circumferential graben of Alba Fossae are at higher elevations, on average, than those of Tantalus Fossae: indeed, the western quadrant of Alba Mons lies more than 1 km higher on the midflank than its eastern counterpart (McGovern et al., 2001). Additionally, it became clear that the circumferential faults cut into the midflank of the volcano, casting doubt on the view that they were caused purely by surface loading (e.g., Wise, 1976; Turtle and Melosh, 1997) of the volcanic edifice (McGovern et al., 2001).

Consequently, McGovern et al. (2001) proposed a new, updated model for the volcano-tectonic deformation of the volcano informed by the MOLA data. This model combined three stress fields: a regional, constant-rate crustal extensional component; a growing volcanic edifice; and
uplift from a deep, buoyant sublithospheric load (e.g., underplated magma), focusing more on intralithospheric loading (e.g., magmatic intrusions such as dikes and sills, or underplating) than the previous surface load models (Wise, 1976; Turtle and Melosh, 1997). With this approach, McGovern et al. (2001) explained the lower-flank faults that transition from circumferential to radial as conjugate shear planes, such that these faults may have both dip-slip and strike-slip displacements. These workers proposed that such oblique-slip displacement could allow dikes to preferentially follow these linear fractures and influence radial graben orientation.

A subsequent finite element model (FEM) study (Cailleau et al., 2003) noted that faults circumferential to Alba Mons formed after the radial graben, suggesting a temporal change from a radially to a circumferentially oriented extensional stress field. The model of Cailleau and co-authors supported the view that local subsidence, paired with regional extension, drove the formation of the extensional, circumferential faults on the volcano. These authors next studied the radial faults with an updated FEM (Cailleau et al., 2005) and argued that, based on observations of converging fault patterns, the radial structures of Tantalus Fossae resulted from local, Alba Mons-related stresses at a time of widespread volcanism. This later study (Cailleau et al., 2005) focused on fine-tuning the model of McGovern et al., (2001), which could not successfully predict the formation of radial graben in the northwestern portion of the volcano, nor the regional structures with pit craters (termed “catenae”) in the eastern area. Cailleau et al. (2005) posited that local dike injection was initiated from the Alba Mons volcano rather than from a regional source. These workers took this view because, during the formation of Tantalus Fossae and the volcanic plateau at Alba Mons, there was no comparable activity in the area of Ceraunius Fossae, even though this area is closer to Tharsis. Instead, Cailleau et al. (2005) proposed that a hot spot in the vicinity of Alba Mons, combined with a regional stress that was “dominant at the periphery,” was responsible for both circumferential and some radial graben on the flanks of Alba Mons. As for the radial graben of Ceraunius Fossae to the south, Cailleau et al. (2005) agreed with numerous earlier studies that, on the basis of their topographic signature, older age, and orientations relative to regional tectonic systems (Raitala, 1988; Tanaka, 1990; Anderson et al., 2001), these structures originated from the volcanic and tectonic activity of Tharsis. Reactivation of Ceraunius Fossae late in Alba Patera’s (previous name of Alba Mons) history is likely (Tanaka, 1990; Cailleau et al., 2005). Yet, as for previous work, the model of
Cailleau et al. (2005) did not address the striking difference in number and spacing of graben on either side of the Alba Mons summit (Ivanov and Head, 2006).

Ivanov and Head (2006) agreed that the normal faults on Alba Mons’ flanks are, in general, the youngest features of the volcano (and placed them in early Amazonian), and that these structures postdate the formation of the central edifice. These authors reconsidered the early hypothesis that the majority of Alba Fossae formed as a response to the loading of the summit dome and solidification of the magma reservoir (Wise, 1976; Walker, 1984, 1988). Tantalus Fossae, Ivanov and Head (2006) argued, may instead represent the long-lived and presumably deep-seated main tectonic zone (resulting from a Tharsis-related, regional stress field) that existed before the formation of Alba Mons, and that was reactivated because of Alba’s volcanic loading. Displacement along circumferential Tantalus Fossae faults accommodated tilting of the eastern flank lobe of Alba Mons, and this deformation could be responsible the asymmetry of both the volcano’s topographic form and the distribution of volcanic units on and around the shield (Tanaka, 1986). In their study, Ivanov and Head (2006) employed then-newly available Thermal Emission Imaging Spectrometer (THEMIS) infrared image data (with a resolution of 100 m/px) to assess in relatively high resolution both individual structures and the cross-cutting relations between graben and lava flows.

Following THEMIS, orbiting cameras imaged the surface of Mars at increasingly higher resolution (see Section 2.1). With these new data, especially when combined with topography from, for instance, the MOLA DEM, it became possible to investigate smaller faults and thus more complex cross-cutting patterns, explore relative age relations in more detail, characterize fault morphology more fully, and search for evidence of erosion. It is with this wealth of high-resolution images and data that structural geologists began to study the Alba Mons region graben to a greater extent than before, focusing on individual faults’ geometric properties and age-relations within fault systems, further refining theories of formation for these structures.

For example, methods such as fault displacement and length ratio scaling were applied to these later structural studies, techniques used in the study of faults on Earth for decades (Cowie and Scholz, 1992; Dawers et al., 1993). Displacement–length scaling can provide information on
factors leading to Martian fault growth and fault population evolution (e.g., Schultz, 1991, 1997; Polit et al., 2009). In the case of Alba Mons graben, this method involves measuring for individual graben-bounding normal faults the total fault length ($L$) and the maximum vertical displacement ($D_{\text{max}}$), which requires horizontal and vertical measurements (and, therefore, high-resolution topographic data). Studies of fault populations on Earth have found that the relationship between maximum displacement and total fault length is, generally, linear in nature (Dawers et al., 1993). Nonetheless, it has been shown that this scaling ratio is lower by sometimes as much as a factor of five for Martian and Mercurian faults, possibly because of the lower surface gravitational accelerations on those worlds compared with that of Earth (Schultz et al., 2006).

**Figure 4.** The relationship between vertical fault displacement ($D$) and fault length ($L$), shown here for an unrestricted normal fault. Ideally, maximum vertical displacement ($D_{\text{max}}$) is situated at the center of the fault and $D$ goes to zero at the tips. Figure from Fossen (2010).

In a structural study of the Tantalus Fossae graben, Polit et al. (2009) used $D_{\text{max}}/L$ ratios and fault displacement profiles to compare graben on the flanks of Alba Mons with graben of similar strike and morphology in the plains to the north of the volcano. These authors paid particular attention to the possibility of fault restriction (i.e., the inhibition of faults from penetrating beyond a given crustal depth by changes in rheological properties). Such restriction would be manifest as a plateaued profile of fault displacement versus length, in contrast to a peaked displacement profile for a fault that is not mechanically restricted to a particular stratigraphic depth (Soliva et al., 2005) (see Figure 4). Polit et al. (2009) found that the graben-bounding faults on the flanks of Alba Mons do not, in general, show evidence for vertical restriction, whereas faults farther to the northeast do appear to be restricted at depth. This observation has
implications for $D_{\text{max}}/L$ scaling because ratios for the faults that are mechanically restricted do not scale linearly, in contrast to the generally linear scaling ratio of unrestricted faults (e.g., Dawers et al., 1993). Additionally, Polit et al. (2009) concluded that the faults closer to Alba Mons possess greater extensional strain, and are therefore more likely to be the result of local stresses centered in the Alba Mons vicinity, than those farther from the shield, to which these workers attributed an origin from regional stresses arising at the Tharsis center.

It is important to note that, although many studies and models over the years converged upon a dike-related origin for graben in the Tharsis region (e.g., Mège and Masson, 1996; Ernst et al., 2001; Cailleau et al., 2005), Polit et al. (2009) found no evidence for any volcanic activity that might have been associated with such dikes, were they present (e.g., pit craters, troughs, or emanating lava flows) in either of the two areas these authors studied (the graben on the flanks of Alba Mons and those that extend into the northern plains). Finally, Wyrick et al. (2011) conducted a structural study of circumferential and radial Alba Fossae faults on the northwest flanks of Alba Mons where they measured maximum fault displacements and lengths, thus calculating $D_{\text{max}}/L$ ratios, for over 300 normal faults. In the Wyrick et al. (2011) study area, substantial fault lengths tend to reflect fault linkage, which is the primary determinant of fault length, and results in lower $D_{\text{max}}/L$ values.

1.5. Study Rationale
Firstly, I believe that to properly investigate the origin of stresses that caused the Alba Mons region graben, and more importantly, the possibility of these structures reflecting more than a single stress field, the graben systems around the volcano (i.e., Tantalus, Alba, and Ceraunius Fossae) need to be split into smaller study areas than have been assessed so far. By doing so, especially with recent high-resolution image data, it will be possible to test existing hypotheses for the formation and timing of the complex extensional systems of structures around the volcano. My hypothesis is that faults proximal to the volcano reflect at least some component of extensional strain arising from the shield (e.g., through flexural loading), and so fault properties (e.g., orientation, strain amount, etc.) will systematically change with distance to or from the volcano.
To test this hypothesis, my approach is to split these faults into five discrete “study areas,” with that division based primarily on fault orientation and distance to the volcano, and then selecting a further subset of faults in each area for detailed structural analysis. The basis by which I select these study fault subsets is described in Section 4.4. After acquiring detailed measurements of fault properties, I will assess the spatial variation of those properties with distance from Alba Mons as well as distance from Tharsis, with a view to attributing the faults to the volcano, to Tharsis, or to both. I will also focus on the temporal component of tectonic deformation, especially on fault cross-cutting relations and on the absolute model ages of two areas in particular, assessed with crater statistics.

2. Methods
2.1. Data
The primary base maps used for digitizing faults and related landforms for this study include the “Day IR” global mosaic from the Thermal Emission Imaging System (THEMIS) instrument. This instrument arrived in Mars orbit in 2001 aboard the NASA Mars Odyssey orbiter, and acquires image data of the surface in both the visible and infrared, both during the Martian day and at night. Like a conventional imaging system, data from the THEMIS instrument reveal details of the Martian surface and the morphology of the landforms there. The THEMIS Day IR mosaic is particularly useful because it has global coverage of the planet’s surface at a resolution of 100 m/px.

Elevation data for this project come from the NASA MOLA DEM. These data have a native (i.e., ungridded) resolution of 64–128 (m/px), depending on latitude. For this study, a gridded (i.e., interpolated) global DEM with a resolution of 463 m/px was used (Smith et al., 2001). The MOLA data set is used within ArcMap to provide topographic profiles and to conduct other measurements that require elevation values. Where possible, higher resolution (if much more spatially limited) images were used to supplement the base maps. These supplemental data aided in the mapping of smaller-scale features and crosscutting relationships. HRSC images (12.5–25 m/px) cover some parts of the study region. MRO CTX images offer 5.5 m/px spatial resolution of the surface. The CTX images available for the Alba Mons region cover some parts of the
study region that HRSC does not, and so these data together provide an enhanced view of the study region over THEMIS alone.

