Chronology of Wrinkle Ridge Formation and Rate of Crustal Shortening on Lunae Planum, Mars

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European Geosciences Union General Assembly 2017

EGU Outstanding Student Poster & PICO Contest

ABSTRACT

The Lunae Planum, a plain between the Tharsis Montes and the Acidalia Planitia on Mars, represents a transitional zone from a volcanic rise to a lowland plain, respectively. From West to East at N20°, topography changes from 600 m to -750 m. Here, several wrinkle ridges that are compressional tectonic features formed by folding and thrust faulting, mark the surficial deformation of the martian crust. From the analysis of >25 wrinkle ridges in earlier studies a total shortening of ~1123 m and a compressive strain of 0.24% has been suggested for the Lunae Planum.

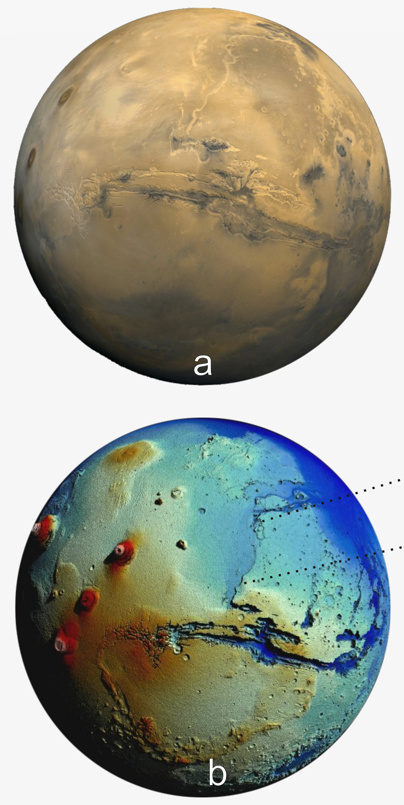
In this study we investigate the chronological order of geomorphic structures and determine the timing and duration of the crustal shortening of Lunae Planum. We use remote sensing mapping techniques and crater size-frequency distribution measurements (CSFD). In our analyses we use HRSC (12.5 m/pixel), CTX (6 m/pixel) and HiRISE (0.3 m/pixel) satellite images and digital terrain models to document geomorphic structures such as, wrinkles ridges, impact craters, crater ejecta blankets and intermontane plains. Our CSFD measurements of wrinkle ridges reveal an age distribution from ~3.9 Ga to ~3.0 Ga, with surfaces getting younger towards the East. Our findings are in accordance with earlier observations of greater shortening amounts towards the West (in older ridges). The age distribution of wrinkle ridges suggests a 9 Ma time interval for the proposed ~1123 m horizontal shortening at a deformation rate of $1.24 \pm 0.2 \times 10^{-7}$ mm/yr for compressional deformation on the Lunae Planum.

INTRODUCTION

The Lunae Planum basin is located at the north of Valles Marineris; a well studied rifting system of Mars. The plains covering the area between Tharsis Montes (volcanoes) in the west and Acidalia Planitia (oceanic plains) in the east are called Lunae Planum. The topography of this area descends from west to east, from 600 m to -750 m (Figure 2a). Wrinkle ridges are observed in the region which are assumed to formed by folding and thrust faulting during the development of the Tharsis rise (Golombek, 1991). Wrinkle ridges are linear, asymmetric morphologic features that are generally located in the plains on Mars and are considered to be of volcanic origin (Figure 4). Wrinkle ridges were first described by Golombek et al. (1991) and Watters and Robinson (1997) by using VIS-EDR and IRTM images collected by the Viking Orbiter. Currently Mars Reconnaissance Orbiter (MRO) and the Mars Orbiter Laser Altimeter (MOLA) datasets provide a significant higher resolution compared to Viking images.

The formation of wrinkles ridges is widely discussed and different mechanisms are suggested to explain their origin. Recent studies suggest that wrinkle ridges are secondary structures shaped under compressive stresses (e.g., Plescia and Golombek, 1986; Golombek et al., 1990; Sharpton and Head, 1988, Watters, 1988 a,b, 1990), while others consider the ridges to be lava intrusions within an extensional tectonic setting (e.g., Scott, 1989, Young et al. 1973, Hodges, 1973).

