

Geometry and segmentation of Cerberus Fossae, Mars: implications for marsquake properties.

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Keypoints:

Cerberus Fossae width and throw decrease from west to east, indicating the direction of long-term propagation of the dike-induced grabens.

Cerberus Fossae are laterally divided into a similar number of major segments and sub-segments, as observed on Earth.

Long-term propagation and segmentation of Cerberus Fossae help to constrain the location of marsquakes during the InSight mission

Keywords:

InSight mission, Cerberus Fossae, fossae segmentation, fossae morphology, stress distribution, marsquakes

Plain Language Summary:

The recent successful landing of the InSight mission on Mars and the deployment of its seismometer SEIS renew the interest of active Martian structures that could trigger seismic events. In this study, we focus on one of these structures,

Cerberus Fossae, which is a large fracture network situated close to the landing site. We perform a detailed mapping of the fossae based on high-resolution satellite images, and we present an analysis of their lateral segmentation and morphology. We bring new constraints on the direction of long-term propagation of the fossae. We also find that the fossae are divided into a similar number of segments, at four different scales, as observed on Earth. These results allow us to assess the overall and local stress concentrations along the fossae, hence to highlight the potential location of seismic events recorded during the mission. Since the marsquake locations are difficult to determine precisely with a single seismic station, our study is a strong asset to reduce uncertainties and to better understand the source properties.

ABSTRACT:

The NASA InSight mission to Mars successfully landed on November 26th, 2018 in Elysium Planitia. It aims to characterize the seismic activity and constrain the internal structure of Mars. We focus on the Cerberus Fossae region, a giant fracture network of ~1200 km long situated east of the InSight landing site, and where M~3 marsquakes were detected during the past two years. It is formed of five main fossae located on the southeast of the Elysium Mons volcanic rise. We perform a detailed mapping of the entire system based on high resolution satellite images and Digital Elevation Models. The refined cartography reveals a range of morphologies associated with dike activities at depth. Width and throw measurements of the fossae are linearly correlated, suggesting a possible tectonic control on the shapes of the fossae. Widths and throws decrease toward the east, indicating the long-term direction of propagation of the dike-induced graben system. They also give insights into the geometry at depth and how the possible faults and fractures are rooted in the crust. The exceptional preservation of the fossae allows us to detect up to four scales of segmentation, each formed by a similar number of 3-4 segments/subsegments. This generic distribution is comparable to continental faults and fractures on Earth. We anticipate higher stress and potential for marsquakes within intersegment zones and at graben tips.

1. Introduction

Launched on May 5th 2018 and successfully landed on Elysium Planum on November 26th, 2018, the NASA's Discovery Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission is dedicated to the study of the Martian interior (Banerdt et al., 2020). The main instrument, the Seismic Experiment for Interior Structure (SEIS; Lognonné et al., 2019) seismometer is designed to record Martian seismic activity from different seismic sources: atmospheric turbulence (Spiga et al., 2018), airbursts and meteorite impacts (Daubar et al., 2018; Stevanović et al., 2017) and internal seismic activity of the planet (Clinton et al., 2018). In this study we focus on the potential seismic activity of major tectonic structures close to the landing site (Golombek et al., 2020).

Situated ~1200 km to the northeast of the landing site, the giant fracture set of Cerberus Fossae is one of the closest major visible structures (Fig. 1a) that could generate marsquakes recordable by the SEIS seismometer. Before the InSight mission, Taylor et al. (2013) considered Cerberus Fossae as an active seismic source, with an estimated seismic moment release of the order of 10^{17} N.m.yr⁻¹. Since the InSight landing, SEIS has recorded several hundreds of events (Ceylan et al., 2021; Clinton et al., 2021; Giardini et al., 2020; Lognonné et al., 2020), but only ~10% of them are clearly identified as marsquakes. Furthermore, the difficulty to observe clear seismic phases arrivals and polarizations on seismic records allowed Giardini et al. (2020) to determine the location of only two main events (M-3 S0173a and S0235b events). Despite the large uncertainties, both events were located within the Cerberus Fossae region (Fig. 1b). This first striking observation was associated with the study of Brinkman et al., (2021), who have shown that extensional slip motion occurred during these marsquakes (Fig. 1b), raising the possibility of ongoing and localized tectonic activity on Mars.

In order to better constrain the potential location and magnitude of such marsquakes originating from this major system, it is important to characterize in detail its surface trace and its along-strike structural discontinuities (i.e. step-overs, bends, secondary faults and fractures). Lateral fault and fracture segmentation is an important property that has a strong impact on rupture initiation, propagation and arrest (e.g. Aki, 1979; Barka & Kadinsky-Cade, 1988; Biasi & Wesnousky, 2016, 2017; Manighetti et al., 2007, 2015; Shaw, 2006; Sibson, 1986; Zhang et al., 1999). In this study, we use high resolution satellite images (Martian Reconnaissance Orbiter’s Context Camera CTX with an horizontal spatial sampling of 6m/pixel; Malin et al., 2007; High-Resolution Imaging Science Experiment HiRISE with an horizontal spatial sampling of 25cm/pixel; McEwen et al., 2007) to map in detail the entire Cerberus Fossae system. We build Digital Elevation Models (DEM) from stereo pair images in order to study the fine morphology of the fossae. We analyze the lateral segmentation of the fossae and highlight several scales of segmentation. We do not aim to prove the existence of dikes at depth but rather discuss the growth process and the direction of long-term propagation of the whole system. Finally, we discuss the preferential location of seismic events deduced from our analysis to help to better constrain the location of events recorded by InSight.

2. General context of Cerberus Fossae.

The Cerberus Fossae cross-cut one of the youngest Martian volcanic terrains dated to Late Amazonian (1 Gyr to present; Plescia, 1990, 2003; Tanaka et al., 1992). It is located on the Elysium Planitia, near Elysium Mons (Fig. 1a) and is ~1200 km long (coordinates between 6-12°N and 157-174°E). It is formed of four to five major sub-parallel fossae (long linear and narrow depressions on Mars, labeled G1 to G5 on Fig. 1b; modified from Taylor et al., 2013), ranging from ~250 to ~600 km long, and trending N110°E in the northwest part (western fossae) to N100°E in the southeast (eastern fossa). From orbit, fossae appear as

giant fractures that Ernst et al. (2002) identified as the result of possible giant dike swarms at depth, radiating from Elysium Mons. Using a flexural loading model, Hall et al. (1986) showed that the global stress field induced by the Tharsis rise might also be responsible for the formation of the fossae. In any case, it is thought that the fossae formed in a regional extensional stress setting, either due to pure graben faulting (Vetterlein & Roberts, 2010) or fracturation processes above growing dike(s) at depth (e.g. Berman & Hartmann, 2002; Burr et al., 2002; Head et al., 2003; Nahm et al., 2015, 2016; Plescia, 1990), as commonly observed on Earth (e.g., Gudmundsson, 1984; Hjartardóttir et al., 2016; Magee & Jackson, 2021; Rowland et al., 2007; Rubin, 1992; Rubin & Pollard, 1988; Tentler, 2005). Many studies have also pointed out the local influence of the combined effect of dike intrusion and sub-surface cryospheric melting, which led to large lava flows and catastrophic floods of melt water at the surface of Mars that shaped the surrounding plains of the near fossae regions (e.g., Burr et al., 2002; Cassanelli & Head, 2018; Nahm et al., 2015, 2016; Pendleton, 2015; Plescia, 2003).

Taylor et al., (2013) have inferred that Cerberus Fossae might be an active tectonic structure, able to release a seismic moment of 10^{15} - 10^{17} Nm.yr⁻¹. They associated this late tectonic activity (i.e., <10 Myr) with recent volcanic activity evidenced by young lava flows (Vaucher et al., 2009). Recently, Horvath et al. (2021) even identified a <250 ka old pyroclastic volcanic deposit in the central part of the fossae, supporting the hypothesis that geological activity continues to the present day. Since 2018, the InSight mission has confirmed that multiple seismic events (or marsquakes) of M~3.5 originated in the vicinity of Cerberus Fossae (e.g., Giardini et al., 2020), in good agreement with pre-mission estimations (Böse et al., 2017; Panning et al., 2017). The moderate-sized magnitudes are supposedly too low to trigger surface ruptures. Recently, Grindrod et al. (2018) reported locally no co-seismic deformations at a single location along the fossae G2 by performing sub-pixel correlation analysis (i.e. COSI-Corr; Leprince et al., 2007) on HiRISE images over a period of 8 years. However, Roberts et al. (2012) studied the potential paleo-marsquakes that occurred along fossae G2 by analyzing along strike distributions of boulders triggered by ground shaking. They found a dense distribution of boulders over a distance of 90-150 km, which could have originated from a sequence of several paleo-marsquakes in the last 2.5 Ma (see also section 4.2.2).