To assign inferred lithologies and stratigraphic ages to faults in this study, the most recent global geological map was used. This updated map by Tanaka et al. (2014) reports adjusted absolute ages for several units, including those within the study region. (For example, geological units associated with Ceraunius Fossae are updated from Noachian-age to early and late Hesperian.

2.2. Study Areas
Previous analyses of the extensional systems associated with Alba Mons considered the graben sets as a group. It is my view, however, that the complexity of faulting in the Alba Mons region necessitates the partitioning of these fault systems into smaller study areas. This opinion is based on the presence in some places of at least four different and resolvable fault strike orientations, the general complexity of cross-cutting relationships of faults in the region, the possibility of fault reactivation, and the prospect that some areas experienced both regional- and local-scale stresses (and possibly both simultaneously) at different times. For these fault systems to be compared and contrasted properly, and to attempt to craft a synthesis of deformation history as recorded by these fault populations, dividing this large study region into smaller areas is necessary.

I therefore divided the study region into five smaller study areas. Previous work has referred to all faults to the east and northeast of Alba Mons, at latitudes of approximately 35º N and above, as Tantalus Fossae (i.e., Öhman and McGovern, 2014). However, there are discrete spatial trends in this area, including the circumferential faults that curve around the mid and lower flanks of the volcano, that do not continue to latitudes greater than 44º N (Figure 2). Similarly, the faulted area formally named Ceraunius Fossae in fact encompasses three discrete patches of graben systems, separated by younger lava flows in lower-elevation areas. This fossae system extends from the mid-flanks of Alba Mons to 19º N latitude, which is approximately 1,200 kilometers south of the volcano central caldera complex. Additionally, fault strike varies considerably between these three patches. Nearest the volcano, the deepest faults trend predominantly north–south, whereas the adjacent “patch” to the south has curved faults, and farther south still there is
major structural complexity, with up to four distinct strike orientations. For the purpose of this study, then, I divided both Tantalus and Ceraunius into “north” and “south” areas. The fifth study area, “Tractus”, is comparatively distant from the volcano (~900 km from the caldera complex), but is included in this project because of its structural similarity to the other faulted areas. Additionally, it is necessary to compare faults near the volcano with those that are farther away, to test the extent to which local- versus regional-scale stresses have acted upon this part of Mars.

Table 1. Study areas in this study. Geological descriptions and inferred stratigraphic ages are from the Tanaka et al. (2014) global geological map. Colored boxes correspond to map colors in Figure 7.

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Centered at</th>
<th>Geologic unit(s)</th>
<th>Fault strike</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalus North</td>
<td>99° W, 48° N</td>
<td>▉Amazonian-Hesperian volcanic unit (AHv) ▉Middle Noachian highland unit (mNh)</td>
<td>NE</td>
</tr>
<tr>
<td>Tantalus South</td>
<td>102° W, 39° N</td>
<td>▉AHv</td>
<td>N to NE</td>
</tr>
<tr>
<td>Ceraunius North</td>
<td>108° W, 33° N</td>
<td>▉Late Amazonian volcanic unit (lAv) ▉Late Amazonian volcanic field unit (lAvf) ▉Amazonian volcanic edifice (Ave) ▉AHv ▉Early Hesperian volcanic unit (eHv)</td>
<td>N</td>
</tr>
<tr>
<td>Ceraunius South</td>
<td>108° W, 23° N</td>
<td>▉lAvf ▉AHv ▉Late Hesperian volcanic unit (lHv) ▉eHv</td>
<td>N</td>
</tr>
<tr>
<td>Tractus</td>
<td>101° W, 26° N</td>
<td>▉lAv ▉AHv ▉lHv</td>
<td>N</td>
</tr>
</tbody>
</table>

2.3 Mapping Methods and Techniques

Mapping was performed with ESRI’s ArcGIS ArcMap v. 10.6, using as a base map the THEMIS Day IR global image mosaic, together with a global hillshade derived from MOLA topography, and supplemented with high-resolution images as needed and where available. Landforms were mapped at a scale of 1:200,000 and saved in separate ArcGIS shapefiles for each study area.

Mapped structures include fault scarps, pit crater chains, sinuous channels, and impact craters. Fault scarps were mapped as linear features, identified as such with the THEMIS base map with help of the MOLA DEM. Inferred fault down-dip direction was recorded with a hatched line symbology. Fault strike was calculated with the EasyCalculate10 Add-In for ArcMap, which finds the azimuth of the bearing of the fault scarp polyline; this value was then converted into strike (and given as a three-digit number between 0° (000) and 180° (180)). In addition to fault
scarps, pit crater chains were mapped by recording an approximate strike of the chains of craters separately, for use in comparison of fault and pit crater chain orientations. Several examples of sinuous channels of indeterminate origin are present in the study region, and so were also digitized as linear features with polylines that follow their curved morphology. Impact craters of all sizes at mapping scale were mapped as circular features, for use in crater statistics studies.

The geodetic distance of a given structure to Alba Mons was measured with the Euclidean distance tool in ArcMap. The latitude of each fault is used as a proxy for its distance from the Tharsis region, because that major volcanotectonic rise is centered approximately at the equator. To represent the centers of individual faults, the centroids of their shapefile polylines were calculated.

2.4. Analyses for All Mapped Faults

All normal faults in the study region were identified with the image and topographic data described above. For each of these structures, key geometric and geological properties were recorded including fault length, strike, elevation, geological unit in which they occur, their distance from Alba Mons, distance from Tharsis, and any cross-cutting relationships with adjacent faults with different strikes.

Most graben have one bounding fault, often referred to as the “primary” fault that has more vertical displacement than the other. Where a difference in vertical relief (and thus inferred fault throw) was identified for the bounding faults of a given graben, the larger fault was interpreted as the primary fault and its location and down-dip direction recorded. Primary and secondary faults are predicted to form together (Illies, 1981), and so the location and dip direction of the primary fault may indicate the source of the stress field which activated faulting. Additionally, in rift-type extensional provinces, transfer faults will switch primary faults from one graben segment to another (Mège and Masson, 1996; Ernst et al., 2001), and so evidence for such switching was also noted.

Finally, cross-cutting relationships were recorded, and relative age determinations made, for all faults in the project. A thorough examination of the study region was conducted using the highest
resolution image data available, and locations of cross-cutting and stratigraphic relationships were investigated to determine the relative ages of mapped faults. This is important because many areas, especially “Ceraunius North,” “Ceraunius South”, and “Tantalus South,” have at least three distinct fault orientations (see Section 3.1.2) that plausibly indicate multiple phases of faulting and/or changes in stress orientation(s).

2.5. Fault Analysis
Several faults (graben-bounding pairs) in each study area were selected for detailed structural analysis. These study fault subsets were selected on the basis of their suitability for three-dimensional geometric investigations at the resolution of the MOLA topographic data, which has substantially lower horizontal resolution (463m/px) than the THEMIS global image base map (i.e., 100m/px). When selecting the subset of study faults from the entire fault population of this region, consideration was given to the importance that selected faults be a good representation of structural trends for their respective study areas. As a result, and to the maximum extent possible, the data set of study faults included faults of as broad a range of orientations, depths, and spatial extents as possible. For the derivation of a ratio relating fault length to displacement, it is also preferable that study faults be as isolated as possible, i.e., they must have had minimum mechanical linking with adjacent faults, and must also have minimal modification by cross-cutting, impact cratering, infill by lavas, and mass-wasting. Satisfying these latter criteria for faults in the study area was challenging, however, due to the high level of structural complexity of the graben systems here, especially in the “Ceraunius South” study area. I measured fault length and graben width from the base map of THEMIS images and MOLA elevation, and I measured the vertical relief of a given fault scarp as recorded with the MOLA cross-sections. Only hard-linked (i.e., physically linked at the surface) faults are considered to be continuous.

Topographic profiles were placed every ~5 kilometers along the length of these study faults (avoiding obstacles such as impact craters and adjacent faults where possible). Special care was taken to identify the location of fault scarps within the resolution of MOLA data, which can differ from THEMIS base map images by tens of meters in some cases. From the resulting profiles, values for vertical relief and width were then obtained. The vertical relief of a given fault was assumed to be a proxy for the vertical component of fault displacement (throw). For
each fault, then, the maximum vertical displacement value was taken as the greatest relief value from the profiles along a given fault. A ratio of maximum vertical displacement ($D_{\text{max}}$) to total fault length ($L$) was then calculated for each study fault. (This ratio is the displacement–length ratio ($D_{\text{max}}/L$) of the fault.)

2.6. Crater Statistics Analysis

Absolute model ages were calculated for two study areas, “Tantalus South” and “Ceraunius South.” These areas were chosen because they are proximal and distal to the volcano, respectively, and because sufficient CTX and HRSC image coverage is available. By determining model ages for these surfaces with all craters present, I can test the stratigraphic interpretations for the units in these areas by Tanaka et al. (2014). Moreover, by calculating model ages with only those craters in each of these areas that are not faulted, we can place an estimate on the timing and even duration of extensional deformation in “Tantalus South” and “Ceraunius South.” To map the primary impact craters at each site, I used the CraterTools extension (Kneissl et al., 2011) for ArcMap 10. Absolute model ages were determined for each site with the “Craterstats program” (e.g., Michael and Neukum, 2010), using the model production function and chronology of Ivanov et al. (2001). The CraterStats model ages are calculated by Poisson timing analysis (Michael et al., 2016), given assumed scaling relations between impactor diameter and crater diameter. The determination of model ages with Poisson timing analysis returns plots of model age uncertainty as a probability density function, marked by vertical lines at the 50 ± 34 percentiles (Michael et al., 2016). Because systematic uncertainties in the chronology model are much larger than errors from counting statistics (by at least several hundred million years) and are not very well constrained, I give model ages in Section 3.5 only to two significant figures.

3. Results

In this section, I report on the results of fault mapping and analysis, structural measurements of select study faults, and cratering statistics for select study areas. First, results for the entire study region (i.e., all five study areas together) are shown in maps and graphs; the maps include faults color-coded by mean elevation, by strike, by geologic unit, and by total fault length, and the graphs show how these properties differ for each study area, and in comparison with fault strike.
Next, qualitative descriptions of the five study areas are given, including general fault strike and observations of any abrupt changes or cross-cutting patterns that occur, comparisons between normal fault strike and orientations of other linear features (i.e., pit crater chains), and other relevant morphological observations of landforms in the study area. Then, the results for in-depth structural analyses of a select subset of normal faults in each of the five study areas are reported, followed by the crater statistics results.

3.1. Study Region Results

3.1.1. All mapped faults by elevation

Figure 5. All faults mapped in this study, color-coded by mean elevation along strike.