In this study we investigate the chronological order of wrinkle ridges and determine the timing and duration of the crustal shortening of Lunae Planum. The Lunae Planum has been mapped based on remote sensing techniques (Greeley and Guest, 1987). Wrinkle ridges, intermontane plains, craters, crater ejectas and fossae morphologic units of Lunae Planum has been analysed and mapped with HRSC and CTX satellite images (MRO). On the other hand, Crater-size frequency distribution method has been applied to the wrinkle ridge ages. Crustal shortening has been calculated by measuring parameters such as elevation offset, width and total relief of wrinkle ridges. A total of 88 topographic profiles were taken along the ridges from high resolution MOLA (256 ppd) digital terrain models.



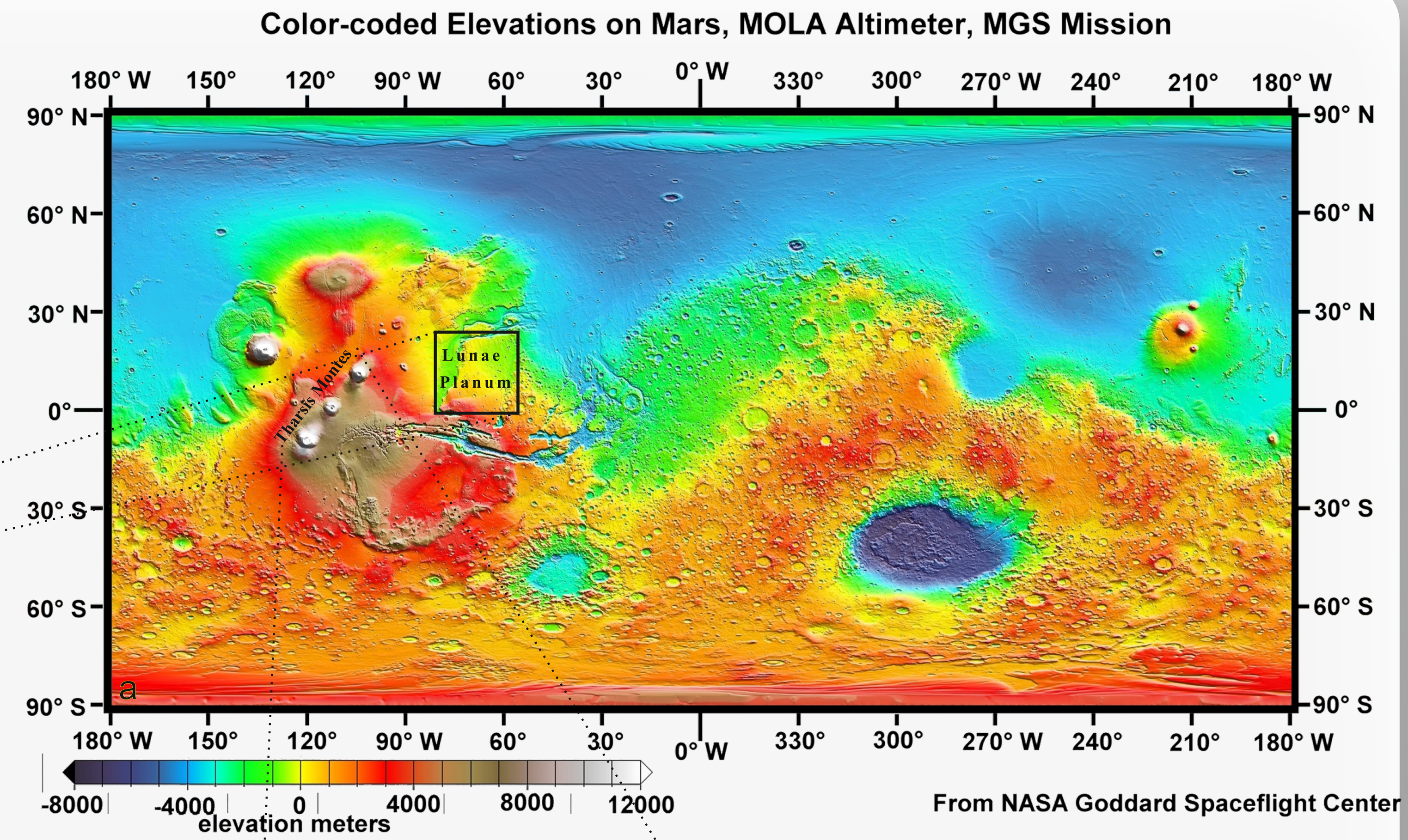


Figure 1. a) On the natural colour satellite image the Lunae Planum is slightly indistinguishable flat topography lying at the Northern hemisphere of Mars. b) The plain is distinct on the digital elevation model of the planet and is located east to the highest mountains of the planet (Tharsis Montes).