[FIGURE 1 AROUND HERE]

3. Data analysis and results

3.1. Detailed fault mapping of Cerberus Fossae

Available geological and fault maps of Mars highlight the major structures composing the Martian crust (e.g., Knapmeyer et al., 2006; Tanaka et al., 1992). However, they are mainly based on low resolution satellite observations (e.g. MOLA, the only dataset available at that time and covering the entire planet) which are not of sufficient resolution to depict geological structures at smaller

scale (average horizontal spatial sampling of 463m/pixel ; Smith et al., 2001). Here we used high-resolution satellite images (6 m/pixel CTX and 25 cm/pixel HiRISE images) to perform detailed mapping of the entire Cerberus Fossae system. The resolution of these images made it possible to identify a large amount of new fossae (black lines, Fig. 1b) that were not mapped by Knapmeyer et al. (2006) (red lines, Fig. 1b). For example, fossae G1 and G2 are visible on MOLA data, while smaller fossae G3, G4 and G5 are not. Still, the latter fossae were observed in previous studies (e.g. Berman & Hartmann, 2002; Grindrod et al., 2018; Plescia, 1990; Taylor et al., 2013), based on medium to high resolution satellite images (Viking, THEMIS, HRSC, CTX, HiRISE). G4 may be the eastern extension of G1, but there is no clear evidence of continuous surface expression between them (the gap is more than 100 km long). Most of the mapped traces are clearly expressed at the ground surface (G1, G2, G4; Fig. 1 and 2a, 2b, 2c), while some of them are less distinct, especially along G3 and G5, where shallow traces (Fig. 2d), narrow fractures (Fig. 2e) and discontinuous traces (Fig. 2f) are observed, possibly related to early collapse of a putative lava conduit or melting and consequent collapse of the cryosphere at depth. The length of the fossae ranges from 260 to 610 km. Their traces are sub-parallel and spaced from 20 to 60 km apart (G1, G2, G3 and G5). Vetterlein & Roberts (2010) measured the height of the walls of the fossae and found a maximum vertical height of ~1 km (i.e., summed walls are 2 km high in the case of a symmetric fossa) in the western part of G1, which is the closest section of the Cerberus Fossae system to Elysium Mons.

[FIGURE 2 AROUND HERE]

3.2. Lateral segmentation of Cerberus Fossae

All faults and fractures are structurally segmented along their trace regardless of their scale, slip mode or tectonic context. The segments constitute small sub-parallel delineations on the fault strike, separated by jumps corresponding to zones of slip deficit, hence stress concentrations (e.g., Barka & Kadinsky-Cade, 1988; Klinger, 2010; Manighetti et al., 2015; Segall & Pollard, 1980). Moreover, Manighetti et al. (2015) have shown that faults on Earth are segmented at hierarchical scales, i.e. faults are divided into three to four major segments, themselves divided into two to three secondary segments. Previous studies have already shown that faults on Mars are laterally segmented (e.g., Donzé et al., 2021; Hauber et al., 2014; Polit et al., 2009; Schultz, 1989), and the fossae of Cerberus are no exception (Vetterlein & Roberts, 2010). They are formed by numerous segments at different scales, separated by various structural discontinuities, such as step-overs (Fig. 2g), complex relay zones (Fig. 2h) and en-échelon structures (Fig. 2i).

We analyzed the lateral segmentation of the Cerberus Fossae system based on our complete surface mapping (Fig. 3 and Supp. Fig. S1). Due to the very low erosion rate on Mars, segments are well preserved in the morphology. They are well connected in the western and northern parts of the fossae system (G1, G2; Supp. Fig. S1), whereas they are rather isolated and offset in the eastern

and southern parts (G3, G4 and G5). We are able to identify up to four scales of segmentation on G2 and G4, and three scales on G1 and G3 (see detail in Fig. 3 and Supp. Fig. S1). Note that we do not describe G5's segmentation in this section since its trace is too discontinuous. Note also that our definitions of segments of G1 are slightly different from those defined by Vetterlein and Roberts (2010). We justify our choices in the discussion (see section 4.2.1).

[FIGURE 3 AROUND HERE]

As an example, we give below a detailed description of G4's lateral segmentation (Fig. 3). The detailed description of the segmentation of the entire Cerberus Fossae system can be found in Supp. Fig. S1 and Supp. Text S1. We define major segments as those separated by the largest structural discontinuities found, such as large step-overs, and/or secondary splay faults, and/or major bends along the surface traces. These zones also appear as the largest slip deficit in the summed throws profile (Vetterlein and Roberts, 2010). Here, G4 is ~435 km long and trends N100°E. It is divided into three main segments of 100 to 180 km long, separated by step overs >3 km wide. Each major segment of G4 is formed by two to five secondary segments of ~50 km long, mostly separated by 1 to 3 km step overs (inside major segments 2 and 3) or connected through slight bends of 20° in the surface trace (inside major segment 1). Inside most of secondary segments (i.e., the isolated ones), it is possible to observe tertiary segments (Fig. 3), which are ~15 km long on average and separated by slight changes in the azimuth (<10°) and smaller step overs (between 500 m and 1 km wide). Quaternary segments of ~7 km long on average are observed into several tertiary segments (Fig. 3 and Supp. Fig. S1). They are separated by small step overs <300 m wide and azimuth changes <10°. Tertiary and quaternary segmentations are hardly distinguishable in the western parts of the G1 and G2 fossae, where major segments are well connected and thus the smaller scale discontinuities are smoothed out.

The complete analysis of the segmentation reveals that the different fossae in the Cerberus region are laterally segmented into a limited number of segments, i.e., with a frequency between 2 and 7 segments/sub-segments at every scale we observe, with a maximum of 3 to 4 segments/sub-segments within fossae/segments (Fig. 4a). We provide below some statistics about the number of segments we clearly identified (Fig. 3 and Supp. Fig. S1). In many parts of the fossae, the evolved linkage along the surface trace makes it difficult to identify small segments (especially the tertiary and quaternary ones), preventing the potential identification of the total number of segments/sub-segments. We thus observe that 50% (2) of the fossae are divided into three major segments, 25% (1) into five major segments and 25% (1) into six major segments. Since we consider only four fossae at this scale, these percentages have to be used with caution. More robust statistics can be obtained from the 16 major segments for those we identified secondary segments. It seems that ~25% (4) of the major segments are divided into two secondary segments, ~13% (2) into three secondary segments, ~44% (7) into four secondary segments, ~6% (1) into five secondary segments,

~6% (1) into six secondary segments and ~6% (1) into seven secondary segments. The 60 secondary segments identified are themselves divided into two (15%), three (35%), four (35%), five (10%) and six tertiary segments (5%) (for a total of 71 tertiary segments identified). Finally, 24% of the tertiary segments are divided into two quaternary segments, 53% into three quaternary segments, 12% into four quaternary segments and 12% into five quaternary segments (for a total of 53 quaternary segments identified).

Figure 4b shows a complementary plot of the data which represents the length of each n-order segment/sub-segments as a function of the length of each (n-1)-order segment/sub-segments (length of major segments as a function of the length of secondary segments for instance). The black linear relations $LS_n \sim (0.3 \pm 0.1) * LS_{n-1}$ suggests that the fault/segments are sub-divided in a similar number of segments/sub-segments, which is about three (Fig. 4b).

[FIGURE 4 AROUND HERE]

3.3. Lateral morphological variations of Cerberus Fossae

We use HiRISE stereo pair images to compute high-resolution DEMs along the Cerberus Fossae system (see locations on Fig. 1b) using the SOCET SET mapping software (©BAE Systems). The stereo images are selected at different locations on the fossae in order to get an overall view of the lateral variation of the morphology along the Cerberus Fossae system. Stereo pairs were identified through ISIS image processing software package (USGS). They are calibrated based on the HiRISE camera specifications, corrected from jitter effects by the USGS ISIS software and then implemented into SOCET SET. Bundle adjustment is made in an absolute reference frame defined by MOLA. The coarser first iteration of DEM calculation is seeded on the gridded MOLA elevations at a resolution of 2 m/pixel. It is then followed by a refined DEM computation at higher resolution (up to 1 m/pixel). Post-processing DEM corrections are performed on outlying points to discard aberrant calculations (see red and green areas on Fig. 5 G1-A, G1-C and G2-A). Figure 5 presents the resulting DEMs, for which we extract a series of topographic profiles across the fossae (Supp. Fig. S2). Fossae are fairly symmetrical, with flat “rift shoulders”, especially in the eastern and southern parts of the system along G3, G4 and G5. The latter fossae present a narrow fracture zone with steep slopes (~75-80°), and minimum vertical throw and width of ~50 m and ~100 m, respectively (see G4, Fig. 5). The bottom of the fossae is mostly formed by a layer of sediments, but it is also possible to observe preserved flat ground surfaces that have been subsided (G4B; Fig. 5 and 6). On the other hand, the western fossae (G1, G2) are wider (~1000 m maximum) and deeper (~500 m maximum of depth), associated with several slope breaks in the topographic profiles (Fig. 5, 6, and Supp. Fig. S2). The lower parts are characterized by sediments eroded from the upper parts of the fossae, and forming fan structures associated with shallow slopes (~30°; Fig. 5 and 6, see also Vetterlein & Roberts, 2009). Steep slopes (~70°) situated above these fan structures form the main walls of the fossae (Fig. 5, 6, and Supp. Fig. S2). They are composed of more competent rocks (such as basalts, Jaeger et al.,

2010; Plescia, 2003). At some locations, the steepest slopes are associated with erosional syn-tectonic morphologies, such as triangular facets (on G2; Roberts et al., 2012; Vetterlein & Roberts, 2009). We also observe similar morphologies along G1 (Fig. 6), which are situated on the top of the steepest slopes we measure (G1-C; Fig. 5 and Fig. 6a). They are different from common erosional spur and gully morphology (i.e. mass wasting without tectonic activity) that have been observed on the slopes of martian troughs (e.g. Valles Marineris, Lucas et al., 2009; Nedell et al., 1987; Peulvast et al., 2001). While regular spurs and gullies show a sinuous base controlled in our case by sub-horizontal lithological contrasts (Fig. 6c), the base of the triangular facets follows a straight trend (Fig. 6b and 6c), which we interpret as the surface expression of a possible highly-dipping fault scarp (Burbank & Anderson, 2011). Similar morphologies have been observed in Valles Marineris on Mars (e.g., Peulvast et al., 2001). The Cerberus facets are about 200 m long and their base 80 m wide, and they are characterized by layers of sediments, lava flows and ashes from past volcanic activities (smoothed terrains in Fig. 6; Tanaka et al., 1992). The area covered by the facets can extend over large distances away from the main fossa axis, where retrogressive erosion processes can be observed (G1-C, G2-A, G3-B Fig. 5: see also Pendleton, 2015). Altogether, these morphologies highlight the possible interactions between tectonic (i.e., graben formation) and erosional processes at the surface and sub-surface (i.e., possible circulation of fluids induced by the melted cryosphere), that occurred in the evolution of Cerberus Fossae (see also discussion in section 4).