*Figure 5* shows the mean elevation of all faults mapped as part of this study. The faults on the upper and mid-flanks of Alba Mons stand at relatively high elevation, which is expected since
they are situated on a broad volcanic edifice, but there are also areas in the “Ceraunius North” and “Ceraunius South” study areas south of the volcano that are situated at elevations of between 3 and 6 kilometers. The lowest elevation faults are in the “Tantalus North” study area to the northeast of the volcano, and are situated below 0 m elevation (i.e., the Martian “sea level”, given as that elevation where the gravitational potential of the planet is equal to the mean radius (Smith et al., 2001)).

3.1.2. All mapped faults by strike

*Figure 6.* All faults mapped in this study, color-coded by along strike.

*Figure 6* shows all mapped faults in the study region color-coded by strike (that is, the bearing relative to 0° of the normal fault scarp). The specific strike value for each structure corresponds to the angle of a line that extends from the start and end point of the digitized fault trace. It is clear both that fault strike is generally consistent in each study area, and a generally continuous
northeasterly change in strike at progressive latitudes, but there are also instances of abrupt changes in strike and patches of cross-cutting faults in places.

**Figure 7.** All faults mapped in this study, color-coded by geological unit (from Tanaka et al., 2014).

**Table 2.** Number of faults, mean fault strike, and standard deviation for all structures mapped in this study. *For Rose Diagrams of fault strike see Appendix.*

<table>
<thead>
<tr>
<th>Study Area</th>
<th># Faults</th>
<th>Mean Strike (°)</th>
<th>Strike S. D. (±°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalus North</td>
<td>1,054</td>
<td>039</td>
<td>16</td>
</tr>
<tr>
<td>Tantalus South</td>
<td>1,320</td>
<td>022</td>
<td>14</td>
</tr>
<tr>
<td>Ceraunius North</td>
<td>3,676</td>
<td>003</td>
<td>19</td>
</tr>
<tr>
<td>Ceraunius South</td>
<td>3,728</td>
<td>004</td>
<td>16</td>
</tr>
<tr>
<td>Tractus</td>
<td>1,518</td>
<td>004</td>
<td>16</td>
</tr>
</tbody>
</table>

Study Total: 11,296  Study Mean: 015
The geospatial distribution of fault strike for each of the five study areas is given in Table 2. It is clear from this tabulation that, in order of descending latitude, fault strike is notably different in the northern study areas (i.e., “Tantalus North” and “Tantalus South”), compared with the three study areas that are south of Alba Mons (“Ceraunius North,” “Ceraunius South,” and “Tractus”). The geological unit classifications published by Tanaka et al. (2014) were added to the fault database, to analyze patterns of fault strike in regard to interpreted bedrock geology and relative stratigraphic age. From a comparison, then, of fault trace mapping and geological unit (Figure 7), it appears that bedrock geology cannot be relied upon to determine the origin of faults in the study region.

Table 3. Total faults, mean fault strike, and standard deviation of fault strike by geological unit. Colored boxes correspond to colors on map, to aid legibility.

<table>
<thead>
<tr>
<th>Geological Unit (youngest to oldest)</th>
<th># Faults</th>
<th>Mean # Strike (°)</th>
<th>Strike S. D. (±°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Amazonian volcanic unit (lAv)</td>
<td>51</td>
<td>005</td>
<td>20</td>
</tr>
<tr>
<td>Late Amazonian volcanic field unit (lAvf)</td>
<td>64</td>
<td>167</td>
<td>15</td>
</tr>
<tr>
<td>Amazonian volcanic edifice (Ave)</td>
<td>58</td>
<td>016</td>
<td>17</td>
</tr>
<tr>
<td>Amazonian-Hesperian volcanic unit (AHv)</td>
<td>5,312</td>
<td>018</td>
<td>22</td>
</tr>
<tr>
<td>Late Hesperian volcanic unit (lHv)</td>
<td>1,752</td>
<td>005</td>
<td>17</td>
</tr>
<tr>
<td>Early Hesperian volcanic unit (eHv)</td>
<td>4,571</td>
<td>002</td>
<td>17</td>
</tr>
<tr>
<td>Middle Noachian highland unit (mNh)</td>
<td>92</td>
<td>048</td>
<td>10</td>
</tr>
<tr>
<td>Total/mean</td>
<td>Study total: 11,900</td>
<td>Study mean: 011</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 lists the total faults in each geological unit (i.e., those from the geological map of Tanaka et al. (2014)), as well as the mean fault strike for each of the geological units that comprise the study region. The only conclusion that can be made from this data is that bedrock geology is not controlling the strike of these faults (based on the high standard deviation for fault strike mean in Table 3), and the fact that every geologic unit in this region is host to faults with a wide range of strike (and, in the case of study areas “Ceraunius North” and “Ceraunius South,” a lot of cross-cutting). However, it is worth noting that the two southernmost study areas (“Ceraunius South” and “Tractus”) are almost entirely comprised of Hesperian (3.7–3.0 Ga) geologic units with thousands of mapped faults that strike nearly due north (Table 3).
3.1.4. *All mapped faults by total fault length*

![Image of fault map]

**Figure 8.** All faults mapped in this study, color-coded by length.

The geospatial distribution of normal fault length is shown in *Figure 8*. Overall, the longest faults are found in the “Tantalus North” study region to the northeast, and generally are progressively shorter with increasing proximity to Tharsis. Note, however, that the apparent abundance of shorter faults in the “Ceraunius North” and “Ceraunius South” study areas is partly due to the complexity of faulting in these areas, e.g., a large number of cross-cutting faults with different strikes. Such cross-cutting results in two fault traces that presumably were a previously longer, single fault. However, relatively short faults that show no evidence of being the result of truncation are also found in each study area.
3.2. Study Area Results

3.2.1. “Tantalus North”

This is the northernmost regional study area lying to the northeast of Alba Mons (*Figure 5*). Faults here cut into the “Amazonian-Hesperian volcanic” (*Ahv*) and “middle Noachian highland” (*mNh*) geological units (*Figure 7*). The northernmost mapped faults propagate into terrain that is considered to be near the dichotomy boundary of Mars, separating the relatively smoother and younger northern lowlands and the older, rugged southern highlands (e.g., Carr, 2006). There are 1,054 mapped normal faults in this area, which also features two pit crater chains (one of which is formally named Phlegethon Catena: Tanaka et al. (2014)) (*Figures 9 and 10*).
Figure 9. All faults mapped in the “Tantalus North” study area, color-coded by strike. Note the abrupt change in strike between those faults that continue into this area from the adjacent study area to the south (“Tantalus South”).
Faults in this study area generally trend northeast, with a mean strike of 039° (see Table 2). At 42–45° N, there is an combination of two fault arrays, defined on the basis of strike, that cross-cut one another, with some faults slightly curving around the volcano (i.e., the warm colors at the southern margin in Figure 10). The bulk of faults in this study area form graben that are hundreds of meters deep and several kilometers wide, trend northeast, and appear to be older in age than faults that strike more north-south, based on cross-cutting relationships (Figure 9, dark blue colors). At 45–54° N, all faults trend northeast, are mainly parallel to one another, and thus rarely intersect. At 50–54° N, faults begin to fan out toward north and northeast, with strikes ranging from 011° to 074° (Figure 9). Within this study area, there is one 416 km-long, ~1.6 km-

Figure 10. Trend of pit crater chains mapped with pits over 1 km in diameter (hot pink) mapped alongside all normal faults mapped (black) in the “Tantalus North” study area. The long pit crater chain (right) is formally named Phlegethon Catena. The base map is color-coded MOLA elevation atop a MOLA-derived hillshade.
deep pit crater chain (named Phlegethon Catena) that trends approximately 049° (*Figure 10*). Faults adjacent to this pit crater chain (within ~80 km) strike parallel to its general trend (049°).

3.2.2. **“Tantalus South”**

![Figure 11. All faults mapped in the “Tantalus South” study area, color-coded by strike.](image)

This study area is primarily located on the eastern flanks of Alba Mons, and all faults here cut into the “Amazonian-Hesperian volcanic” (*Ahv*) geological unit. There are 1,320 faults mapped in this area (*Figure 11*). As for “Tantalus North,” this study area also includes two very long pit crater chains, Phlegethon and Archeron Catenae (the former of which extends into the more northerly area).

Approximately 75% of mapped faults strike northeast (between 015° and 060°), with a mean strike for the entire study area of 023° (*Figure 11*, light blue–green colors). However, some
cross-cutting occurs in the center–north of the area (*Figure 11*, yellow–orange colors), with the other 25% mapped faults that strike more northerly to northwesterly (between 135° and 015°) (*Figure 11*, yellow–orange colors).

*Figure 12.* Trend of pit crater chains with pits over 1 km in diameter (hot pink) mapped alongside all normal faults (black) in the “Tantalus North” study area. Central pit crater chain is Phlegethon Catena, and in the southeast is Archeron Catena. The base map is color-coded MOLA elevation atop a MOLA-derived

The array of faults (25% of the study area total) that strikes north–northwest is entirely located within ~450 km radius of the volcano’s caldera complex. These faults and fault segments have linked in a stepwise fashion that makes longer graben appear to slightly curve (~0.1 degree/km) around the flanks (*Figure 11*, yellow colors). Pit crater chains (Phlegethon and Archeron Catenae), both of which trend 035° in this study area (*Figure 12*), are slightly oblique to the
mapped faults. The northeast-trending faults appear older, but they are in turn are cut by younger (or more recently active) pit crater chains.

3.2.3. “Ceraunius North”

Figure 13. All faults mapped in the “Ceraunius North” study area, color-coded by strike. Strikes here are complex. The mean strike is N–S (003°); however, there are several areas with incongruent patches of faults (red and blue colors) that have been cut by these N–S-striking faults.

This study area includes faults that lie directly south and southeast of Alba Mons, and which deform the Amazonian-Hesperian volcanic unit (AHv) and the Early Hesperian volcanic unit (eHv) (Figure 13). This study area also includes a smaller number of mapped faults in the Amazonian volcanic edifice (Ave) (~30 faults), Late Amazonian volcanic unit (lAv) (~10 faults), and the Late Amazonian volcanic field unit (lAvf) (~10 faults).
Figure 14. Trend of pit crater chains with pits over 1 km in diameter (hot pink) mapped alongside all normal faults (black) in the “Ceraunius North” study area. The base map is color-coded MOLA elevation atop a MOLA-derived hillshade.

There are a total of 3,676 faults mapped in this area, and 83 pit crater chains with individual pits over 1 km in diameter.