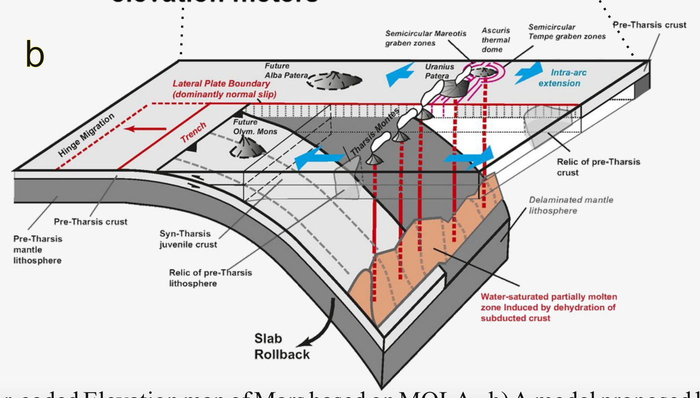


Figure 2. a) Color-coded Elevation map of Mars based on MOLA. b) A model proposed by Yin 2012, showing the spatial relationship of the Tharsis rise and associated subduction.

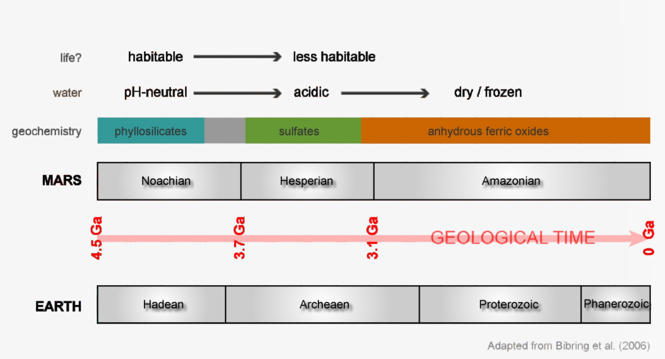


Figure 3. The geological time scale of Mars. Adapted from Bibring et al. 2006.

METHODOLOGY

Our analysis is based on determining the amount of total shortening and calculating an absolute age for wrinkle ridges based on the crater-size frequency distribution. More than 12 ridges on the Lunae Planum were investigated in detail, taking 88 topographic profiles (Figure 6). We calculate the shortening after Plescia (1991), by measuring the elevation offset, width and total relief of wrinkle ridges. The width corresponds to the distance of the two lowest points across the wrinkle ridge, where the slope angles reach minimum; the limit between wrinkle ridge limb and intermontane plain (Figure 5). The total relief is measured by taking the difference between the elevation of the lowest flat and the highest point of the ridge. The elevation difference between the two plains across the ridge corresponds to the elevation offset value (Figure 5).

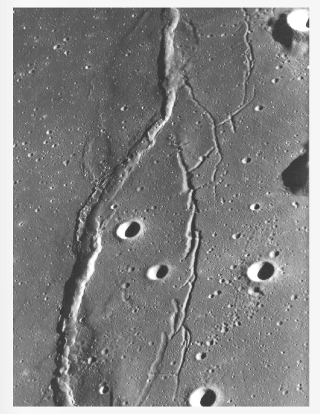


Figure 4. The wrinkle ridges of Lunae Planum. NASA/USGS - ESA/DLR/FU Berlin (G.Neukum)