In the upper parts of some fossae (G1, G2), we observe a slight increase of the slope in the last few meters. This could mark the presence of materials harder than the underlying sediments, such as duricrust in the regolith close to the ground surface (Jakosky & Christensen, 1986).

[FIGURE 5 AROUND HERE]

[FIGURE 6 AROUND HERE]

We compile in Figure 7a and 7b the summed throw and mean width of the fossae, inferred from the mean topographic profiles from each HiRISE calculated DEM (see all mean profiles in Supp. Fig. S2). It clearly shows the difference in throw and width from west to east and north to south along Cerberus Fossae. G1 presents the largest throw and width (blue dots, Fig. 7). The western part of G2 has similar width and throw than G1, but they decrease rapidly toward the east (see green dots). G3 follows a similar behavior, showing an overall smaller throw and width than G1 and G2, associated with a decrease of the relative throw and width toward the east (yellow dots, Fig. 7). G4 (red dots) do not show clear lateral variation but they are, with G5 (brown dots), presenting the smallest widths and throws of the Cerberus Fossae system. Altogether, these observations show an overall decrease of the fossae dimension toward the east and the south. We also show in figure 7c the MOLA elevations at each site. It is interesting to note that they decrease fairly linearly from west to east, contrasting with the large step seen in width and throw measurements between

northwestern G1-G2 fossae and southeastern G3-G4-G5 fossae.

[FIGURE 7 AROUND HERE]

We estimate the summed throw values of G1 from the three mean topographic profiles calculated for each DEM (Fig. 5 and Supp. Fig. 2), and find a good agreement with the measurements done by Vetterlein & Roberts (2010) from MOLA data (see description below). In their study, they did not perform width measurements because the scarps are assumed to have undergone collapse (e.g., rock falls, landslides) that widened them and which therefore could have affected their interpretation. Still, based on their throw measurements, we estimate a range of widths by measuring three different distances across the fossa: a “maximum” or “apparent” width (W_a ; Fig. 8) that encompasses the whole structure (including potential collapse and eroded material); the width measured at the top of the triangular facets and/or expected fault scarp (i.e. the steepest slope; W_t ; Fig. 8), which in an ideal case with no erosion would be the best parameter representing the fossa width; and the width measured at the base of the steepest slope (W_b ; Fig. 8), which would represent a minimum structural width of the fossa. Thus, W_a and W_b give the range of fossa widths, which is a good proxy of the minimum and maximum uncertainties in our measurements. In order to have a full coverage of the fossa, we perform our analysis from CTX images at the locations of the measurements done by Vetterlein & Roberts (2010) from MOLA data tracks. The results are shown in figure 9 and present the fossa width variation along G1. As expected, the largest range of widths (i.e., between W_a and W_b ; orange areas in Fig. 9b) is observed along the sections accommodating the largest deformation, indicating a more evolved section of the fossa that has been submitted to erosional processes and collapse. On the other hand, along the most immature parts of the fossa (i.e., close to the tips), the range of widths is smaller, since the fossa shoulders are better preserved ($W_a \sim W_t$). The overall fossa width and summed throw profiles are equivalent (see Fig. 9a and 9b). On figure 9b, we did not measure the width associated with the sub-parallel segment situated between segment 5 and 6 (dotted lines in Fig. 9a; segment labeled “9.1” in Vetterlein & Roberts (2010) since it is not a colinear segment and seems to be an older fossa structure crosscut now by segment 5 (Supp. Fig. S1 and Text S1). Figure 9c indicates that the fossa width (W) is two times the fossa throw ($W \sim 2 * T$) if we consider that both throws are equal (northern and southern throws, Fig. 8), which seems to be the case in most parts of the fossa. Note that some values show large width measurements for very small throws (grey area in Fig. 9c). We consider these values as outliers since they are mostly situated near fault/segment tips where the small summed throw (< 500 m) might be underestimated by non-resolved MOLA measurements.

[FIGURE 8 AROUND HERE]

[FIGURE 9 AROUND HERE]

4. Discussions

4.1. Evolution and direction of long-term propagation of Cerberus Fossae

We observe that Cerberus Fossae exhibit systematic changes in fossa widths and vertical throws from west to east (Fig. 5 and 7). These observations are summarized in figure 10: fossae are wider with higher vertical throw in the western and northern part of the system (Fig. 10b; G1 and G2) than in the eastern and southern part (Fig. 10b; G3, G4 and G5). This implies that the cumulative displacement accommodated by Cerberus Fossae decreases from the west(-northwest) to the east(-southeast), and suggests that the deformation has propagated over the long-term toward the east(-southeast) i.e., away from Elysium Mons situated to the northwest (Fig. 1a). We suggest that the igneous activity beneath Elysium Mons was both the source for melts and regional tectonics stresses that were responsible for dike development and stress propagation towards the east(-southeast) at Cerberus Fossae. Other evidence supports this interpretation: i) the morphology also changes along strike. On one hand, more mature fossae G1 and G2 seem to have been submitted to erosional processes (i.e. slope variation of the flank of the fossa, boulders, triangular facets; see Fig. 5 and 6) associated with sediment deposits (Fig. 6; see also triangular facets in the western part of G2, Roberts et al., 2012; Vetterlein & Roberts, 2009). On the other hand, assumed younger fossae G3, G4 and G5 are well preserved (homogeneous steep slopes of the flanks of the fossa; Fig. 5), denoting a decreasing exposure time to surface processes from west to east.; ii) fault segments are well connected in the western part of the fault system, while they are not in the eastern part (Fig. 3 and Supp. Fig. S1). This indicates relatively longer activity of the dike-induced graben system in the west, where successive ruptures favored the linkage between dike at depth and fossa segments at the surface. Moreover, smaller scales of segmentation (i.e., tertiary and quaternary segmentation) are better observed in the eastern fossae (e.g., G4), representing the less evolved part of Cerberus Fossae (i.e., lesser degree of segment linkage in the eastern fossae).

The accumulation of stress and the eastern propagation of the dike system took place during a long period of time, from the building of the slopes of Elysium Mons (peak of volcanic activity at 2.2 Gy; Platz & Michael, 2011) to the volcanic activity of the Central Elysium Plains at the origin of the fossae (from 250 My to 2 My; Vaucher et al., 2009). However, stream lines and triangular facets are locally observed along the fossae, suggesting the action of fluids eroding their flanks. At some locations, triangular facets along G1 (Fig. 6) seem to be situated on top of the steepest slopes, which could be comparable to hanging valleys on Earth (e.g., Burbank & Anderson, 2011). This morphology could be explained by three main (non-exclusive) mechanisms: i) during the early formation of the fossae, the rise of the dikes interacting with shallow pressurized groundwater or cryosphere (e.g. Burr et al., 2002; Head et al., 2003; Pendleton, 2015; Plescia, 2003) and the resulting water floods eroded the early formed dike-induced fault scarps; ii) the opening rate of the fossae was significantly higher than the erosion rate; or iii) the slope breaks across the fossae highlight lithological contrasts between sediments (shallow slopes) and steep slopes (basalts), which would

induce a differential erosion. Our preferred hypothesis would be the first one, since we have no clear evidence to assess the second one. The third hypothesis is not in contradiction with the first one, and might play also a role in the morphology of the fossae.

Our morphological observations (Fig. 6) and the strong correlation between fossae width and throw (Fig. 9) suggest that the fossae are structurally shallow graben bounded by steep walls. Note that the strike and inferred dip are in good agreement with moment tensor solutions found by Brinkman et al. (2021) for recent marsquakes. It is unclear if these faults correspond to Mode II shearing cracks (i.e., steep normal faults) or are actually part of large Mode I opening cracks (joints) that would form the fossae. It is likely that both Modes are interacting each other in a complex pattern since the early formation of the graben, as observed in experimental models (Fig. 10a; e.g., Mastin & Pollard, 1988). The progressive linkage between first formed steep fissures at the surface and fractures at depth lead to the formation of normal dip slip responsible for the subsidence of the center part of the graben (stage 3; Fig. 10a). The subsidence of the center parts of the Cerberus Fossae and the observation of the triangular facets supports this shearing deformation. However, as said above, the rheological contrast between igneous rocks reaching the surface through the fractures and the surrounding material might also contribute to the formation of the facets.

[FIGURE 10 AROUND HERE]

Assuming that the actual fossae morphology is mainly due to dike propagation at depth, width measurements can be used to study the location and size of dikes at depth. The maximum fault heave is a proxy for dike thickness (e.g., Rubin & Pollard, 1988), which means that in our case, the fault heave would be half of the difference between W_t and W_b (i.e. the width at the top and the base of the steepest slope, respectively). Therefore, the dike thickness along G1 ranges from 8 m to 375 m, with an average width of ~ 49 m. The maximum dike thickness is situated where the fossa width and throw are maximum close to the center part of G1 (Fig. 9). Those values might be underestimated since the top and the bottom of the fault scarp is eroded and/or covered under sediments layer, respectively (Fig. 10b).