Sixty percent of mapped faults in the “Ceraunius North” study area strike approximately north–south (165° to 015°), with a mean strike for the entire study area of 003° (Table 2). Additionally, about 24% strike northeast (015° to 060°) (Figure 13, blue-green colors), and a smaller number of faults (~16%) strike northwest (between 165° and 120°) Figure 13, red–orange colors). There are abundant pit craters in this area, including long, regional chains that comprise Phlegethon and Archeron Catenaе, as well as smaller-scale (3–100 km long) pit crater chains. These structures are generally parallel to sub-parallel with faults, but there are instances where they are nearly perpendicular (Figure 14). Phlegethon and Archeron Catenaе both trend 028° in this study area,
and when compared with mean fault strike in the study area (003°), are oblique to these faults. Of note, however, normal faults adjacent (within 200 km radius) to these catenae are parallel with them. Smaller-scale (3–100 km long) pit crater chains that contain at least one pit crater over 1 km in diameter in this study area (n = 83) trend at a mean 015°, ranging from 153° to 072°.

3.2.4. “Ceraunius South”

Faults in the “Ceraunius South” study area generally trend north–south, with a mean strike of 004° (Table 2), but there is considerable cross-cutting of faults of different strikes. Most mapped faults in this study area (~90%) deform the “early Hesperian volcanic unit” (eHv). There are 3,728 faults mapped in this region, and 42 pit crater chains.

Figure 15. All mapped faults in “Ceraunius South” study area, color-coded by strike.
This area has substantial cross-cutting of faults in the northeast (*Figure 15*, blue colors). Some of the faults that strike northeast are in fact on the horsts of larger, adjacent graben.

The long, deep regional catanae here strike 070° (*Figure 16*). There are also 42 pit crater chains (2–56 km long), of which most are parallel with the surrounding faults (from 154–015°), but some are perpendicular to the mean fault strike (up to 090°) (*Figure 16*).

**Figure 16.** Trend of pit crater chains with pits over 1 km in diameter (hot pink) mapped alongside all normal faults (black) in the “Ceraunius North” study area. The base map is color-coded MOLA elevation atop a MOLA-derived hillshade.
3.2.5. “Tractus”

Faults in the “Tractus” study area generally trend north–south, with a mean strike of 004° (Table 2). This study area shows minimal evidence of fault cross-cutting relations. However, there are wide, faulted, east–west-striking graben along the 28° N parallel (Figure 17, bright red lines).

Figure 17. All mapped faults in “Tractus” study area, color-coded by strike.
Figure 18. Trend of pit crater chains with pits over 1 km in diameter (hot pink) mapped alongside all normal faults (black) in the “Tractus” study area. The base map is color-coded MOLA elevation atop a MOLA-derived hillshade.

Faults in this study area are generally parallel to sub-parallel to one another, although there are large graben that strike perpendicular to the overall pattern in the northern areas (red lines). A long, deep pit crater chain (formally named Tractus Catena) dominates the western portion of this study area. This feature trends 013°, which is subparallel to most faulting to the east of the feature (~001°) (Figure 18).
3.3. Study Fault Results by Study Area

Figure 19. The 62 (31 graben-bounding pairs) study fault locations for this study. The base map is color-coded MOLA elevation atop a MOLA-derived hillshade.

Here, I present the results for select subsets of normal faults in each of the five study areas. The 62 study faults are in 31 pairs because they represent the two bounding faults (primary and secondary) of a graben. These faults were selected based on their isolation from other faults (which nominally reduces the prospect for fault linkage), craters, mass wasting deposits, and other landforms that might impede a structural study.

The following results include ranges and mean measurements for fault strike, total fault length, maximum graben width (i.e., the horizontal distance between the pairs of fault scarps), maximum
vertical relief (i.e., the inferred vertical fault displacement), and the dip direction of the primary fault. These results also include the $D_{max}/L$ ratio and displacement profile for each study fault.

3.3.1. “Tantalus North” study fault results

Fourteen faults (seven pairs of graben-bounding faults) in this study area were selected for more in-depth structural analysis. Results for this study area are presented in Table 4. For individual measurements, see the Appendix. Study faults in “Tantalus North” have the highest mean lengths and widths of the five study areas. Due to the long fault lengths (44–131 km), this area has the lowest measured $D_{max}/L$ ratio values ($2.0 \times 10^{-3}$) in the study region.

<table>
<thead>
<tr>
<th>Fault Property</th>
<th>Value Range</th>
<th>Value Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike</td>
<td>027–057°</td>
<td>040°</td>
</tr>
<tr>
<td>Total length</td>
<td>44–131 km</td>
<td>95 km</td>
</tr>
<tr>
<td>Maximum graben width</td>
<td>4.6–9.4 km</td>
<td>6.9 km</td>
</tr>
<tr>
<td>Vertical relief (displacement)</td>
<td>85–391 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Primary fault dip direction</td>
<td>n/a</td>
<td>Mixed</td>
</tr>
<tr>
<td>$D_{max}/L$</td>
<td>1–4.5 $\times 10^{-3}$</td>
<td>2.20 $\times 10^{-3}$</td>
</tr>
</tbody>
</table>
Fault displacement profiles for the study area show both peaked and plateaued profile shapes (Figure 20). For example, fault pair “AE3E” and “AE3W” shows the characteristics peaked profile shape. In contrast, fault pair “AE9E” and “AE9W” shows a plateaued displacement profile: displacement for this pair maximizes at ~125 m at a distance of around 20 km along the length, and remains largely constant across the structure until ~80% of the length. Of the 14 faults measured, six are peaked and eight are plateaued (Figure 20). Note that the profiles shown in Figure 20 are given without scaling, i.e., they are shown with their true dimension. These same profiles are shown in Figure 21 normalized by length and maximum displacement.
3.3.2. “Tantalus South” study fault results

Ten faults (five pairs of graben-bounding faults) in this study area were selected for more in-depth structural analysis. Results for this study area are presented in Table 5. For individual measurements, see the Appendix.

<table>
<thead>
<tr>
<th>Fault Property</th>
<th>Value Range</th>
<th>Value Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike</td>
<td>016–033°</td>
<td>024°</td>
</tr>
<tr>
<td>Total length</td>
<td>33–99 km</td>
<td>68 km</td>
</tr>
<tr>
<td>Maximum graben width</td>
<td>3.6–12.8 km</td>
<td>6.8 km</td>
</tr>
<tr>
<td>Vertical relief (displacement)</td>
<td>19–449 m</td>
<td>189 m</td>
</tr>
<tr>
<td>Primary fault dip direction</td>
<td>n/a</td>
<td>West</td>
</tr>
<tr>
<td>$D_{max}/L$</td>
<td>$0.6 \times 10^{-3}$–$4.7 \times 10^{-3}$</td>
<td>$2.6 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Figure 21. Fault displacement profiles, normalized by length and maximum displacement, for all 14 study faults in the “Tantalus North” study area.
Study faults in “Tantalus South” have the second highest mean lengths (68 km) and widths (6.8 km) of the five study areas. Due to the long fault lengths (33–99 km), this area has the second lowest measured $D_{\text{max}}/L$ ratio values ($3.0 \times 10^{-3}$) in the study region. Fault displacement profiles for the study area show that eight of the ten profiles are peaked, with the remaining two being plateaued.

3.3.3. “Ceraunius North” study fault results

Fourteen faults (seven pairs of graben-bounding faults) in this study area were selected for more in-depth structural analysis. Results for this study area are presented in Table 6. For individual measurements, see the Appendix.

<table>
<thead>
<tr>
<th>Fault Property</th>
<th>Value Range</th>
<th>Value Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike</td>
<td>339–027°</td>
<td>000°</td>
</tr>
<tr>
<td>Total length</td>
<td>34–97 km</td>
<td>58 km</td>
</tr>
<tr>
<td>Maximum graben width</td>
<td>3.3–11.5 km</td>
<td>6.0 km</td>
</tr>
<tr>
<td>Vertical relief (displacement)</td>
<td>67–398 m</td>
<td>222 m</td>
</tr>
<tr>
<td>Primary fault dip direction</td>
<td>n/a</td>
<td>Mixed</td>
</tr>
<tr>
<td>$D_{\text{max}}/L$</td>
<td>$1.0 \times 10^{-3}$–$6.8 \times 10^{-3}$</td>
<td>$4.0 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Study faults in “Ceraunius North” have the second lowest mean lengths (58 km) and the second-highest values for maximum vertical displacement (222 m). Due to the short fault lengths (34–97 km) and high vertical displacement, this area has the highest measured $D_{\text{max}}/L$ ratio values ($4.0 \times 10^{-3}$) in the study region. Fault displacement profiles for the study area show that eleven of the fourteen profiles are peaked, with the remaining three being plateaued.

3.3.4. “Ceraunius South” study fault results

Ten faults (five pairs of graben-bounding faults) in this study area were selected for more in-depth structural analysis. Results for this study area are presented in Table 7. For individual measurements, see the Appendix.
Study faults in “Ceraunius South” have the second lowest mean graben widths (3.8 km) and the highest values for maximum vertical displacement (229 m). This area has the second-highest measured $D_{\text{max}}/L$ ratio values ($3.7 \times 10^{-3}$) in the study region. This finding may reflect the comparatively short fault lengths (the mean of which is 64 km) but relatively high vertical relief (and, thus, interpreted vertical displacement components on the faults) of these structures (i.e., a mean of 229 m, 22% greater than the mean vertical relief for all 62 study faults: see Appendix). Fault displacement profiles for the study area show that all ten profiles are peaked.

3.3.5. “Tractus” study fault results

Fourteen faults (seven pairs of graben-bounding faults) in this study area were selected for more in-depth structural analysis. Results for this study area are presented in Table 8. For individual measurements, see the Appendix.

Table 8. Results for selected faults in the “Tractus” study area (n = 14).

<table>
<thead>
<tr>
<th>Fault Property</th>
<th>Value Range</th>
<th>Value Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike</td>
<td>357–032°</td>
<td>008°</td>
</tr>
<tr>
<td>Total length</td>
<td>18–108 km</td>
<td>64 km</td>
</tr>
<tr>
<td>Maximum graben width</td>
<td>1.9–5.2 km</td>
<td>3.8 km</td>
</tr>
<tr>
<td>Vertical relief (displacement)</td>
<td>70–655 m</td>
<td>229 m</td>
</tr>
<tr>
<td>Primary fault dip direction</td>
<td>n/a</td>
<td>Mixed</td>
</tr>
<tr>
<td>$D_{\text{max}}/L$</td>
<td>$1.1 \times 10^{-3}$–$7.4 \times 10^{-3}$</td>
<td>$3.7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Study faults in “Ceraunius South” have the second lowest mean graben widths (3.0 km) as well as the lowest mean value for maximum vertical displacement (101 m). Due to the low vertical displacement, this area has the second-lowest measured $D_{\text{max}}/L$ ratio values ($3.1 \times 10^{-3}$) in the study region. Fault displacement profiles for the study area show that all fourteen profiles are peaked.

Table 7. Results for selected faults in the “Ceraunius South” study area (n = 10).