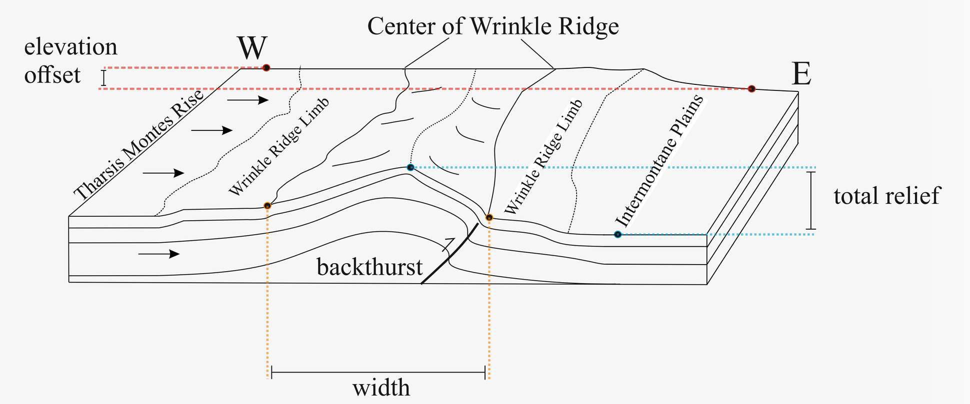


Figure 5. The schematic representation of the modeling parameters used to calculate the amount of shortening on the wrinkle ridges.

According to Plescia (1991) the total shortening is the sum of the faulting shortening and folding shortening. Accordingly the faulting shortening can be expressed as:

$$S_{fa} = E_o / \tan(25)$$

where (a) is the dip of the fault and Eo is the elevation offset. (The dip of the fault is unobserved. Golombek (1991) suggests that folding is accompanied with low-angle reverse faulting and reverse faults are considered to have a dip angle of 25 degrees on the average.)

The folding shortening can be expressed as:

$$S_{fo} = S_i - S_d$$

Where Si is the integrated length across the ridge surface and Sd is the horizontal point to point straight line distance across the ridge.