Also, graben half width is a proxy of dike upper tip depth (Hjartardóttir et al., 2016; Magee & Jackson, 2021; Pollard et al., 1983; Trippanera et al., 2015), which in our case would imply an average depth of ~ 488 m in the center part of fossa G1, decreasing slightly toward the west (~ 300 m) and strongly toward the east (~ 90 m). These depths might highlight heterogeneities and shallow layering in the sub-surface that would affect the dike emplacement at depth (see also the following section). Note also that the regional elevation decreases fairly linearly from west to east (Fig 1b and 7c), which might imply that dike upper tips could be located at a constant depth (or elevation) that would affect the fossa widths at surface. However, the decrease in width and throw is not linear and show a major step between G1, G2 and G3, G4 and G5 (Fig. 7a and 7b), suggesting

possible variations in dike locations at depth. In any case, if this relation is correct, the small fossa widths (eastern tips of fossae G1, G2 and fossae G3, G4 and G5) would indicate the location where the dikes are close to the surface.

4.2. *Generic segmentation along Cerberus Fossae*

4.2.1. *Comparison with terrestrial faults and implications for fault growth*

Detailed analysis of the Cerberus Fossae system shows that the along-strike segmentation is not random, but is similar at its four largest scales (i.e., 3 to 4 segments at each scale; Fig. 4). These results are equivalent to the number of major segments and secondary segments found for a large population of normal faults in Afar (rifting context on Earth) but also along reverse and strike slip faults (Manighetti et al., 2015 and references therein). These similar observations support the idea that Cerberus Fossae are faults and fractures and that their growth process on Mars is similar than on Earth. Graben segmentation at the surface is intimately linked to dike emplacement at depth (Pollard et al., 1983), and more particularly dike thickness changes that are driven by segmentation during dike propagation (e.g. Magee & Jackson, 2021 and references therein). In our case, the eastward propagation of dikes from Elysium Mons probably occurred by successive formation of new dike segments at the eastern tip of the existing ones (Healy et al., 2018; Rubin, 1995; Townsend et al., 2017). The new dike segment lengthens rapidly and widens until reaching a critical thickness that could trigger surface faulting and fracturing at its top (Trippanera et al., 2015). We infer minimum dike thickness as low as 8 m on G1, thus it is necessary that the top of the dike reaches shallow depths to induce surface faulting (~90 m estimated at the eastern tip). This propagation process is similar to normal fault growth on Earth, where phases of displacement accumulation occurring at constant length (Bull et al., 2006; Giba et al., 2012; Nicol et al., 2005) alternate with phases of lateral fault propagation through the formation of new fault segments (e.g. Manighetti et al., 2015 and references therein). The absence of plate tectonics and the presence of a thick, rigid lithosphere on Mars would favor the propagation of the dike over long distances, and would promote fracture linkage at surface near Elysium Mons (i.e., thicker dikes and more evolved fossae) while isolated offset segments are located near the eastern propagating tips (i.e. thinner dikes and less evolved fossae).

Our definition of segments along G1 is slightly different from that defined by Vetterlein & Roberts (2010). In their study, they measured vertical throw from MOLA data and identified nine to ten colinear segments —regardless of their length, separated by cumulative slip troughs in the summed throw profile (Fig. 9a). Thus, they obtain more small isolated segments near the fossa tips while longer ones are situated in the center parts of the fossa. However, their throw profile (Fig. 9a) shows that inside each segment, secondary peaks and troughs are observed, indicating sub-segments contained in the major segments (e.g. Manighetti et al., 2015). Since they are separated by smaller step-overs and slip troughs compared to the other major segments we identified, we consider

that the four western segments determined by Vetterlein & Roberts, 2010 are secondary segments of major segment 1 (Fig. 9 and Supp. Fig. S1). The other center and eastern major segments we defined are in fairly good agreement with their study. Nevertheless, future work is needed to better characterize the throw and width variations along all fossae (i.e. complete CTX DEM of the Cerberus Fossae fault system), since high-resolution data is mandatory to fully describe fault segmentation and propagation (Ze & Alves, 2019).

Segment length is often related to the depth of underlying heterogeneities such as rheological and mechanical contrasts. For instance, previous studies on Earth described a relation between the length of fault segments (deduced from rupture traces of large continental earthquakes) and the thickness of the brittle seismogenic layer ($\sim 18 \pm 5$ km on Earth; Klinger, 2010). Using experimental and numerical models, Lefevre et al. (2020) and Jiao et al., (2021) have also respectively shown that the inter-Riedel distance (or assumed segment length) is dependent on the brittle material thickness. On Mars, thermal models of the Martian interior estimated before the InSight landing a seismogenic lithospheric thickness from 30-100 km (Plesa et al., 2018) to 40-150 km (Knapmeyer et al., 2006). After the InSight landing, Knapmeyer-Endrun et al. (2021) have shown that the crustal thickness below the lander would range between 24 and 39 km (extrapolated from gravimetric data from 24 to 72 km for the whole planet), including a major discontinuity at 6-11 km deep (transition from highly altered and fractured to unfractured rocks). Along the Cerberus Fossae system, four scales of segmentation are identified in this study, with an average length of ~ 7 km for the quaternary segments (Fig. 4b). Based on the studies cited above, it is unlikely that this value is related to the thickness of the seismogenic crust. However, it could be related to the shallower layer identified by Knapmeyer-Endrun et al. (2021) at the InSight landing site, indicating that the changes in the rock lithologies/properties with depth could extend to further regions on Mars. The mean length of major, secondary and tertiary segments is respectively, 112 km, 36 km and 15 km. While the mean length of secondary segments is included in the range of Moho depth inferred on Mars (Knapmeyer-Endrun et al., 2021), the length of major and tertiary segments could highlight possible other discontinuities at depth.

4.2.2. Regional and local stress concentrations: constraints on marsquake locations recorded by the InSight mission

The first results of the InSight mission have shown that locating marsquake epicenters using one seismic station is very challenging. While most of the major quakes seems to come from the Cerberus region (e.g. Clinton et al., 2021; Giardini et al., 2020), the location uncertainties remain significant (about $\pm 3^\circ$ and $\pm 10^\circ$ in epicentral distances and azimuth, respectively). Our study provides some strong constraints that could be used to better define the location of tectonic marsquakes. Indeed, it is well known that fault and fracture segmentation has an impact on stress distribution (e.g., Barka & Kadinsky-Cade, 1988; Crider & Pollard, 1998; de Joussineau & Aydin, 2009; Manighetti et al., 2009, 2015;

Saucier et al., 1992; Segall & Pollard, 1980; Soliva & Benedicto, 2004). While aftershocks occur usually at the edges of high coseismic slip patches or in regions of low coseismic slip (e.g., Mendoza & Hartzell, 1988), a significant amount of small seismic events take place in the inter-segments zones (e.g., Liu et al., 2003). They correspond to areas of long-term slip deficit where heterogeneous types of faults and fractures are present and residual stresses concentrate. Thus, they are likely to trigger potential seismic events, which is useful in the context of the InSight mission. Most of the faults on Mars were formed during its main active period, more than 3 Gy ago (Anderson et al., 2008; Carr & Head, 2010; Schubert et al., 1990). Currently, those faults are not likely to experience high strain rates due to the lack of plate tectonics. Until InSight, recent strains on Mars were expected to be dominated by thermal contraction of the planet (Taylor et al., 2013). The recent joint discoveries of seismic events with extensional slip motion localized at Cerberus (Brinkman et al., 2021), detection of low frequency events possibly associated with lava circulation at depth (Kedar et al., 2021), and geological evidences of recent (<1 Ma) volcanic activity (Horvath et al., 2021) suggest active ongoing volcano-tectonic activity along Cerberus Fossae. On Earth, a simple model of a circular rupture is assumed for small shallow earthquakes (i.e. $M_w < 7.5$), leading to scaling relations between the rupture length and the seismic moment such as $M_0 \propto L^3$ (Aki & Richards, 2002; Denolle & Shearer, 2016; Scholz, 2019). It results in an average 1 km rupture length for a M_w 3.5 earthquake, similar to the magnitudes of the largest events observed by InSight. Therefore, if this law is valid in the Martian context, the larger events detected so far by InSight would not be able to break entirely the smallest segments (i.e., quaternary) identified in this study (Fig. 4b). This gives insights on the spatial scale to look at for surface deformations triggered by the marsquakes (rock falls, landslide) from new orbital data. Roberts et al. (2012) recently estimated rupture length of paleomarsquakes from fallen boulder populations along Cerberus Fossae (fossa G2). It seems unlikely that the ~ 100 km surface ruptures they defined have been formed by a single large event, but rather by a series of smaller events that generated a maximum rupture length at kilometric scales. The potential recent activity highlighted by Roberts et al. (2012) in a restricted area might reflect cluster of moderate size events occurring in a short time period as compared to their mean recurrence interval (e.g., Scholz, 2019).

Assuming an active context of dike and fracture propagation along Cerberus Fossae, we can expect that most of the seismicity will be located at shallow depth, since on Earth it occurs mostly between the upper dike top and the surface (Ágústsdóttir et al., 2016; Passarelli et al., 2015; Rubin & Gillard, 1998; Ukawa & Tsukahara, 1996). However, the estimated first results from the InSight mission rather suggest hypocentral depths of 20-30 km for the main events (e.g., Brinkman et al., 2021; Stähler et al., 2021). On the other hand, the lateral propagation of the system toward the east implies that the seismicity could be also located at depth near the propagating dike tips (Green et al., 2015; Rubin & Gillard, 1998; Sigmundsson et al., 2015). Indeed, Rivas-Dorado et al. (2021)

have shown that Martian conditions are favorable to develop giant dike systems (e.g., Elysium Fossae) that could reach much greater depths (15-20 km).

