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GEOLOGICAL TIMELINE & EXTENSION OF MARTIAN FAULTING IN THE ALBA MONS REGION OF MARS

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INTRODUCTION

Alba Mons is a Martian volcano-tectonic complex that lies to the north of the Tharsis region (Tanaka, 1990). This area has the thickest Martian crust at 90 km (Kim et al., 2023). Alba Mons is one of the largest volcanic complexes in the Tharsis region, far larger than any volcano on Earth, with a diameter of roughly 1400 km (East-West) by 1000 km (North-South) with a collapsed caldera at the center (Öhman & McGovern, 2014). Alba Fossae is located to the northwest of Alba Mons, where extensive normal faulting has taken place. Excellent exposure of volcanic rocks, ancient fluvial systems, and fault scarps makes this region an ideal place to explore the geologic history of the Alba Mons volcanic edifice (Tanaka, 1990).

To better understand the geologic history of the Alba Fossae region, I analyzed high-resolution orbital imagery using a mosaic (released April 2023) constructed from images taken by the CTX camera aboard the Mars Reconnaissance Orbiter. This exercise involved determining cross-cutting relationships between volcanic flows, ancient fluvial systems, and fault scarps. The sequence of geologic events in this area has been previously studied (Karimova, 2017), but hasn't been revisited with the new data from the Mars CTX Camera. I also explored the overall extensional aspect of Alba Fossae by investigating fault displacement to length relationships and determined the degree of extension in the Alba Fossae region. To determine these relationships, I measured each fault segment length using Google Mars and then measured the fault's heave and throw values. This same process was used to determine the degree of extension along a single transect perpendicular to the faults in the Alba Fossae region. After the calculations were completed, I then assembled displacement vs. length graphs for comparison to these relationships in terrestrial faults. For context, it is important to note the difference between Alba Mons and large volcanoes on Earth. Alba Mons spans 5.7 million square kilometers (Cattermole, 1990). Mauna Loa, Earth's largest volcano, spans just 5,271 square kilometers (USGS survey). The size difference is significant and must be considered when comparing terrestrial and martian volcanoes.

BACKGROUND

Alba Mons is a large shield volcano on Mars with a diameter of roughly 1400 km (East-West) by 1000 km (North-South) that was volcanically active during the early to middle Amazonian period (3.0 Gya to 2.5 Gya) (Öhman & McGovern, 2014 ; Ivanov & Head, 2006). The summit of Alba Mons reaches a height of around 7 km (Ivanov & Head, 2006).

The volcano has regions of circumferential faulting along its outer edges, including the Alba Fossae region which is located northwest of the collapsed caldera complex at the center of the volcano (Fig. 1). These large fault systems are a result of applied lithospheric forces from the Tharsis region (Carr, 1980 ; Tanaka et al., 1991), and they've been influential in the evolution and history of Alba Mons (Ivanov & Head, 2006). As Alba Mons became inactive, it relaxed, and the lithospheric stress began to manifest itself via faulting around the volcanic region. The mass of Alba Mons is large enough that it loaded the lithosphere and caused the formation of circumferential faults. The Alba Fossae fault zone is also home to lava flows and fluvial