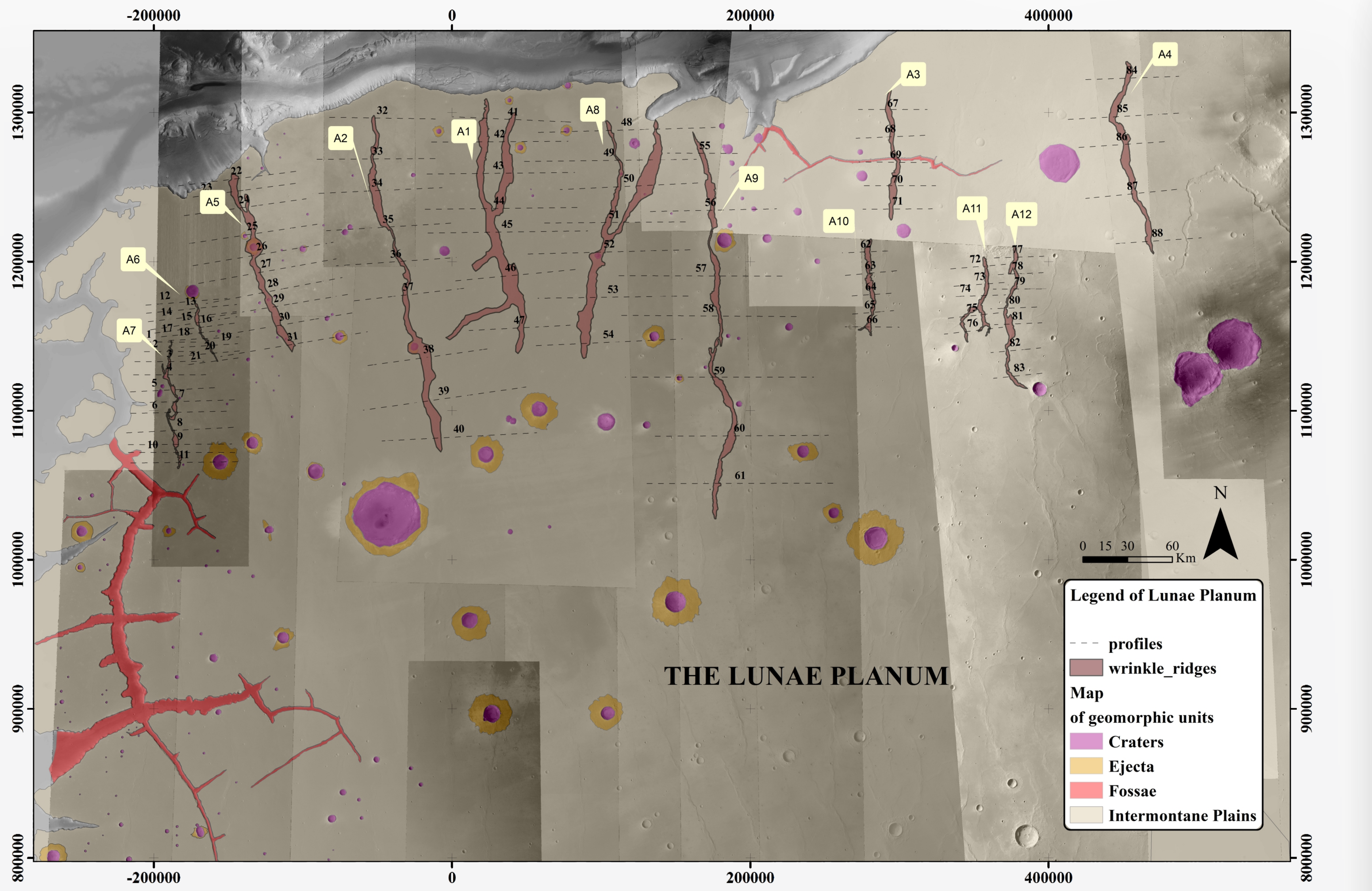


Figure 6. The north-south oriented wrinkle ridges on the Luane Planum, have a width of up to 10 km and a length of at least 50 km reaching up to 200 km. The ridges are asymmetric and have an average distance of 50 km from each other. The main volcanic rock forming wrinkle ridges is basalt. We classified 12 wrinkle ridges and collected 88 topographic profiles to evaluate the crustal shortening of the study area

Wrinkle ridges on the Luane Planum, have a width of up to 10 km and a length of at least 50 km reaching up to 200 km. The ridges are oriented in north-south direction, are asymmetric in E-W profiles and have an average distance of 50 km. Their eastern limbs form steeper scarps related to faulting. Lithologically, previous studies on this region suggest that the main volcanic rock forming wrinkle ridges is basalt. In addition, ongoing geological processes such as Aeolian and crater impactions erode the wrinkle ridges.

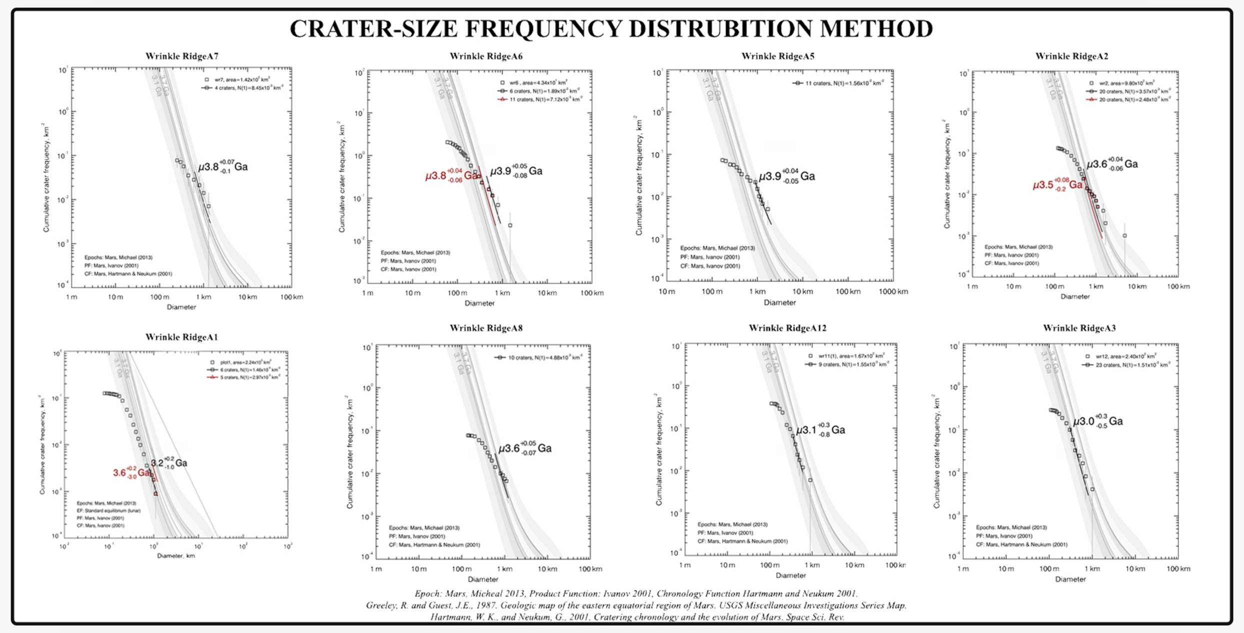


Figure 7. The crater-size frequency distribution method suggested ages ranging from 3.9 Ga to 3.0 Ga. We observe that ridges are younger at the east and older on the west close to the Tharsis Montes.