<table>
<thead>
<tr>
<th>Fault Property</th>
<th>Value Range</th>
<th>Value Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strike</td>
<td>347–018°</td>
<td>007°</td>
</tr>
<tr>
<td>Total length</td>
<td>10–98 km</td>
<td>43 km</td>
</tr>
<tr>
<td>Maximum graben width</td>
<td>2.1–4.9 km</td>
<td>3.0 km</td>
</tr>
<tr>
<td>Vertical relief (displacement)</td>
<td>37–279 m</td>
<td>101 m</td>
</tr>
<tr>
<td>Primary fault dip direction</td>
<td>n/a</td>
<td>East</td>
</tr>
<tr>
<td>$D_{\text{max}}/L$</td>
<td>$0.7 \times 10^{-3}$–$6.7 \times 10^{-3}$</td>
<td>$3.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
However, seven of these faults are “peaked asymmetric left”; that is, the maximum displacement is not situated at the center of the fault’s length, but is instead skewed toward their respective northern tip. (As stated above, these profiles are given in the Appendix.)

3.4. Study Fault Results Collectively

In Figure 22, fault $D_{\text{max}}/L$ ratios from this study are plotted alongside data from previous studies. Data from this study are shown as hot pink dots. They plot slightly lower than data for faults on Earth. My data, however, plot on top of another Mars normal fault study (data provided by C. L. Kling, personal communication, November 2018).

**Figure 22.** $D_{\text{max}}/L$ ratios for this study (points in hot pink) plotted with corresponding measurements for structures on Earth (studies list in key). Also shown (in teal) are points from a separate study of normal faults, this time in Noctis Labyrinthis, Mars (courtesy of C. L. Kling).
3.4.1. $D_{max}/L$ ratios

**Table 9.** Extensional strain estimate measurements for select study faults.

<table>
<thead>
<tr>
<th>Study Fault</th>
<th>Study Area</th>
<th>Strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AE9</td>
<td>Tantalus North</td>
<td>1.7</td>
</tr>
<tr>
<td>TA2</td>
<td>Tantalus South</td>
<td>2.0</td>
</tr>
<tr>
<td>CN2</td>
<td>Ceraunius North</td>
<td>5.3</td>
</tr>
<tr>
<td>CS1</td>
<td>Ceraunius South</td>
<td>2.6</td>
</tr>
<tr>
<td>TR1</td>
<td>Tractus</td>
<td>3.0</td>
</tr>
</tbody>
</table>

3.4.2. Extensional strain

I measured the amount of horizontal extension recorded by five fault-bound graben in the study region (one per study are). Extensional deformation was measured as longitudinal strain, whereby the horizontal distance between bounding fault scarps was measured, followed by a measure of the horizontal component of fault displacement (heave), i.e., the geometric horizontal dimension of the graben walls when viewed from above. Taking the difference in these length values as a percentage of the total distance between fault scarps, an estimate of horizontal extensional strain was calculated for each graben. These measurements are given in Table 9.

3.5. Crater Statistics Results

With a view to determining how much time elapsed since the most recent incidents of faulting proximal to Alba Mons, impact craters over 2 kilometers in diameter were mapped from CTX and HRSC imagery for two sites. Craters below this diameter threshold may be secondary craters, the inclusion of which in my counts would provide an erroneously old surface model age. Obvious secondary craters were excluded on the basis of their occurrence in clusters or chains, but far-field secondaries cannot be readily recognized, and the contamination of counts by unrecognized secondaries is expected to become increasingly severe at smaller crater diameters. All craters in each of the two study sites were mapped as circles in a single polygon. A subset of these craters is visibly faulted, and those craters were recorded in a separate shapefile.
As described in Section 2.6, all mapping was carried out with the CraterTools plug-in for ArcMap. Once the craters were recorded, they were analyzed with the CraterStats program (Michael et al., 2013). First, a model age for the surface from all mapped craters was calculated, followed by an age given only by those craters that show no evidence of being offset by fault motion, which corresponds to the time elapsed since the end of deformation (Section 2.6). This approach was followed for both study areas, and the results are described below.

3.5.1. “Tantalus South” crater statistics results

**Figure 23.** The “Tantalus South” study area is shown with a grey outline, and the area for which crater statistics were obtained is outlined in black. All craters over 2 km in diameter are shown in red; craters uncut by tectonic processes are shown in blue.
A total of 10 craters with diameters over 2 km were identified and mapped in “Tantalus South”, in the areas where HRSC imagery was available (Figure 23, black outline). This moderate-resolution imagery (~10 m/px) revealed craters that have been deformed by normal faults, i.e., their rims and/or floors have been deformed by normal faults and thus were in place before at least the last instance of strain. Two of the 10 craters in this study area were found to be faulted, and eight were found to be intact.

Of note, estimates for both total surface age and elapsed time since deformation both have substantial margins of error, likely due to the small number of impact craters in the areas for which crater statistics were obtained. This is a limitation of the technique. Nonetheless, taking the calculated Poisson ages for each site (Michael et al., 2016) the total the surface area examined here is 2.2 Gyr and the last deformation (faulting) occurred at 1.9 Ga. Per these model ages, there was a ~300 Myr period during which faulting occurred.

3.5.2. “Ceraunius South” crater statistics results

A total of 21 craters with diameters over 2 km were located and mapped in “Tantalus South”, in the areas where HRSC imagery was available (Figure 24, black outline). This moderate-resolution imagery revealed craters that have been deformed by normal faults since impact. Ten of the 21 craters in this study area were identified as faulted, and eleven were found to be intact.

Figure 24. The “Tantalus South” CraterStats surface age estimates. (Left) Surface age for statistics area. (Right) Time of last deformation in statistics area. Both plots are shown with a cumulative plot, and absolute model ages are shown with a Poisson distribution.
As for the “Tantalus South” study area, the absolute model ages for the total surface age and the time since deformation for “Ceraunius South” both have substantial margins, again probably because of the limitation of small-number statistics. However, on the basis of these estimated ages, the surface area is 3.4 Ga and the last deformation (faulting) occurred at 2.5 Ga. This means that there was a ~900 Ma time period when faulting occurred.

Figure 25. The “Ceraunius South” study area is shown with a grey outline, and the area for which crater statistics were obtained is outlined in black. All craters over 2 km in diameter are shown in red; craters uncut by tectonic processes are shown in blue.
4. Discussion

In this section, I interpret my mapping and structural analyses results, and discuss the significance of differences in fault properties across the study region—first for all faults mapped, and then for the subset of study faults. The results and implications of the crater statistics analysis are then discussed. I also attempt to ascribe fault populations to either regional or local stress fields, against which I compare the findings of previous studies.

4.1. All Faults

Here, I discuss the results for all faults mapped and measured in the entire study region ($n = 11,767$), including properties such as fault elevation, length, strike, and geological unit in which it occurs. These results will help in the identification of any differences in properties based on their distance from Alba Mons and Tharsis, and reveal what factors affect the individual properties of the faults.

4.1.1. Fault elevation

Fault elevation was measured as the mean elevation along the length of the fault scarp. This value ranges from $-1,087$ to $5,713$ m for all mapped faults in the study region; the mean fault elevation for all faults is $2,554$ m. The lowest values are found northeast of Alba Mons, and the

![Figure 26. The “Ceraunius South” CraterStats surface age estimates. (Left) Surface age for statistics area. (Right) Time of last deformation in statistics area. Both plots are shown with a cumulative plot, and absolute model ages are shown with a Poisson distribution.](image-url)
highest values are located on the volcano’s flanks, and other high-elevation areas, as described below.

From a qualitative (i.e., visual) assessment of Figure 5, it appears that Alba Mons flank faults (i.e., the structures found in the “Tantalus North,” “Tantalus South,” and “Ceraunius North” study areas) are likely associated with the volcano because they deform bedrock units that are composed of lava flows from the volcano itself. These faults must thus have been active (i.e., either they formed entirely, or recorded the last instance of strain) after to the emplacement of the units that they deform. Therefore, it is very likely these faults were at some point affected by the stress field(s) associated with Alba Mons, even if the magnitude of such stress(es) was low compared with any regional stresses. High-standing terrain in “Ceraunius North” and “Ceraunius South” has been largely protected from coverage by flows from the volcano, and this preservation makes it possible for multiple populations of cross-cutting faults to be preserved. The older of the fault populations in these complex terrains may predate Alba Mons and therefore only represent Tharsis-related stress fields (although it is possible that the faults have been reactivated by subsequent Alba Mons-related stresses).

In a quantitative assessment, in which mean elevation is plotted by fault strike (Figure 26), there is no statistical correlation ($R^2 = 0.1831$) for these two fault properties. This result makes it unlikely that elevation of tectonic structure plays a meaningful role in influencing the strike of that structures. There is, however, evidence for two separate clusters of faults when grouped by mean elevation. The smaller cluster corresponds to those faults from the relatively low elevation study area “Tantalus North,” to the northeast of Alba Mons, that lie near the Mars dichotomy boundary and have a mean strike of 39°. The larger cluster corresponds to faults in the other four study areas collectively that are in higher elevation areas, such as the flanks of Alba Mons (“Tantalus South” and parts of “Ceraunius North”) and the high ridges in “Ceraunius North” and “Ceraunius South”. The mean strike values for these other four study areas is about 8°.

This finding of a difference in strike with elevation, then, may simply reflect the fact that these “Tantalus North” faults are radial only to Alba Mons, whereas the rest of the structures are either radial only to Tharsis or are radial to Alba and Tharsis. Moreover, these low-elevation faults may be younger than the rest of the structures (overall), because although they are low-lying they
have not been obscured by lava flows from the volcano—which is what certainly happened in the low-lying areas to the southeast of Alba Mons that are relatively smooth. Therefore, the faults within Tantalus North could reflect a stress field that became manifest after most of the rest of the structures in the region had formed.

4.1.2. Fault length
The property of fault length was taken as the geodesic length along each fault scarp. (Geodesic length is that length along the surface of a biaxial ellipsoid that defines the major and minor axes of Mars.) Values for this property range between 0.43 km and 281.7 km for all mapped faults in the study region, with a mean of 15.5 km. Faults with comparatively lower fault length values are more often than not likely segments of longer faults cut by younger, cross-cutting faults with different strikes.

Figure 27. Fault strike plotted by elevation (n = 11,767).
This phenomenon can be seen in Figure 8, where faults are color-coded by total length. It is clear that faults tend to be shorter (between 400 and 6,000 m) in the southwestern study areas (“Ceraunius North” and “Ceraunius South”) than in the other three study areas. On the basis of strike, many of these shorter faults may be previously longer faults that have been segmented by younger, cross-cutting structures. This complexity is likely due to the older (early Hesperian) bedrock in which these faults of multiple orientations (strikes) are found (see the purple unit eHv in Figure 7); these structures could therefore have accumulated more extensional strain, including from differently oriented stress fields, and might also have avoided being obscured by lava flows due to their high elevation.