5. Conclusions

We performed a detailed mapping and structural analysis of the Cerberus Fossae system based on HiRISE and CTX images, in addition to stereo pair images used to calculate high resolution Digital Elevation Models. The relation between fossa width and throw supports volcano-tectonic processes as the main origin of fossae formation. They would have formed by the propagation of dikes at depth, possibly related to the rise of Elysium Mons, located further to the NW. The analysis of the lateral segmentation at the surface highlights up to four scales of segments. Most of the fossae/segments are divided into three to four segments/sub-segments, as it has been observed on Earth. The overall linkage between segments decreases from west to east, as do the overall fossae widths and throws. Altogether, the evidence is in good agreement with a long-term direction of dike-induced fault propagation toward the east. In the frame of the InSight mission, our study helps to identify the zones of potential seismic activity, at the regional scale (i.e., expected increase of seismicity toward the east where the fossae are immature) and the local scale (i.e., in inter-segment zones where stress concentrations likely occur).

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Figures and figures captions

Perrin et al., Figure 1

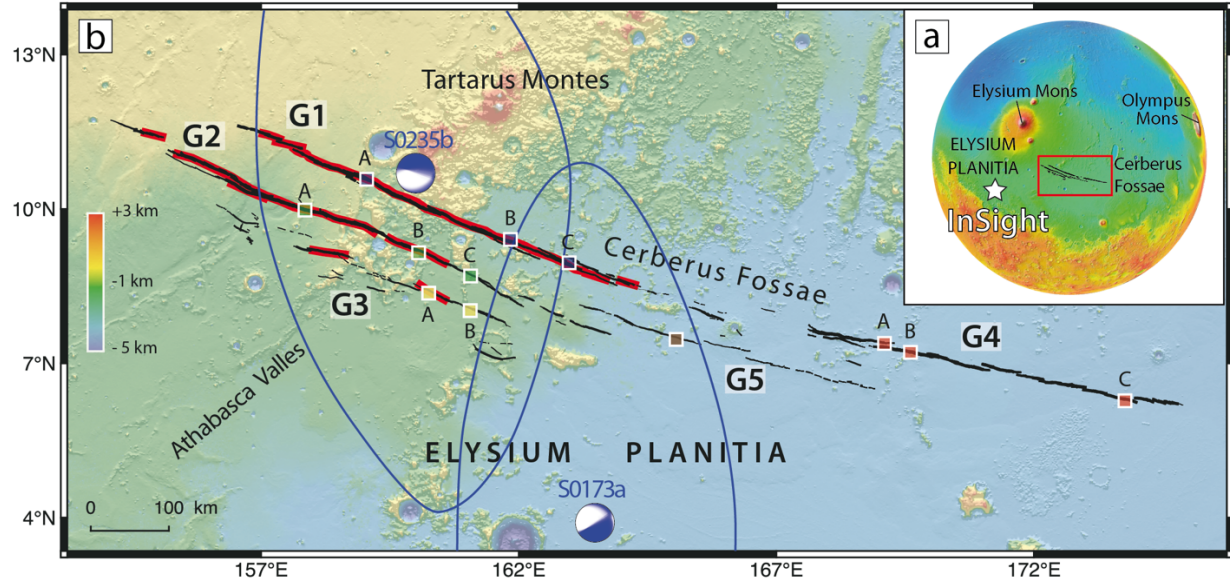
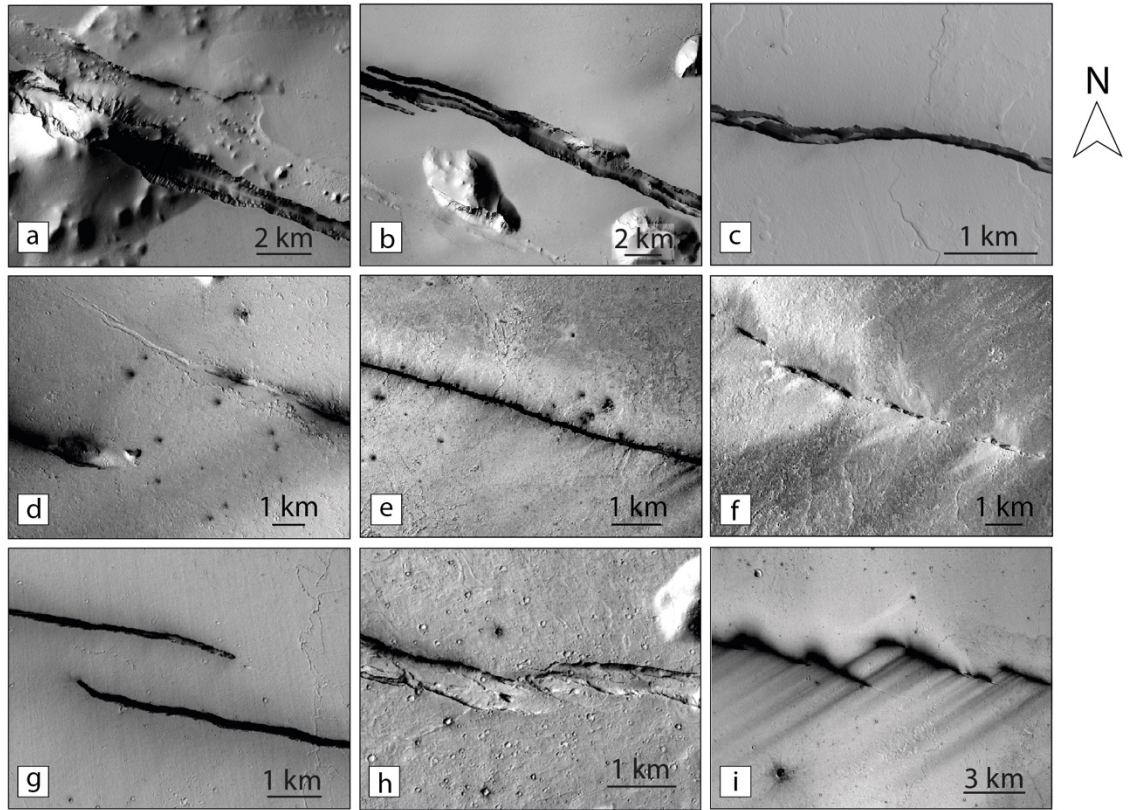


Figure 1: (a) Topographic map of Mars (MOLA; Smith et al., 2001). The InSight landing site is indicated by the white star. The area of interest is included in the red rectangle; (b) Tectonic fault map focusing on Cerberus Fossae. Red lines are low resolution surface traces mapped by Knapmeyer et al. (2006). Black lines are surface traces from this study. Colored rectangles on each fossa point out HiRISE stereo pairs images used in this study (Fig. 5). G1 to G5 indicate the five major sub-parallel fossae (modified from Taylor et al., 2013). The blue ellipsoids and focal mechanisms of events S0173a and S0235b are modified from Giardini et al. (2020) and Brinkman et al. (2021), respectively.

Perrin et al., Figure 2



CTX images of the Cerberus Fossae surface traces, from clear and large fossae along (a, b) G1, and (c) G4, to (d) shallow, (e) narrow and (f) discontinuous traces along G3, G2 and G5, respectively; (g, h, i) Examples of relay zones between segments at different scales along G4.