The age constrain of wrinkle ridges have been calculated by using crater impactions The measurement of crater size-frequency distributions (CSFDs) is a commonly used method to date surfaces of terrestrial planetary bodies. Neukum and Ivanov (1994) suggested that by using the radiometric dating of lunar rock samples (meteorites) and settings of meteor impactions possible to apply CSFDs with a production function results obtained with different epochs (eg. Hartmann, Michael), we can estimate the age of the surface (absolute model age, AMA). Here we report the results of several counts performed on wrinkle ridges of Lunae Planum, Mars (Figure 7).

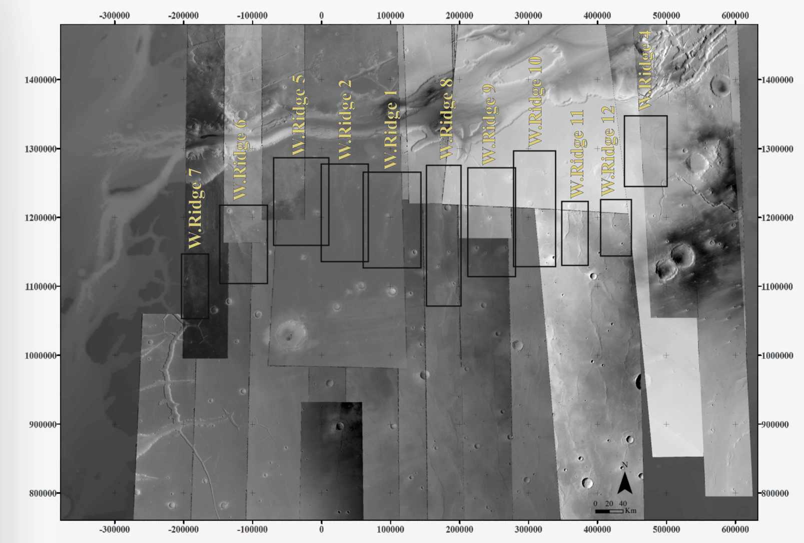


Figure 8. 22 High Resolution Spectrometric Camera (HRSC) images have been used in order to map the wrinkle ridges given in the black boxes.

Image ID	W.Rrige 7	W.Rrige 6	W.Rrige 5	W.Rrige 2	W.Rrige 1	W.Rrige 8	W.Rrige 9	W.Rrige 10	W.Rrige 3	W.Rrige 11	W.Rrige 12	W.Rrige 4
H5221_0000.ND3.JP2												X
H5203_0001.ND3.JP2											X	X
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H1158_0000_ND3.JP2				X								
H1169_0001_ND3.JP2			X									
H1180_0000_ND3.JP2	X	X										
H1429_0000_ND3.JP2						X						
H1612_0000_ND3.JP2												X
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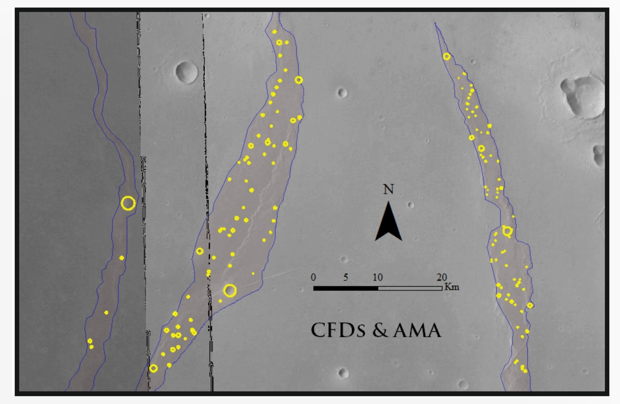
Table 1. List of High Resolution Spectrometric Camera (HRSC) images used in mapping the ridges and calculate the size of craters.