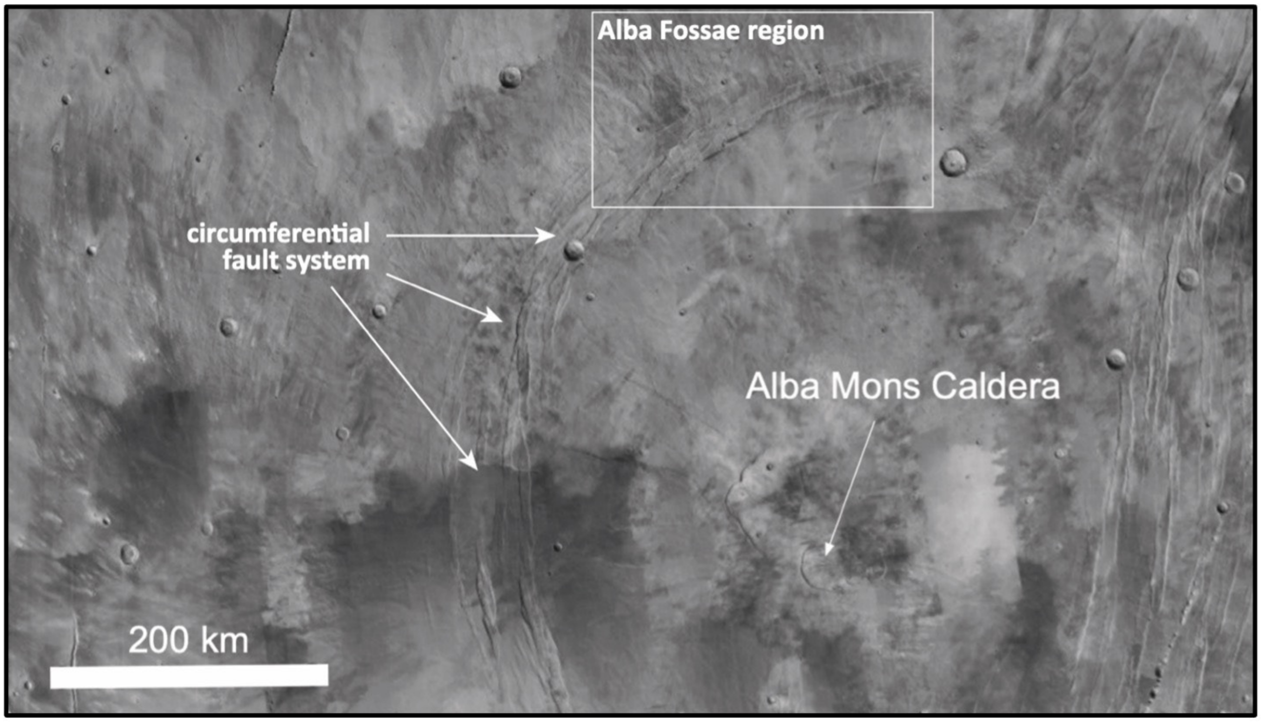

Figure 1. Snapshot from the CTX mosaic which shows the Alba Mons Caldera and the Alba Fossae region where the analysis was conducted, and the circumferential faults can be seen.

systems that interact with various fault segments.

The north-south trending faults formed as a result of tectonic effects from the Tharsis volcano complex stretching the surface as the volcano arose. This set of faults interacted with the circumferential faults on the outskirts of Alba Mons (Ivanov & Head, 2006). The graben of the Alba Fossae system both cut through and were cut by lava flows on the flanks of the volcano (Ivanov & Head, 2006). This is one of the relationships explored within this region. The faulting history of Alba Fossae spans a long period of time. The graben systems were active at certain points from the Hesperian (3.5-3.7 Gya) to the early Amazonian (2.5-2.6 Gya) periods (Ivanov & Head, 2006). The faults and fluvial systems play a major role in the geologic history of this region on Mars and Alba Mons is a small portion of that history (Tanaka, 1990). The fluvial systems in the region of Alba Fossae are thought to have been active both before and after the volcano's activity (Karimova, 2017). The last event is believed to be the formation of the circumferential faulting which outlines the northwestern portion of Alba Mons (The region of study). The timeline of events is disputed by different studies that have examined the region (Karimova, 2017 ; Ivanov & Head, 2006). Using the new CTX camera mosaic I explored the region in greater detail to establish an accurate timeline of geologic events.

Exploring the relationship between displacement and fault segment length has been done several times on Earth in large surveys of faults (Walsh & Watterson, 1988). The relationship between the displacement and length can be expressed through an equation: D = cLn. Where D is the displacement value, length is L, n is some scaling value of the relationship, and c is the rock strength value. The values of n range from about 0.5 to 2 for normal faults on Earth. In a study done in 2022, the relationship equation was determined to be D = 0.3L0.92 and this was based on a survey containing data from 4,059 normal faults from 66 sources around the world (Lathrop et al., 2022). Several factors are taken into consideration when conducting surveys of this nature. Different fault segment lengths will have different length vs. displacement relationships. This survey measured both inactive and active faults. The circumferential faults in Alba Fossae are thought to have been inactive for the past 500 million years (Ivanov & Head, 2006).

It has been suggested that fault displacement and fault length relationships don't follow a linear model, but instead propagate to its near maximum length and then, over time, displace with little tip propagation

(Walsh et al., 2002). Faults most likely grow following the hybrid model which has two distinct phases. The first phase accounts for about 20% to 30% of the fault's life. In this phase, the fault reaches the near maximum propagation length and about 10% to 60% of the fault's displacement occurs. The second phase has almost no propagation and this is where 40% to 90% of the displacement occurs (Rotevatn et al., 2019). Different times during the fault's lifespan will correspond to different length vs. displacement relationships. This is why exploring inactive faults on Earth and comparing them with the circumferential faults in Alba Fossae is critical. The fault must be at maximum displacement when measuring the fault length and examining the length vs. displacement relationship.