Fault length data was quantitatively analyzed as a function of distance to the approximate center of Alba Mons, taken as the center of the nested caldera complex (situated at 40.0° N, 109.7° W), and also as a function of latitude (as a proxy for distance from Tharsis, because the enormous shield volcano Pavonis Mons is situated almost precisely in the center of the Tharsis Rise, and the center of that edifice is at 0.5° N, 112.8° W).

Although the color-coding of fault length in Figure 8 supports the view that there is a spatial correlation of fault length with distance from the volcano, there is no statistical basis for this apparent correlation ($R^2 = 0.0062$) (Figure 28). This finding suggests that proximity to Alba Mons has little effect on the length of faults in the study region. Likewise, proximity to Tharsis appears to have no statistically significant effect ($R^2 = 0.0441$) on fault length in the study region.
Each mapped fault in this study was assigned a geological unit based on the most recent bedrock geology map of Mars (Tanaka et al., 2014). Then, the number of faults and mean fault strike was calculated for each geological unit in the study region (Table 3). As with fault length, the number of faults in each geological unit is affected by the segmentation of faults, particularly in highly deformed areas (i.e., “Tantalus South”). However, this number may also be a function of bedrock age (due to older units having more time to accumulate strain and faults) and even elevation (e.g., the probability that a fault, once formed, would be obscured by a subsequent lava flow from Alba Mons is greater for low-lying faults than those at higher elevations). Naturally, the fault count is also affected by the spatial extent of a given geological unit, together with the boundary of a particular study area and the study region itself.

**Figure 28.** Fault length plotted by distance from Alba Mons for all mapped faults (n = 11,767).

4.1.3. *Geological units deformed by faults*

Each mapped fault in this study was assigned a geological unit based on the most recent bedrock geology map of Mars (Tanaka et al., 2014). Then, the number of faults and mean fault strike was calculated for each geological unit in the study region (Table 3). As with fault length, the number of faults in each geological unit is affected by the segmentation of faults, particularly in highly deformed areas (i.e., “Tantalus South”). However, this number may also be a function of bedrock age (due to older units having more time to accumulate strain and faults) and even elevation (e.g., the probability that a fault, once formed, would be obscured by a subsequent lava flow from Alba Mons is greater for low-lying faults than those at higher elevations). Naturally, the fault count is also affected by the spatial extent of a given geological unit, together with the boundary of a particular study area and the study region itself.
Figure 7 shows all mapped faults color-coded by mapped geological unit (after Tanaka et al., 2014). It appears that older units (e.g., $eHv$) are more densely faulted, which is consistent with a scenario under which an older unit can accumulate more tectonic deformation than a younger unit. Similarly, stratigraphically younger units (e.g., $lAvf$) are relatively sparsely faulted and in fact include smooth, unfaulted terrains (e.g., those situated between “Tractus” and “Ceraunius North”). These younger units are also in low-elevation areas, which face an increased likelihood of lava infill. Therefore, fault areal density (as a function of number of structures) does not uniquely or reliably help in the determination of stress field origin. In other words, a greater fault areal density as determined from mapping alone does not necessarily correspond to a region of higher stress magnitude, and vice versa.

4.1.4. Fault strike and stratigraphic relations
Fault strike was taken as the bearing of a line drawn from one tip to the other of a given normal fault. Of note, fault traces are generally not perfectly linear, particularly for curved faults, so strike values are only an approximation. The large number of measured faults in this study project ($n = 11,767$), likely minimizes the influence of strongly curved faults, however, especially since such structures are uncommon (only found in “Tantalus South,” in this study). Here, I consider fault strike values with regards to the spatial relations of the faults with Alba Mons and Tharsis.

As can be seen in Figure 6, fault strike is not consistent near Alba Mons. Faults strike radial to the volcano in some places and strike tangential and circumferential to the shield in others. It does appear, however, that fault strike gradually changes with latitude ($Table 2$), from north-south in the southern areas to more northeasterly with increasing latitude (and thus with increasing distance from Tharsis). Additionally, fault complexity relative to variance in fault strike and instances of cross-cutting appears qualitatively to increase from the north and east toward the southwest.

For a quantitative assessment, a value of distance from Alba Mons was assigned to each mapped fault from a Euclidean distance raster created in ArcGIS. This raster is generated from a point at the approximate center of Alba Mons (again, the caldera complex), and every cell, within a
designated maximum radius distance, was assigned a linear distance value from this central point.

When fault strike is plotted against distance from the shield volcano, it is clear that no statistically significant correlation \( R^2 = 0.0152 \) exists between these variables (Figure 28). In other words, there is no statistically reliable evidence for systematic change in strike of normal faults with increasing or decreasing proximity to the volcano. This finding suggests that there is not a simple explanation for the variety of fault orientations in the study region, i.e., that the entire fault population cannot be uniquely attributed to either local (Alba Mons) or regional (Tharsis Rise) stress fields.

**Figure 29.** Fault strike plotted by distance from Alba Mons for all mapped faults (n = 11,767).
To explore the prospect for fault strike being a function of distance from Tharsis, that latter parameter was approximated by using degrees of latitude (to a precision of two decimal points), based on the fact that the center of the Tharsis Rise is centered at approximately 0° latitude.

When plotted, there is at best a poor correlation ($R^2 = 0.2721$) between fault strike and distance from Tharsis (as given by latitude) (Figure 29). This finding provides only weak support for the view that a stress field emanating from, and centered at Tharsis has influenced fault strike throughout the region. Such an inference, however, is at odds with the finding of no obvious trend in fault strike with increasing proximity to Alba. It appears, then, that on the basis of these statistical findings there is no systemic change in strike with distance either from or to Tharsis or Alba.

Figure 30. Fault strike plotted by latitude for all mapped faults (n = 11,767).
It was proposed in earlier finite element modelling studies (e.g., Callieau et al., 2003; 2005), that subsidence of a large crustal load and local dike injection from large volcanoes, combined with regional extension, creates stress fields that result in circumferentially oriented extensional strains (e.g., graben) near the volcano, and the formation of radially oriented structures farther away (see Section 1.4). Under this view, then, the faults that are circumferential to Alba Mons arose from at least some component of volcano-related stresses, the faults that are only radial to Tharsis reflect stresses from that volcano-tectonic center, and the faults that are only radial to Alba reflect stresses from the volcano alone. The faults that are radial to both Alba and Tharsis plausibly reflect some component of deformation from each source of stress.

Figure 31. Faults that are (Left) only radial to Alba Mons and (Right) only circumferential to the volcano.

By separating the mapped faults according to strike and cross-cutting relationships, it is possible to tease out these relations and define four categories of faults, which in turn can by analyzed in terms of changes in structural properties with distance from possible stress field origins (i.e., Alba Mons and Tharsis).
The first category comprises mapped faults that are radial or circumferential only to Alba Mons (Figure 30). These faults are located in the “Tantalus North” and “Tantalus South” study areas. In these two areas, there are faults that radiate from the Alba Mons edifice (Figure 30, left), as well as a group of faults that are linked together in such a way that they form a curved pattern about the southeastern sector of the volcano (Figure 30, right). Although it is possible that regional extension played a part in the origin of these faults (see Section 1.4), it is not likely that they would be oriented as they are without the formation of Alba Mons.

The second category is mapped faults that may be radial to both Alba Mons and Tharsis (Figure 31). These faults are located in the “Ceraunius North” and “Ceraunius South” study areas, and strike directly towards the Alba Mons caldera complex (and thus the volcano itself). However, these faults also strike radial to the Tharsis Rise to the south. Although at substantial distances to

Figure 32. Faults that are radial both to Alba and Tharsis. These faults generally strike ~due north.
Tharsis (between 500 and 1,500 km), it is not far-fetched to consider these faults as causally linked to the major volcanotectonic center to the south. Long graben and pit crater chains radiate away from Tharsis from all sides, at virtually all azimuths (e.g., Anderson et al., 2001). For instance, Sirenum Fossae (*Figure 1*), a series of narrow, linear graben, extends southwest from the Tharsis Rise to a distance of more than 3,500 km (Anderson et al., 2001). There is at least precedence, therefore, for major fault systems extending radially from Tharsis to distances at least as great as the normal faults I map in the Ceraunius study areas. Of note, Sirenum Fossae (*Figure 1*) and similar radial structures at other azimuths from Tharsis are attributed to “giant” dike swarm injection from the Rise (Ernst et al., 2001).

The third category is mapped faults that are radial only to Tharsis (*Figure 32*). These faults strike in a way that can only be described as radial to regions other than the Alba Mons volcano itself. Importantly, these faults are located in all study areas, apart from “Tantalus North”; they do not themselves define any one particular study area. Additionally, there are three subcategories of these radial faults, based on strike and cross-cutting relationships: those that strike north–south (~000°) (*Figure 32*, top), those that strike northwest (~160°) (*Figure 32*, middle), and those that strike northeast (~020°) (*Figure 32*, bottom). The subgroup of faults that strike north–south is located in all three of the “Ceraunius North,” “Ceraunius South,” and “Tractus” study areas. The faults that strike northwest are located in “Ceraunius North” and “Ceraunius South”. Finally, the subgroup of faults that strike northeast is located in “Ceraunius North,” “Ceraunius South,” and “Tantalus South.” On the basis of cross-cutting relationships, the north–south striking faults are stratigraphically younger than their counterparts.

When these three subgroups of faults are analyzed in terms of distance from their prospective sources of stress (i.e., Alba Mons and Tharsis, or both, on the basis of predicted stress fields and the strains that would result therein), some spatial patterns are apparent in regards to the faults’ physical properties.
Figure 33. Faults that are only radial to Tharsis that (Top) strike north–south, (Middle) strike northwesterly, and (Bottom) strike northeasterly.
4.2. Study Faults

In addition to studying the properties of the total mapped faults in this study \((n = 11,767)\), a subset of 62 “study faults” was focused on for in-depth analysis, which included measurements of their vertical displacement that, when combined with fault length, allows for the calculation of the fault displacement–length scaling ratio \(D_{\text{max}}/L\). This \(D_{\text{max}}/L\) value, in addition to the properties measured for all faults (e.g., length, strike, and location), are discussed and compared here. Additionally, these study fault properties are summarized in the scope of the three fault categories (based on the orientations of faults to Alba Mons and Tharsis) discussed in Section 4.1.4.

4.2.1. Fault length

Study fault length was measured in the same way as all mapped faults in the region, that is, by geodesic length in a projected map, but more care was taken to ensure that the entire fault scarp length was included in the measurement by mapping the structure at a smaller scale. This mapping was accomplished with supplementary images (CTX and HRSC), where available, which have a higher spatial resolution than the THEMIS DayIR base map. Study fault lengths range from 10–131 km, with a mean of 66 km (see Appendix). Study faults were chosen based on their isolation and preservation, and so these values are generally not affected by segmentation resulting from being cross-cut by later faults (although some exceptions occur). From the image data, however, some study faults do appear to be affected by linkage with adjacent structures, which serves to increase measured fault length.