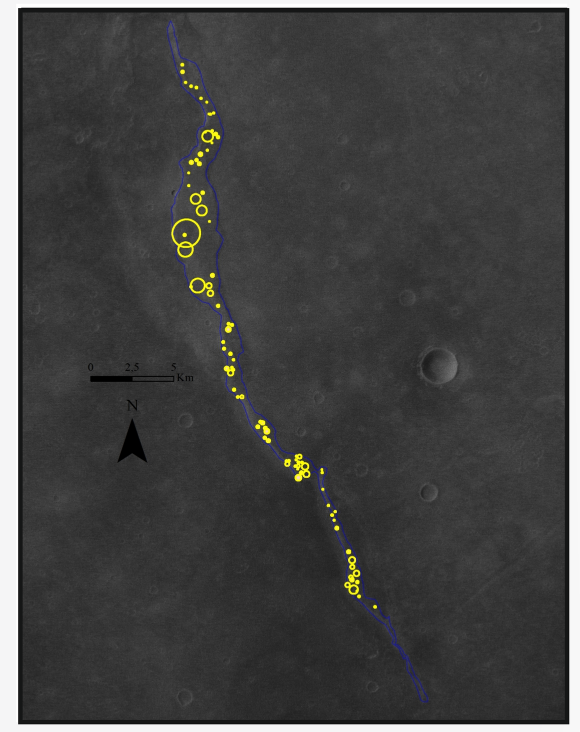


Figure 9. Approximately 200 amount of craters have been counted to obtain an age for each wrinkle ridge.

RESULTS

The previous studies suggested a shortening ratio of 0.29% for the wrinkle ridges at Lunae Planum using Viking images (Golombek and Plescia 1991). They calculate total shortening due to faulting as approximately 1712 m and the shortening due to total folding as 128 m. However, they also underline that other models of internal structure would produce different estimates of shortening and strain. Steeper faults would decrease faulting shortening; shallower faults would increase it.

In this study, we calculate the total shortening as 1123 m (faulting shortening is 1105 m; folding shortening is 18 m). This shortening corresponds to a net compressive strain of 0.24% (0.23% faulting strain; 0.01% folding strain). Consequently, crater-size frequency distribution measurements of wrinkle ridges reveal an age distribution from ~3.9 Ga to ~3.0 Ga (Late Noachian to Late Hasperian) (Figure 7). Our findings are in accordance with earlier observations (e.g., Plescia and Golombek, 1986; Golombek et el., 1990; Plescia, 1991; Sharpton and Head, 1988; Watters, 1988 a,b, 1990) of greater shortening amounts towards the West (in older ridges). The age distribution of wrinkle ridges suggests a 9 Ma time interval for the proposed ~1123 m horizontal shortening at a deformation rate of $1.24 \pm 0.2 \times 10^{-7}$ mm/yr for compressional deformation on the Lunae Planum. (Table 2.)

Table 2. The result of the shortening rate on wrinkle ridges in terms of faulting and folding with their crater-size frequency distribution absolute ages.

W.Ridge Profile Numb.	Samp. Number	Ridge Location	Total Relief (m)	Width(km)	Si (km)	Offset (m)	Shortening Fold (m)	Shortening Fault (m)	Absolute Age (Ga)
11	A7	71.3°	77.81	7.92	9.18	34.10	1.38	80.46	3.8 ± 0.07
10	A6	70.8°	124.79	11.44	12.10	26.12	0.66	56.02	3.9 ± 0.05
10	A5	69.9°	153.92	12.87	14.25	38.15	1.39	81.82	3.9 ± 0.04
9	A2	68.9°	165.42	10.55	12.26	31.76	1.83	74.83	3.6 ± 0.04
7	A1	67.2°	142.71	21.84	23.84	90.21	2	193.45	3.6 ± 0.02
7	A8	66.1°	132.07	15.85	17.92	52.85	2.07	113.33	3.6 ± 0.05
7	A9	64.8°	170.36	18.44	21.42	39.29	2.98	84.25	3.5 ± 0.09
5	A10	62.9°	64.64	6.98	7.96	32.26	0.98	69.18	3.4 ± 0.3
5	A3	62.6°	93.40	12.74	14.31	31.24	1.57	66.99	3.3 ± 0.2
5	A11	61.5°	102.92	8.91	10.32	30.62	1.41	65.66	3.1 ± 0.5
7	A12	61.1°	123.24	10.73	11.53	53.14	0.81	113.97	3.0 ± 0.4
5	A4	59.7°	152.868	12.182	14.03	49.158	1.85	105.42	3.0 ± 0.2

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