METHODS

I used several methods to investigate the evolution of faulting in the Alba Fossae region. I performed image analysis using the mosaic made from images taken by the CTX camera. The images from the CTX camera were the primary source of imagery data that I used when analyzing the geologic timeline of events of the Alba Fossae region. I compared some of the specific faults and areas back to Google Mars to examine the elevation data. Google Mars also had wonderful 3D interaction features. Using the mosaic, I located the geologic features that were present and made note of them.

I identified faults, fluvial systems, and lava flows. I looked at locations within Alba Fossae where there was an interaction between two features. The analysis of these interactions allowed me to determine the geologic timeline of the region. If one feature cuts through another feature, for example, a fault cutting through a lava flow, the fault is younger than the lava flow. I found instances where normal faults cut through fluvial systems, fluvial systems cut through lava flows, and normal faults cut through lava flows. I also found locations where north-south running faults were cut by circumferential faults. I took images of the sites where interactions occurred and then made diagrams/figures that properly illustrate the feature interactions in a simplified view. With the diagrams and the photo evidence, I was able to provide the rough geologic timeline of Alba Fossae. I also used Google Mars to measure 253 total fault segment lengths in the Alba Fossae region. I measured the displacement values of 200 out of the 253 faults. I calculated the overall extension percentage of the region, which required a line to be drawn from the interior of the circumferential faults to the exterior faults. This process was done within Google Mars and the line is shown in Figure 2. The line intersected with 21 different faults. I calculated each fault's heave and throw values. I made graphs to describe the relationship between the fault segment lengths, and the heave, throw, and displacement. The heave and throw values were gathered by capturing elevation profile data along each fault at the highest displacement point on the fault shown in Figure 3.

I calculated the displacement values using the Pythagorean theorem. I measured the throw values of each fault by taking an elevation profile like the one above and subtracting the value denoted by the intersection of the red slope line and the blue line (3) by the value denoted by the intersection of the red slope line and the blue line (4). The heave was measured similarly, first taking an elevation profile like the one above and subtracting the value denoted by the intersection of the red slope line and the orange line (2) by the value denoted by the intersection

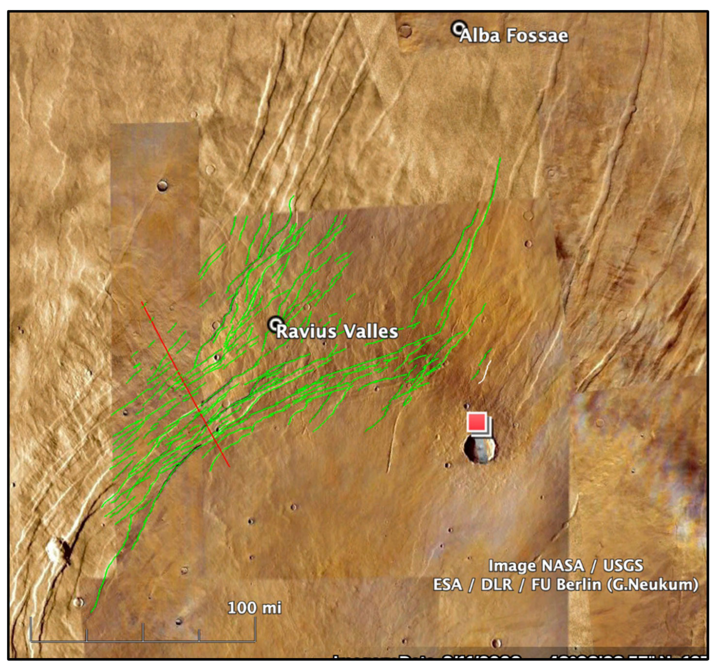

Figure 2. Screenshot from Google Mars of the Alba Fossae region. All 253 faults are traced by the green lines. The red line denotes the reference line used to calculate percent extension.