Mean fault length for study faults generally decreases with latitude. From high to low latitudes, the mean study fault lengths range from 95 km to 43 km (see Appendix). This relationship, however, is statistically significant neither for study fault data (with a coefficient of determination of \(R^2 = 0.1972\)) nor for all mapped fault in the project \((R^2 = 0.0441)\). (These plots are given in the Appendix). This finding likely reflects the fact that final fault length is a function of a number of processes, acting individually or together. For example, for isolated faults, length is a direct measure of strain (i.e., fault length scaled with fault displacement). However, as noted in Section 1.4, fault length can also exceed a given amount of proportionate displacement because of fault linkage and/or mechanical confinement (i.e., wherein a fault is restricted from growing vertically by changes in mechanical stratigraphy and so grows at a greater rate laterally.
than vertically with continued stress). These two phenomena affect fault length statistics for the study region.

Further, per Section 4.1.2, fault length statistics are also affected by the cross-cutting and thus truncation of older faults by younger faults of a different orientation. This process serves to segment longer faults into many shorter segments, yielding a greater number of measured shorter faults than there might actually be. This effect can be observed in “Ceraunius North” and “Ceraunius South” study areas, where CTX and HRSC image data clearly show younger faults that propagate through and divide older faults. However, the study area “Tractus” has a relatively low mean fault length for all faults (17 km) and study faults (43 km), and there is minimal cross-cutting. The overall pattern I observe, of relatively longer faults in the north trending toward relatively shorter faults farther south, therefore still stands.

4.2.2. Maximum fault displacement versus length ($D_{\text{max}}/L$)

The $D_{\text{max}}/L$ ratio of a fault can be used to characterize its growth history, give insight on the mechanical stratigraphy of the subsurface, and identify fault populations because genetically related faults typically have similar ratios (see Section 1.4). The ratio is calculated in this study by dividing the inferred maximum vertical displacement for the fault (the highest value of $D$ found from measuring multiple topographic profiles perpendicular to the fault trace) by the total mapped fault length ($L$).

Fault $D_{\text{max}}/L$ values have been used in numerous studies to assess fault populations on Earth and Mars, and to analyze fault growth patterns (e.g., Scholz et al., 1993; Dawers and Anders, 1995; Schultz and Fori, 1996; Schultz, 2000; Polit et al., 2009). This $D_{\text{max}}/L$ ratio is typically a linear relationship for isolated faults on Earth, Mars, and other terrestrial bodies (hence the goal of only analyzing isolated faults for this project). Differences in this ratio for individual faults within a given tectonically deformed region may indicate that distinct populations of faults exist. A fault population is defined as a spatially extensive array of faults that are “genetically” related to each other, i.e., were formed in the same stress regime and/or deformational event, are closely spaced, have similar strikes, and interact mechanically with one another (e.g., Schultz et al., 2010). Disparate fault systems that deform the same rock type can also be considered to be
genetically related, although inferred lithologies (and thus mechanical properties) in the study region are not uniform (i.e., Tanaka et al., 2014).

Values for $D_{\text{max}}$ versus $L$ found for this study are similar to those reported in previous studies of faults on Mars. In a study of normal faults to the northwest of Alba Mons, Wyrick et al. (2010) found $D_{\text{max}}/L$ ratios of between $2 \times 10^{-3}$ and $2 \times 10^{-1}$. In a study of normal faults to the northeast of Alba Mons (faults that in this study correspond to the “Tantalus North” area), Polit et al. (2009) found a mean $D_{\text{max}}/L$ ratio of $1 \times 10^{-3}$, and a value of $6 \times 10^{-3}$ for faults on the eastern flanks of Alba Mons (which, in this study, lie in the “Tantalus South” study area). Additionally, in another MEAS study normal faults in Noctis Labyrinthus were found to have mean $D_{\text{max}}/L$ ratio values of $1 \times 10^{-3}$ (C. L. Kling, personal communication, November 2018). These reported values are very similar to those I find in this work. For example, my $D_{\text{max}}/L$ means for “Tantalus North” and “Tantalus South” are $2.2 \times 10^{-3}$ and $2.6 \times 10^{-3}$, which is close to those of Polit et al. (2009), and my mean $D_{\text{max}}/L$ values for all study areas are within the same order of magnitude as the Kling results and many of the structures examined by Wyrick et al. (2010). This similarity indicates that the method used in this project is robust, since results in study areas of previous work can be replicated and validated.

These results, including those from this study, are all slightly lower in $D_{\text{max}}$ (or greater in $L$) than those values reported for faults on Earth (e.g., Dawers et al., 1993; Cartwright et al., 1995). This discrepancy may be due to increased fault linkage on Mars compared with Earth, which could in turn reflect the restriction of faults in this region by a mechanical discontinuity. Such a discontinuity may be due to strata of varying strength or competency. In the case of Mars, such strata might include interbedded basalt flows, impact breccia, and permafrost zones (Davis and Golombek, 1989). If a growing fault encounters a mechanical impediment to its vertical growth, it will become restricted. The fault will then continue to grow in length, but its rate of vertical displacement per unit length will decrease. This growth pattern will result in a lower fault $D_{\text{max}}/L$ ratio than would otherwise be the case.

A compounding issue that also likely affects measured $D_{\text{max}}/L$ values is the prospect of image resolution constraining the ability to identify precisely where faults end (i.e., recognizing fault
tips). This issue is less pressing when using higher-resolution supplemental images (i.e., CTX and HRSC data, where available) to map the study fault traces, compared with the THEMIS Day IR base map, even in sites where the MOLA DEM is of insufficient resolution to resolve any vertical relief. Nonetheless, there is still a strong possibility that the faults as mapped have tips that extend beyond their measured lengths because they are not expressed at the surface, or fault process zones can extend far from the fault core but not necessarily show any displacement at the surface (Vermilye and Scholz, 1998).

On the basis of mean $D_{\text{max}}/L$ values, this ratio increases from Tharsis toward Alba, peaking at the faults in the Ceraunius study areas, before decreasing with yet greater distance from Tharsis (and the volcano). Indeed, $D_{\text{max}}$ values for “Ceraunius North” and “Ceraunius South” have means of 222 and 229 m, respectively, and faults here are moderately long (with means of 58 and 64 km, respectively). These values compare with a mean displacement of 186 m, and a mean length of 66 km, for all study faults ($n = 62$) in the project (see Appendix). Faults in the Ceraunius study areas therefore appear to have accumulated slightly more vertical displacement than faults elsewhere, an interpretation supported by the preponderance of peaked displacements profiles in these areas (see Section 4.2.5).

Statistically, however, there is essentially no relationship ($R^2 = 0.0029$) between $D_{\text{max}}/L$ of the study faults and their distance from Alba Mons. This finding does not rule out an Alba Mons-related stress field as at least contributing to the origin of these faults, because of the other factors that affect $D_{\text{max}}/L$ (i.e., like mechanical stratigraphy and fault linkage, as described above). The same view applies to the lack of correlation between $D_{\text{max}}/L$ and distance from the Tharsis region ($R^2 = 0.0830$). Nonetheless, it is clear that the shape of a fault (as a function of its maximum vertical displacement and length) is not by itself a sufficiently powerful discriminator for identifying the given stress field responsible for that fault’s formation.

4.2.3. Graben width

In a plot of graben width (i.e., the horizontal distance between the scarps of bounding faults) with distance to Alba Mons (measured as a linear distance from the caldera complex), there is at best a weak correlation between these variables ($R^2 = 0.2462$). Graben near the volcano tend to
be somewhat wider than those farther from the shield. Although the correlation shown here is poor, if such a finding is geological in nature then it may reflect comparatively higher stress magnitudes and/or longer-lived stresses near the volcano relative to graben farther from the edifice. This view, in turn, suggests that some component of strain accommodated by graben proximal to the volcano arose from the shield itself, perhaps overprinting on structures that were forming from Tharsis-related stress anyway.

It has been proposed that at least some graben in the Alba Mons region reflect dike intrusion (Mège and Masson, 1996; Ernst et al., 2001). For such graben, the width of the structure is about 2–3 times the depth to the dyke tip (Mège and Masson, 1996). Graben width is largely dependent on the initiation depth of the normal fault (Melosh and Williams, 1989) and is influenced by the flexural rigidity of the material it forms in, which in turn depends on layer thickness and material properties (French et al., 2015). Mean graben widths in the study areas nearest the volcano (“Tantalus South” and “Ceraunius North”) range from 6.0–6.8 km, meaning dike tips there would be about 2.0–3.4 km below the surface. In contrast, mean graben width for the study area farthest from the volcano, “Tractus,” is 3.0 km, meaning dike tips (if these structures result from shallow crustal intrusion) would be approximately 1.0–1.5 km below the surface there.

I observed no evidence for lavas emanating from any of the structures I mapped, or spatter cones along graben walls, etc.; the lack of such observations would oppose the view that at least some of these structures are underlain by dikes. Of course, absence of such volcanic evidence is not evidence that magmatic systems do not exist at depth. It is worth pointing out, however, that deeper dike tips under Alba Mons, compared with under the surrounding plains, is consistent with there being greater overburden pressure at a given crustal depth at the volcano as a result of the load of the edifice on the crust. Nonetheless, when graben width is plotted as a function of distance from Tharsis, there is a weak correlation ($R^2 = 0.3027$) (see Appendix). This correlation is poor, but it still signifies a trend in graben width, where graben tend to be narrower near Tharsis, and become wider with distance.
4.2.4. Graben strike

The strikes of the 62 study faults were measured differently than all mapped faults, in that these values were measured as graben rather than individual graben-bounding fault scarps. A line was manually drawn from one graben tip to the other, and then the bearing of this line was calculated in a projected map environment. Therefore, each fault pair has the same strike. This approach was taken to increase accuracy of the strike calculation, especially in cases where fault trace is not perfectly linear, such as for faults that are circumferential to Alba Mons.

When mapped, study fault traces (i.e., the graben-bounding pairs) also appear to progressively strike more northeasterly toward the higher latitudes. The mean strikes for study faults reflect this pattern. In the southern study areas, fault strike is approximately north–south, with a mean strike of 007° in “Tractus,” 008° in “Ceraunius South,” and 000° in “Ceraunius North”. Moving farther north, mean fault strike shifts to 024° in “Tantalus South,” and 040° in “Tantalus North.” (These values are tabulated in the Appendix.)

When these data are statistically analyzed in terms of distance from Alba Mons, however, there is no correlation ($R^2 = 0.0280$). This finding makes sense because, from map view, it is clear that there are faults that strike radial, circumferential, and tangential to the volcanic edifice, a structural pattern that complicates a straightforward relationship between strike and distance from the shield, even were one present. When these data are plotted by distance from Tharsis, however, there is a slight correlation ($R^2 = 0.5648$). This correlation is the single strongest in this project, even if objectively it is hardly robust, for fault spatial relationships with Alba Mons and the Tharsis Region.