Figure

Perrin et al., Fig 3

G4 fault segmentation

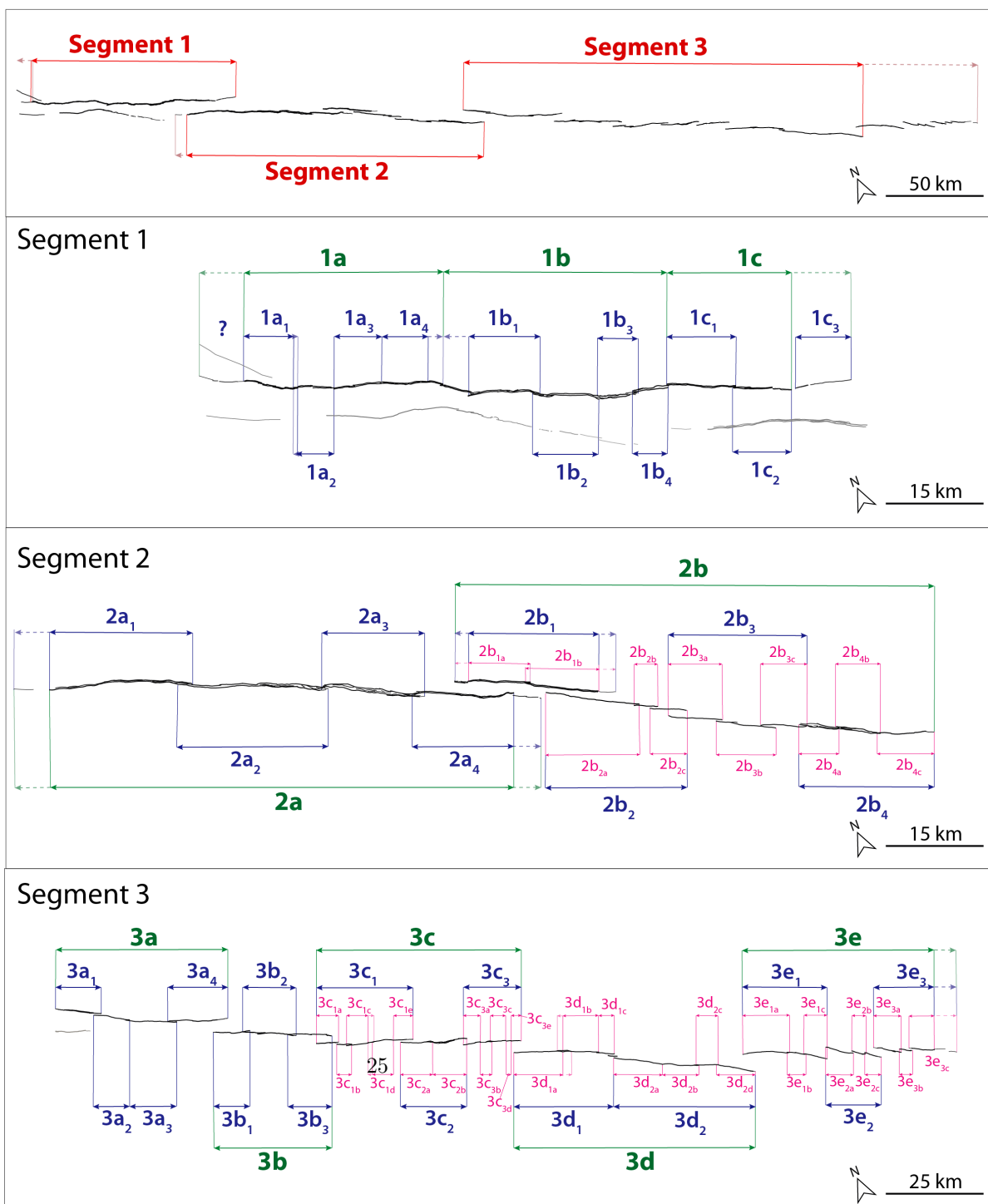
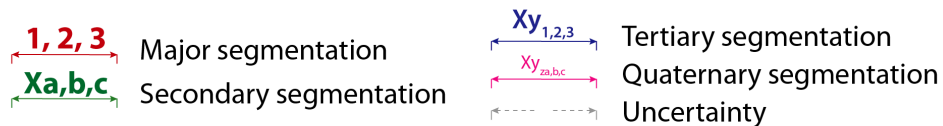


Figure 3: Representation of the four scales of segmentation analyzed in this study. Black lines are traces of fossa G4 of Cerberus Fossae in map view (see other fossae in Supp. Fig. S1). A closer view of the sub-segments in each major segment is shown. A detailed description of the segmentation is available in Supp. Text S1)

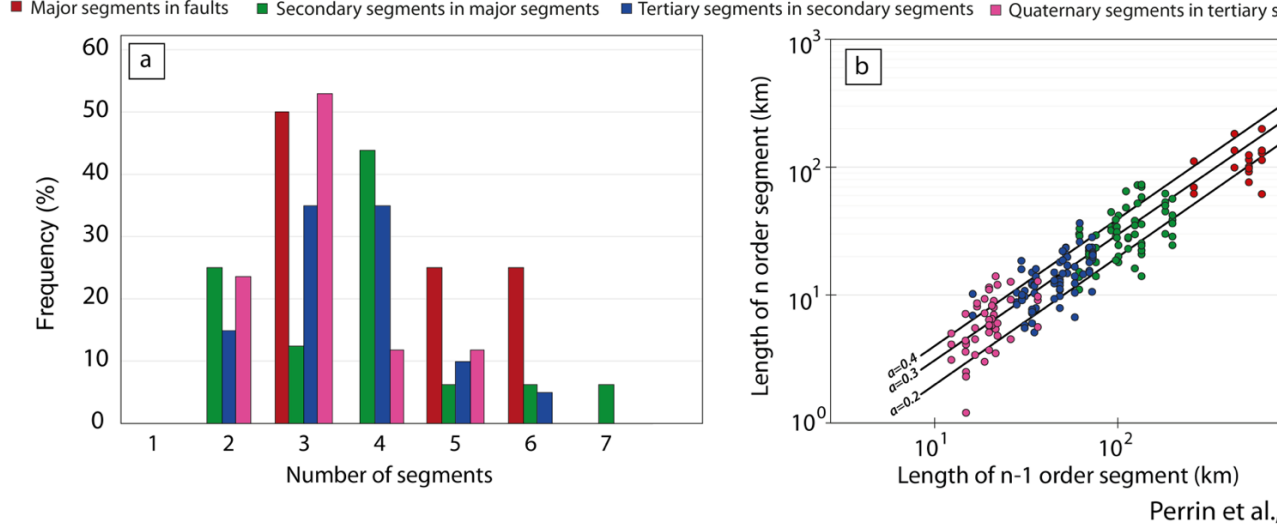


Figure 4: (a) Frequency distribution of the number of segments/sub-segments within faults/segments of the Cerberus Fossae fault system. (b) Relation between the length of each scale of segmentation. The black lines are the linear relations $LS_n = a * LS_{n-1}$ where a is a constant of proportionality ($a=0.2, 0.3$ and 0.4).

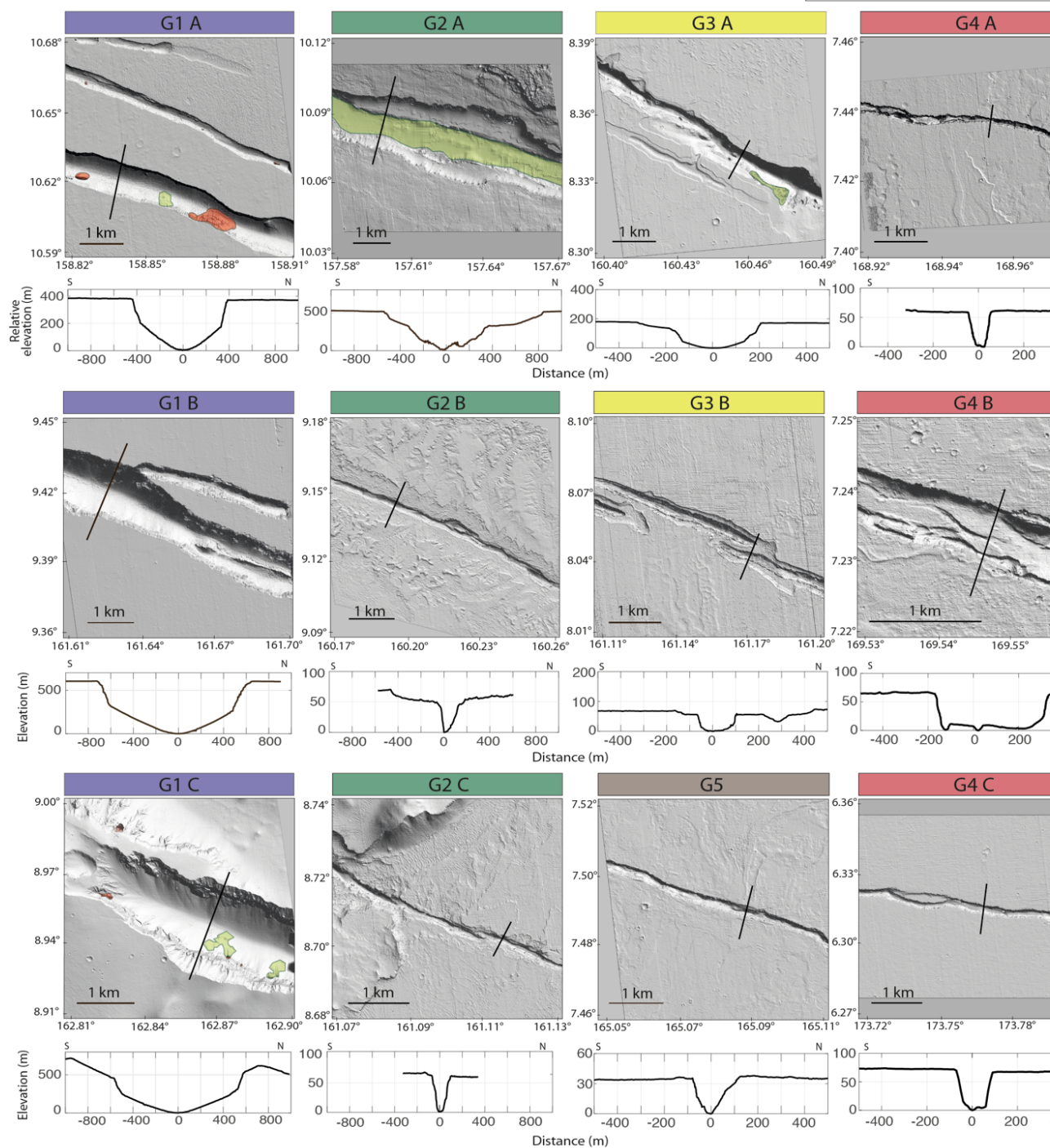
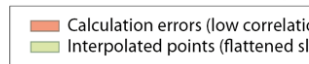
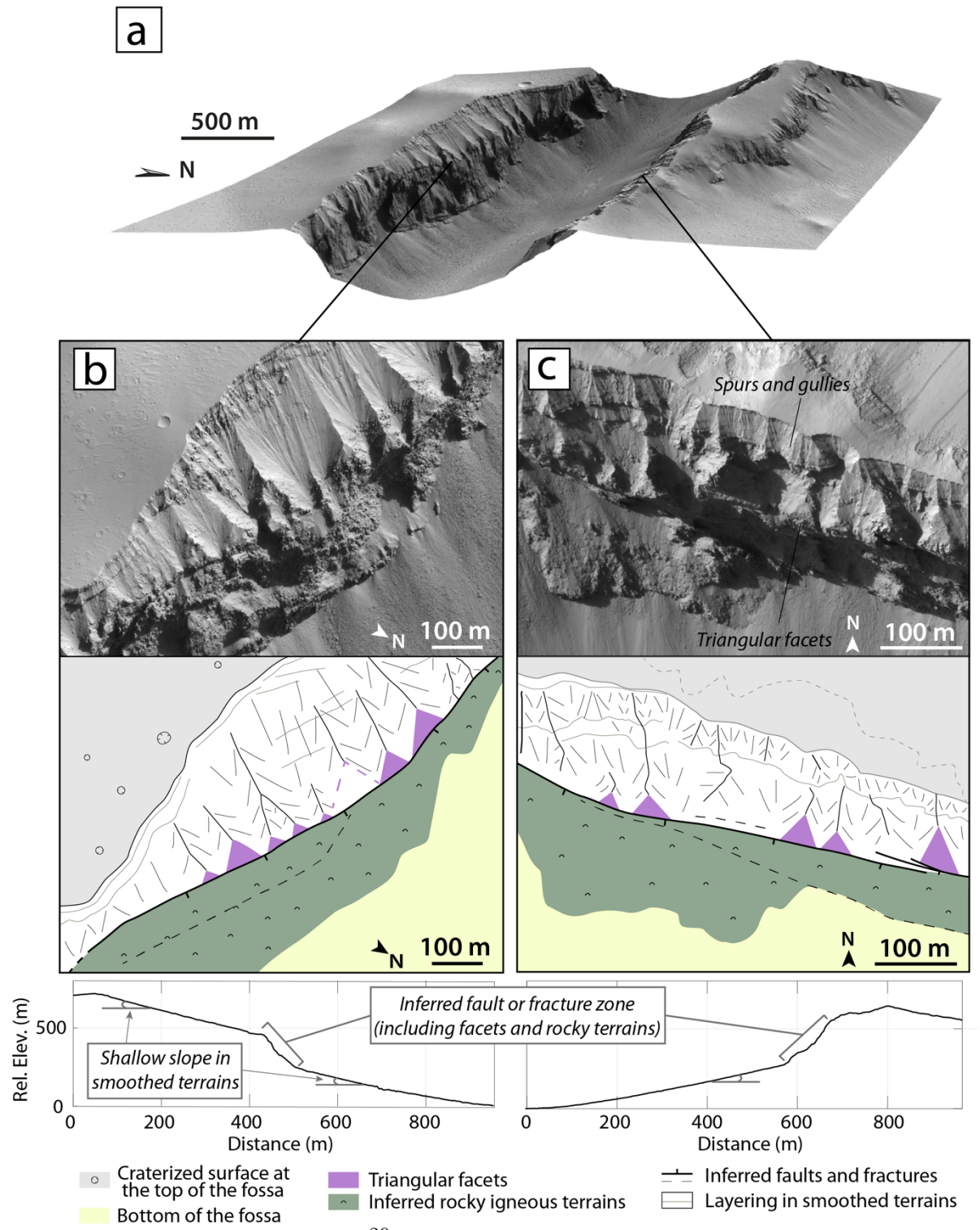