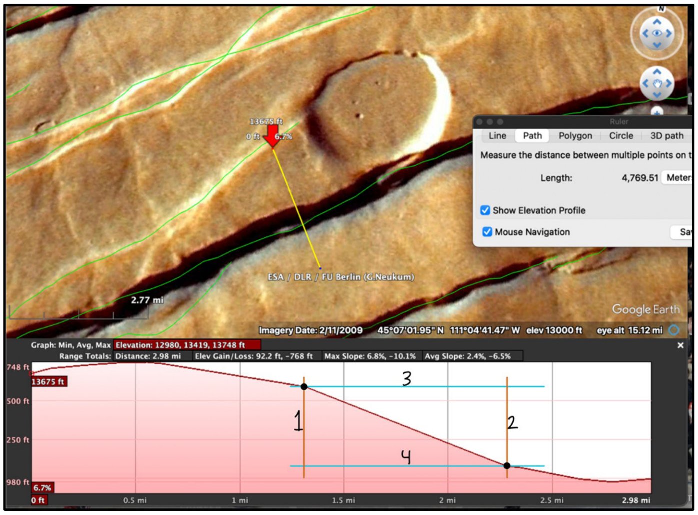

Figure 3. An example of how the heave and throw values were calculated for each fault segment in Google Mars.

of the red slope line and the orange line (1). After calculating the heave and the throw values I was able to calculate the dip separation via the Pythagorean theorem if you assume the slope as a hypothenuse of a triangle. The length vs. displacement relationship of Martian faults was compared to the same relationship for Earth faults. The total length of the extension line was measured. The 21 faults along the transect used to determine the magnitude of extension in this region had their heave values added up to get a total extension value. By taking the length of the transect and dividing it by the summed heaves then multiplying by 100, the fractional extension was determined.

Human error as well as inaccuracies in the Google Mars data set appear in the data. Measuring the individual faults by tracing them out on a computer may affect the data. Google Mars was interacting with Google Earth which left the elevation data intertwined during some measurements. These uncertainties must be accounted for when discussing the overall accuracy of the measurements and calculations that were made.

RESULTS

Based on the imagery analysis, the lava flows are the oldest features in the Alba Fossae region. The fluvial systems followed, supported by evidence that fluvial systems have eroded lava flows in multiple locations. The faults were the last feature, as they displaced both the lava flows and the fluvial systems. A diagram of these interactions and evolutions is shown in Figure 4. The diagrams show lava flows being cut by fluvial systems, circumferential faults cutting through north-south faults, and circumferential faults cutting through lava flows. The timeline is consistent with previous studies of the region (Öhman & McGovern, 2014 ; Karimova, 2017 ; Ivanov & Head, 2006) and the sporadic nature of the volcano's activity through time. Alba Mons has a long history of volcanic eruptions with uncertainty as to when volcanism initiated and terminated. The next step was measuring the 200 faults' displacement and length values which can be seen in Graph A of Figure 5, my data was plotted and is inconsistent with the results seen on Earth through the survey of 4,059 normal faults. The equation that expresses the relationship between fault displacement and fault length is as follows: D = 0.3L0.92 (Lathrop et al., 2022). The Mars data had an equation of D = 12.2L0.31. The difference between these equations arises because Mars faults have longer lengths than displacement values than normal faults on Earth. Graph B in Figure 5 demonstrates the inconsistency between the faults on Earth and Alba Fossae, but the graphs appear to line up. When taking a greater look at the equations that reflect the two different data sets you can see the clear differences between the two, fault displacement to length relationships. The final step was computing the percent extension accommodated by circumferential faulting. The line

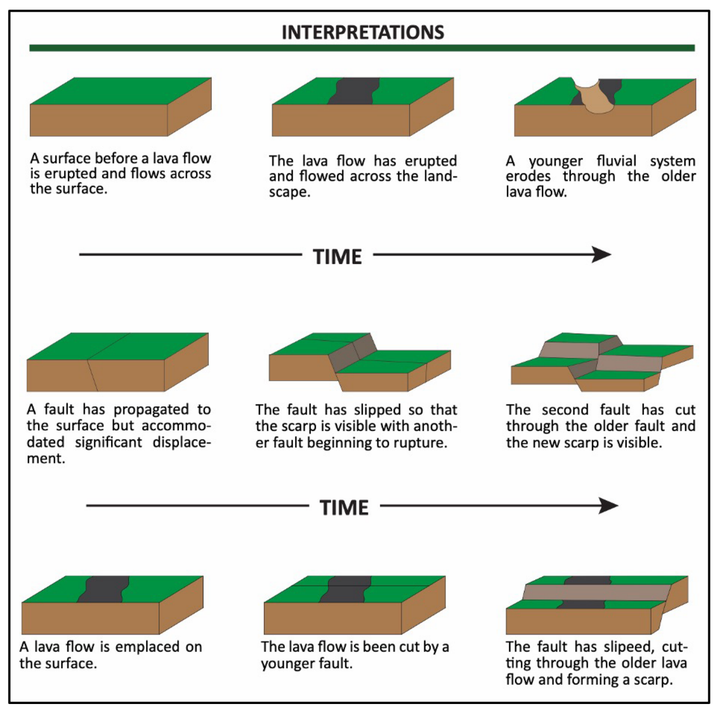

Figure 4. Diagram explaining the morphology, evolution, and overall relationship between geologic features in Alba Fossae.