In Section 4.4, I explore the fault strike correlation with distance from Tharsis, combined with the location of these faults, in the scope of the four categories of faults (circumferential to Alba Mons, radial to Alba Mons, radial to Tharsis, and radial to both).

4.2.5. Fault displacement profiles

With vertical relief as a proxy for vertical fault displacement (i.e., throw), it is possible to characterize how that displacement changes along the length of each study fault (Schultz et al., 2010). These profiles show how displacement is distributed along the structure, which can reveal
if the fault is composed of soft or hard-linked segments, and if the fault is mechanically restricted at depth. A plateaued displacement profile is indicative of the fault being restricted from growing vertically into the crust by some obstacle, such as a change in mechanical stratigraphy, as it continues to grow laterally. A bell-shaped or peaked profile shows unrestricted growth into a medium (Manighetti et al., 2001). Additionally, a fault $D_{\text{max}}/L$ ratio that conforms to linear scaling is indicative of a fault that is not restricted at depth, whereas a transition away from linear scaling (due to decrease in $D_{\text{max}}$ and/or increase in $L$) indicates that the fault may be vertically restricted, and growing laterally without an increase in vertical displacement (Cowie et al., 1993).

Fault displacement profiles were created for the 62 study faults, by taking measurements of vertical displacement ($D_{\text{max}}$) at approximately 5 km-intervals perpendicular to the fault trace. Study faults in “Tantalus North” have a mix of peaked ($n = 6$) and plateaued ($n = 8$) displacement profiles. This finding is similar to that of Polit et al. (2009), who examined several faults in this same area and found a mix of restricted and unrestricted faults. (With numerical modeling, these authors calculated a restriction depth of 2–3 km for some of the faults with plateaued displacement profiles.)

Those structures with plateaued profiles are generally located farther from Alba Mons, indicating that faults may be restricted northeast of the volcano. Qualitatively, faults in the northern parts of the study region are more likely to be restricted, and this likelihood decreases toward the south. This is one possible explanation for why fault lengths are longest (mean of 95 km) in the northernmost study area, “Tantalus North,” if faults have grown in length rather than with depth due to a mechanical discontinuity. Faults in “Tantalus South” and “Ceraunius North” have primarily peaked profiles, indicating little evidence of a mechanical discontinuity in these areas. In “Ceraunius South” and “Tractus” study areas, all profiles are peaked, suggesting that faults in these areas were free to grow into the subsurface without restriction. Indeed, the lack of obvious mechanical restriction for the faults in the Ceraunius study areas is consistent with their relatively higher $D_{\text{max}}/L$ values, indicating that for this portion of Mars, the crust is mechanically homogeneous and not subject to the mechanical stratigraphy that appears to characterize much of the crust proximal to Alba.
4.3. Cratering Statistics

Cratering statistics were calculated in the CraterStats software, by inputting measurements of craters over 2 km diameter within a statistics area. The software applies chronology and production functions to the data, in my case that of Ivanov et al. (2001), to estimate an age of the cratered surface. When deformed craters (those that are clearly faulted) are assessed, and the results are compared to the estimated surface age for both intact and deformed craters, the time between the surface age and the time of last deformation can be calculated. This process was completed for two areas (see Section 3.5), one within the study area “Tantalus South” (on the flanks of Alba Mons) and a second in the study area “Ceraunius South” (distant from Alba Mons and closer to Tharsis). Results suggest that the “Tantalus South” statistics area is 2.2 Ga and the last deformation occurred around 1.9 Ga. In the “Ceraunius South” area, the age of the surface is 3.4 Ga and the last deformation occurred around 2.5 Ga.

These surface age estimates suggest that the flanks of Alba Mons are about 2.2 Ga, which means that the most recent widespread volcanic flows occurred around this time. For ~300 Ma following, deformation (faulting) shaped the landscape into its current form. South of the volcano, and closer to the Tharsis region, the surface age is estimated to be much older (3.4 Ga), and the most recent deformation ended ~600 Ma before it ended on the flanks of Alba Mons. The results imply that the crater count area in “Ceraunius South” did not experience the same deformation that the Alba Mons flanks experienced until 1.9 Ga. These local stresses may not have reached so far from the volcano (~1,000 km from the Alba Mons caldera complex).

This analysis is limited by the small number of craters with diameters over 2 km, and the resolution of image data. A larger statistics area with high-resolution images would be more ideal for this study, and would allow for an analysis of all five study areas in their entirety. Importantly, however, these absolute model ages are consistent with the stratigraphic ages accorded these units in the global geological map (Tanaka et al., 2014).
5. Conclusions

When normal faults, and the graben they form, are classified by orientation and spatial relation to the Alba Mons volcano and the Tharsis Rise, no statistically significant, systematic patterns emerge. A progressive change in fault strike, from north–south to northeasterly, with increasing distance from Tharsis, remains the only statistically significant correlation between fault properties I have found.

However, map results support the view that faults close to Alba Mons show an influence of that volcano on their structural properties. This conclusion is based on the following findings:

1. That faults within about 500 km of the volcano center are circumferential to the shield and/or show evidence of their surface traces being deflected by the edifice, but this pattern is not apparent at greater distances;
2. Ratios of maximum fault displacement versus fault length are greatest in the region between Tharsis and Alba, consistent with the superposition of stresses from both the volcano and the Rise;
3. The only structures that are exclusively radial to Alba Mons, and not at all to Tharsis, are those situated on the northeast flank of the shield, the farthest of any mapped structures to the Rise.

Importantly, the results of crater statistics analysis indicate that, of two sites assessed, deformation occurred more recently in the area farther from Tharsis. This result supports, but does not prove, an interpretation that stresses from Alba Mons came to predominate both at greater distances from Tharsis and after the bulk of deformation driven by the Rise—possibly from dike intrusion—came to an end.

Attempts to identify a distinctive “signature” of a given fault property that could be unequivocally attributed to either Alba (i.e., local-scale) or Tharsis (i.e., regional-scale) deformation were not successful. This outcome probably reflects the challenges inherent in mapping structures over such a large portion of a planet whose crust records more than four billion years of history. Lava infilling, changes in crustal stratigraphy, multiple, superposed
instances of deformation, and even shortcomings in data resolution and coverage can alter or mask any systematic signature that may once have been present. Nonetheless, I show with this study that structural analysis and techniques developed for Earth can effectively be brought to bear on tectonic landforms on other planets, and with ever more available data for planetary bodies, our understanding of extraterrestrial tectonic and volcanic processes will continue to increase.
References


Backstrom, K., and Gudmundsson, A., 1989, The grabens of Sveinar and Sveinagja, NE Iceland, Nordic Volcanological Institute, University of Iceland.


Illies, J.H., 1981, Mechanism of graben formation: Tectonophysics, v. 73, 249–266.


Rose diagrams for all mapped fault strikes in azimuth degrees.

<table>
<thead>
<tr>
<th>Study/Area</th>
<th>Lengths</th>
<th>Mean</th>
<th>Max Widths</th>
<th>Mean</th>
<th>Max Vert. Dip./Depth</th>
<th>Mean</th>
<th>Primary dip dir. (avg.)</th>
<th>Azimuth/Strike</th>
<th>Mean</th>
<th>( \rho_{SSL}/h )</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tantalus North (n=48)</td>
<td>50–132 km</td>
<td>65 km</td>
<td>5.5–9.8 km</td>
<td>7 km</td>
<td>129–701 m</td>
<td>338 m</td>
<td>Merid (tendency to east)</td>
<td>N28°–48°E</td>
<td>N37°E</td>
<td>0.001–0.005 (1.5 x 10⁻⁵)</td>
<td>0.00090 (3.00 x 10⁻⁶)</td>
</tr>
<tr>
<td>Tantalus South (n=32)</td>
<td>35–91 km</td>
<td>65 km</td>
<td>3.6–13.8 km</td>
<td>6.8 km</td>
<td>19–449 m</td>
<td>189 m</td>
<td>East</td>
<td>N16°–31°E</td>
<td>N39°E</td>
<td>0.002–0.005 (2.5 x 10⁻⁵)</td>
<td>0.00079 (2.79 x 10⁻⁶)</td>
</tr>
<tr>
<td>Ceraunius North (n=54)</td>
<td>34–100 km</td>
<td>58 km</td>
<td>3.3–11.5 km</td>
<td>6 km</td>
<td>67–390 m</td>
<td>222 m</td>
<td>West</td>
<td>N18°–22°E</td>
<td>N36°E</td>
<td>0.004 (1.7 x 10⁻³)</td>
<td>0.00408 (0.408 x 10⁻⁶)</td>
</tr>
<tr>
<td>Ceraunius South (n=5)</td>
<td>19–77 km</td>
<td>47 km</td>
<td>4.1–6.5 km</td>
<td>5.3 km</td>
<td>100–836 m</td>
<td>371 m</td>
<td>West</td>
<td>N0°–31°E</td>
<td>N39°E</td>
<td>0.002–0.005 (2.8 x 10⁻⁵)</td>
<td>0.00400 (4.00 x 10⁻⁶)</td>
</tr>
<tr>
<td>Tractus (n=8)</td>
<td>10–402 km</td>
<td>45 km</td>
<td>1.8–4.9 km</td>
<td>3 km</td>
<td>37–279 m</td>
<td>120 m</td>
<td>East</td>
<td>N0°–18°E</td>
<td>N39°E</td>
<td>0.001–0.004 (1.7 x 10⁻⁵)</td>
<td>0.00084 (0.84 x 10⁻⁶)</td>
</tr>
</tbody>
</table>

All study fault measurements by study area.
All study fault measurements.
Fault displacement profiles for all 14 study faults in the “Tantalus North” study area. Bottom profiles are normalized.
All study fault displacement profiles for Tantalus North (formerly designated “AE”). Left profiles are the western faults, middle profiles are the eastern faults, and right profiles are both together.
Fault displacement profiles for all 10 study faults in the “Tantalus South” study area. Bottom profiles are normalized.
All study fault displacement profiles for Tantalus South (formerly designated “TA”). Left profiles are the western faults, middle profiles are the eastern faults, and right profiles are both together.
Fault displacement profiles for all 14 study faults in the “Ceraunius North” study area. Bottom profiles are normalized.
All study fault displacement profiles for Ceraunius North. Left profiles are the western faults, middle profiles are the eastern faults, and right profiles are both together.
Fault displacement profiles for all 10 study faults in the “Ceraunius South” study area. Bottom profiles are normalized.
All study fault displacement profiles for Ceraunius South. Left profiles are the western faults, middle profiles are the eastern faults, and right profiles are both together.
Fault displacement profiles for all 14 study faults in the “Tractus” study area. Bottom profiles are normalized.
All study fault displacement profiles for Tractus. Left profiles are the western faults, middle profiles are the eastern faults, and right profiles are both together.