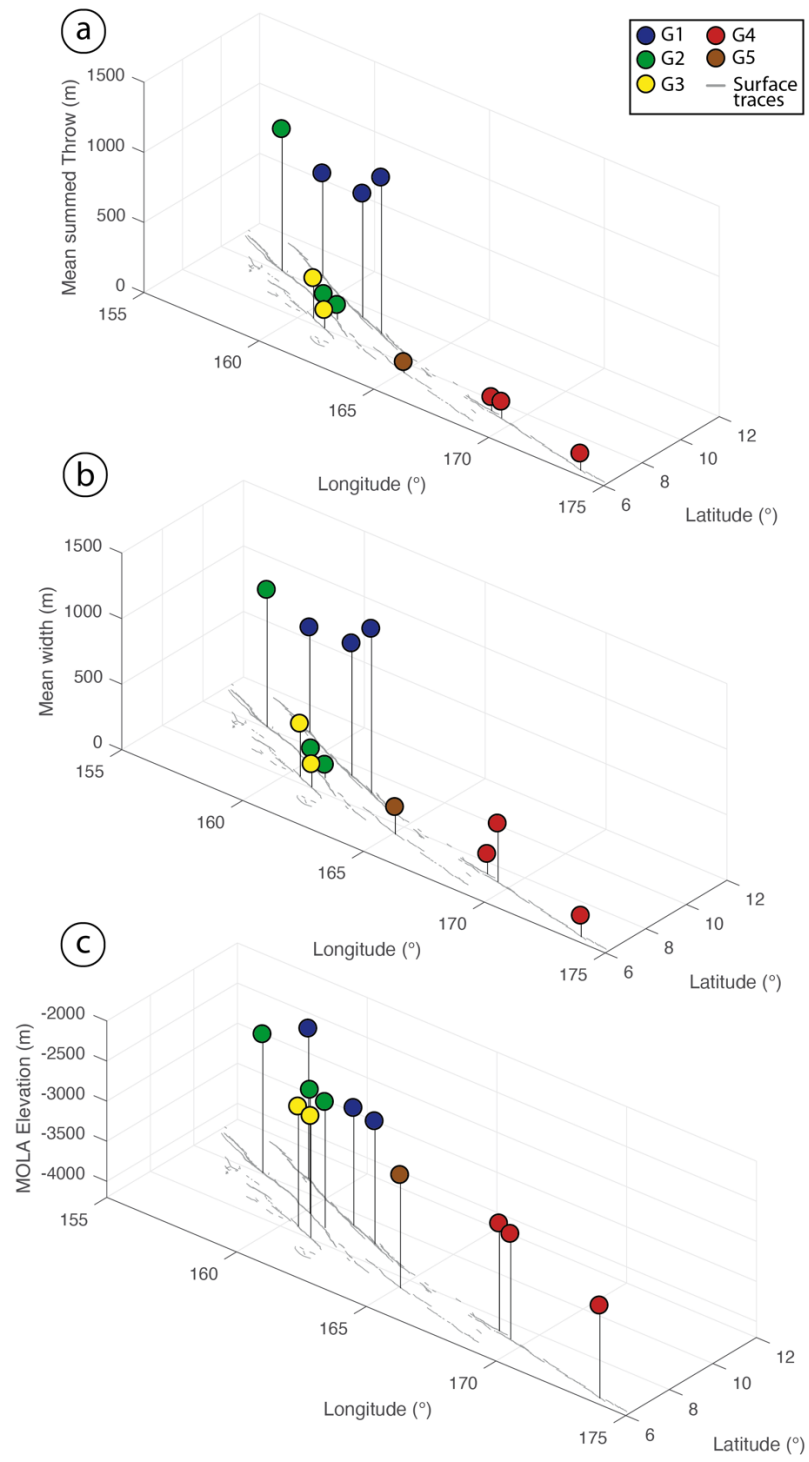
Figure 5: Digital Elevation Models (1m/pixel) built from HiRISE stereo pairs along the five main fossae (G1, G2, G3, G4 and G5) of Cerberus Fossae (see locations on Fig. 1). One across strike relative topographic profile is shown below each DEM (See Supp. Fig. S2 for all and mean profiles).



Perrin et al. ; Fig. 6

Figure

a) 3D view built from stereo pair HiRISE images (ESP_017719_1890; ESP_017218_1890) along G1 (see also G1A on Fig. 5). b) and c) are zooms along the edge of the fossa. Sketches highlight the triangular facets associated with the linear trends that we infer to be the main high-dipping fault traces, separating the green rocky materials (igneous and possibly brecciated rocks) from the white smoothed terrains (mix of ashes, igneous and sedimentary rocks). Note the difference between the morphology of the triangular facets and the spurs and gullies at the top of the fossae. Relative topographic profiles show the slope breaks associated with the interpreted sketches (see Supp. Fig. S2 for all profiles).



New Fig.7; Perrin et al.

Figure 7: Mean (a) summed throw and (b) width of fossae deduced from each calculated DEM (See Fig. 5 and Supp. Fig. S2) showing the general decrease from west and north (G1, G2) to east and south (G3, G4, G5). (c) Corresponding MOLA elevation. Grey lines are surface traces of Cerberus Fossae._

Perrin et al., Fig 8

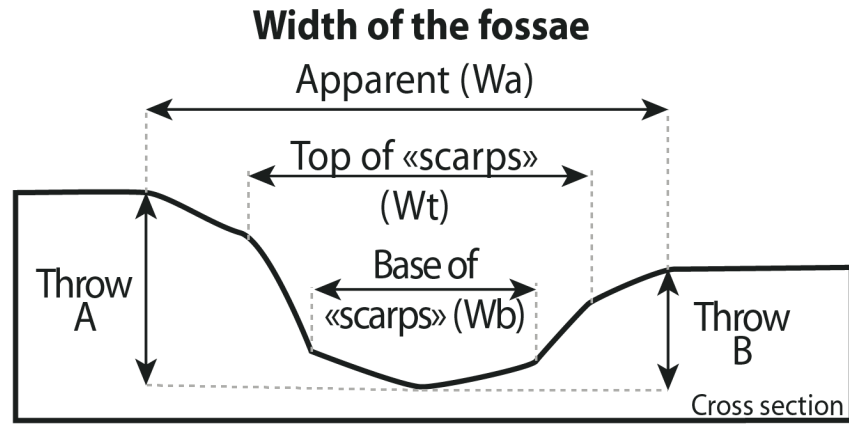


Figure 8: Schematic cross section of a fossa showing the different measurements performed in this study (see text for detail).