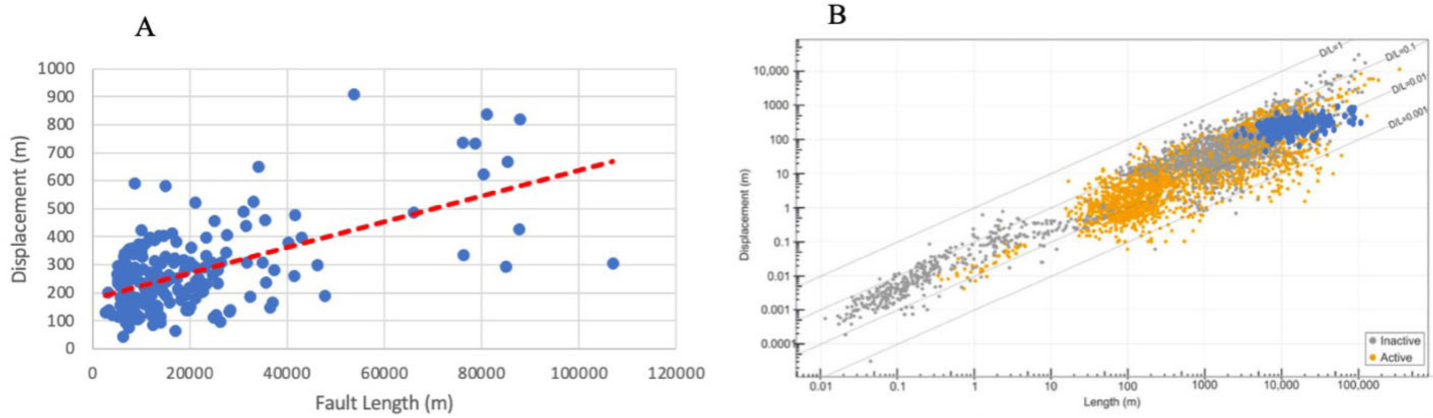

Figure 5. A. 200 faults plotted on a graph where fault length is the x-axis and displacement is the y-axis, both shown in meters. The red dashed line is the average slope that was determined with an R^2 value of 0.339. The relationship equation calculated was $D = 12.2L^{0.31}$. B. All 4059 faults (Lathrop et al., 2022) are plotted on a logarithmic graph overlaid by my 200 faults measured from the Alba Fossae region on Mars. Active vs Inactive faults are specified by the orange and grey dot colors, respectively, and the blue dots being the inactive Martian faults. Remember the equation that describes the fault length vs. displacement relationship on Earth: $D = 0.3L^{0.92}$.

of section is 127 km in length. By adding up each fault's heave value that intersected with the extension line, the total came out to be 7.02 km of extension. By dividing the extension line length by the overall extension and then multiplying by 100, the percent of the extension comes out to 5.53% extension.

DISCUSSION

The circumferential faults within Alba Fossae were formed after the Alba Mons volcanic edifice had been constructed. A large chunk of my research which contained analysis of the geologic timeline of the Alba Fossae region is reinforced by previous timelines laid out (Karimova, 2017) & (Ivanov & Head, 2006). The overall timeline of events is consistent with the volcanic history spanning several time periods, and having a complicated history that is poorly understood. The lava flows were the first feature to form. Erosional features can be seen via fluvial flows cutting through the lava flows and the youngest geologic features are the circumferential faults. The CTX mosaic allowed us to take a deeper and more detailed look into the exact relationships of the region and it was important to confirm the previous studies' results. The volcanic edifice was active and once the volcano went dormant, the stress that was applied to the lithosphere was so large that faults were created to accommodate for the lithospheric load applied by the collapsed caldera. The discrepancy between Earth's fault displacement vs. length relationship and Mars' fault displacement vs. length relationship could be a result of the difference in crustal thickness between the two planets. The overall conclusion that can be made from this research study is that further research is necessary. Many factors need to be accounted for when comparing fault relationships between two planets as well as analyzing a geologic timeline of the region with a complex past. This type of research needs to be done over several years. During this process, it is critical to take into account a wide range of variables to make acute measurements.

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