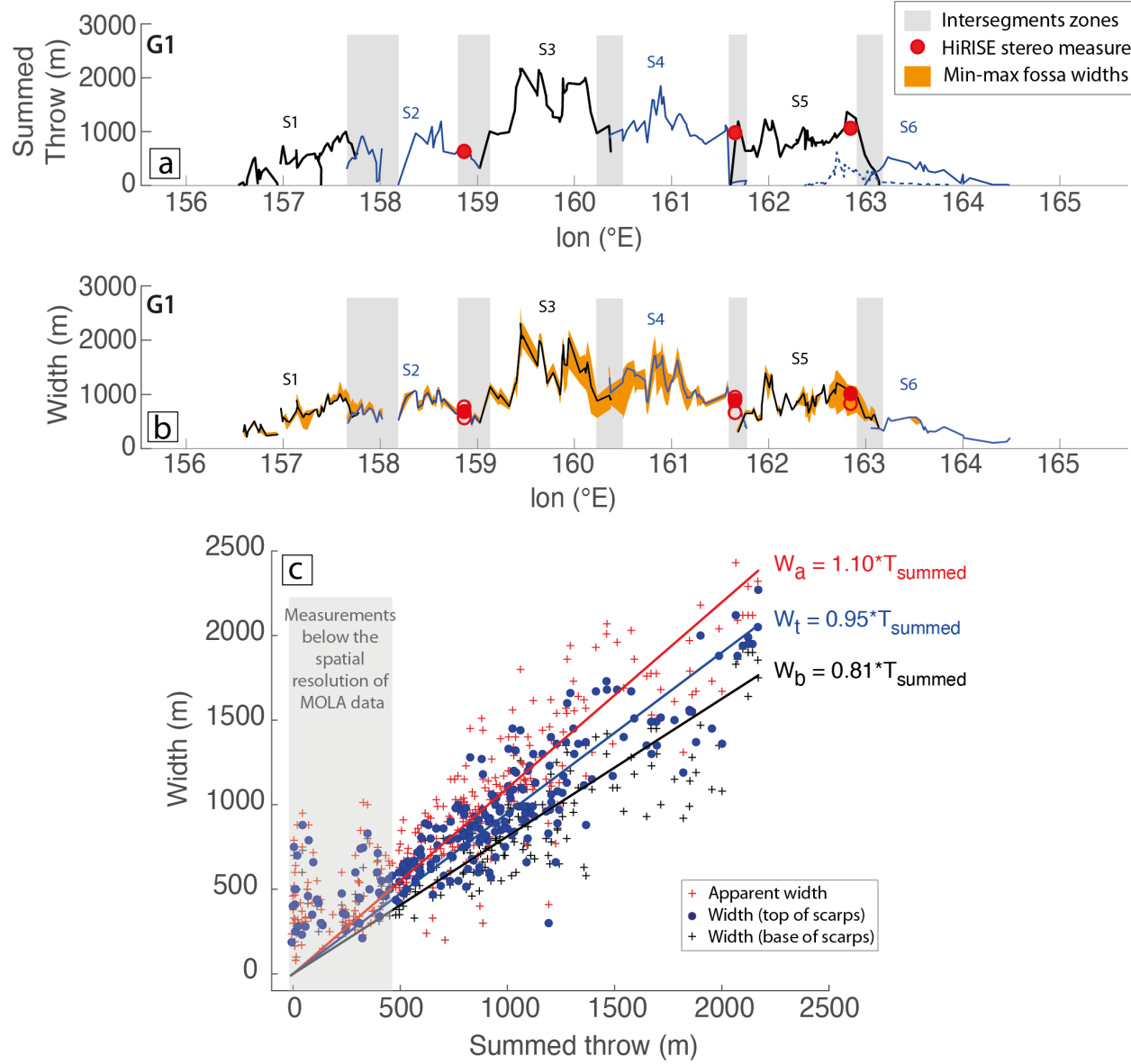
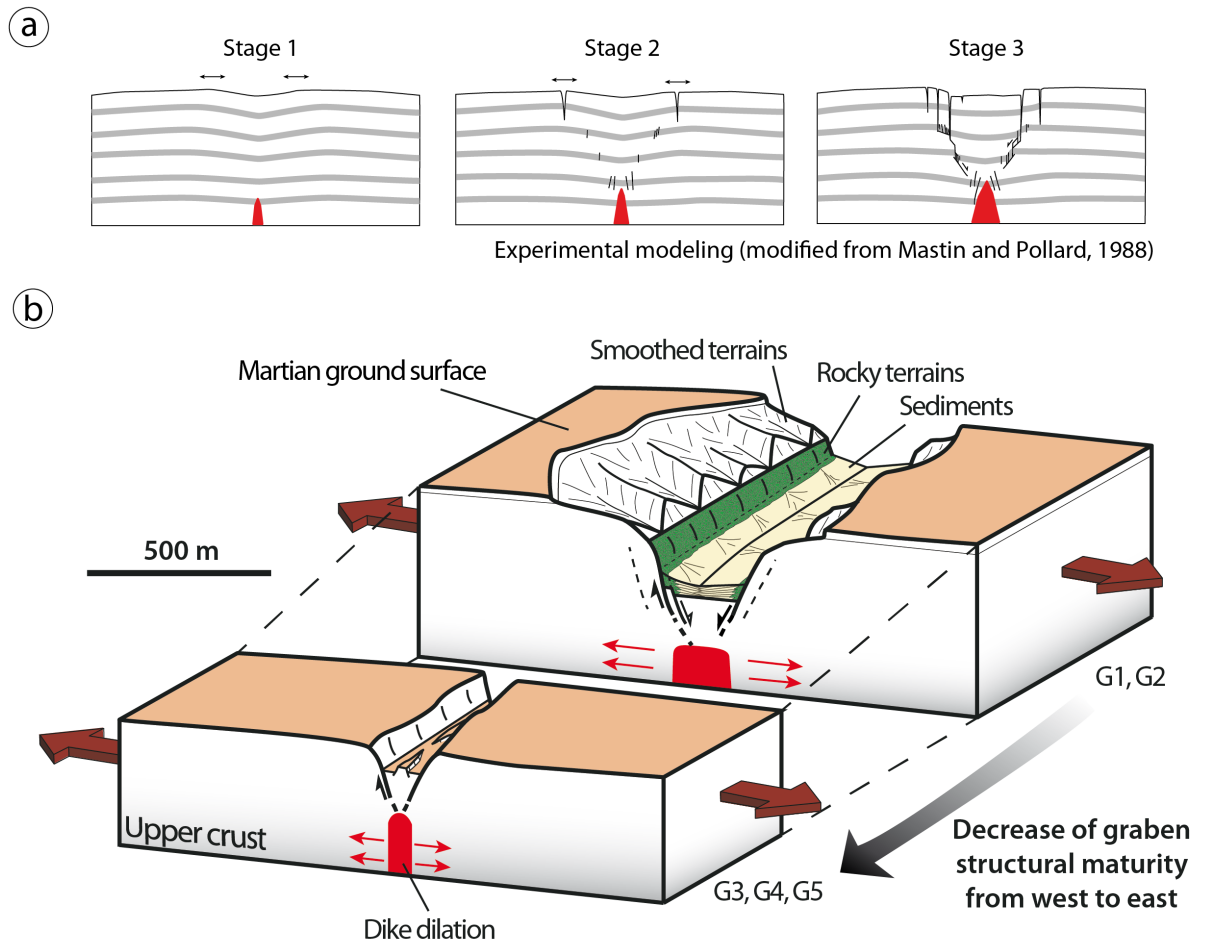


Figure 9: Along strike measurements of throw and width for fossa G1. a) Summed throw profile (MOLA data; Vetterlein and Roberts, 2010); b) Corresponding fossa widths (this study, CTX data). Solid lines are preferred fossa widths (W_t ; see text and Fig. 8) while orange area is determined from maximum (W_a) and minimum (W_b) width measurements (see Fig. 8). Solid red dots are

preferred width measurements made on DEMs built from HiRISE stereo pairs (Fig. 5), while empty red dots are minimum and maximum width measurements. Alternate blue and black profiles represent the major segmentation identified in this study. They are separated by inter-segment zones, highlighted by the grey rectangles (major slip trough, see also fault map on Supp. Fig. S1); c) Relations between the summed throw and the width of fossa G1. Blue dots are preferred fossa width values (W_t) and red and black crosses are maximum (W_a) and minimum (W_b) width values, respectively (see text and Fig. 8). The three colored lines describe the linear law for each dataset, and suggest that the fossa Width~Summed Throw (linear correlation coefficient $R=0.94$ for the preferred blue law, $R=0.95$ for the red law and $R=0.92$ for the black law). Note that the grey shaded area highlights the part of the plot where throw measurements are below the spatial resolution of MOLA data (i.e., 463 m/pixel). This explains why width measurements are possibly associated with possibly low underestimated throw measurements (see more details in the text).



Perrin et al. ; Figure 10

Figure 10: a) Early stages of the evolution of fault and fracture growth above a shallow dike (modified from Mastin and Pollard, 1988). The progressive linkage of steep fractures (stage 1 and 2) leads to the formation of normal dip slip (stage 3). b) Schematic representations and interpretations of the morphology and structure of Cerberus Fossae along its northwestern mature sections (G1, G2) and southeastern immature sections (G3, G4 and G5).