AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL065017

Key Points:

- Present 3-D reconstructions of a stratigraphic sequence of Martian volcanic flows
- Provide constraints on the erosional history of the enigmatic Medusae Fossae Formation
- Derive a new value of the permittivity of the Medusae Fossae Formation

Supporting Information:

- Supporting Information S1

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Citation:
Morgan, G. A., B. A. Campbell, L. M. Carter, and J. J. Plaut (2015), Evidence for the episodic erosion of the Medusae Fossae Formation preserved within the youngest volcanic province on Mars, *Geophys. Res. Lett.*, *42*, 7336–7342, doi:10.1002/2015GL065017.

Received 22 JUN 2015
Accepted 20 AUG 2015
Accepted article online 24 AUG 2015
Published online 30 SEP 2015

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Evidence for the episodic erosion of the Medusae Fossae Formation preserved within the youngest volcanic province on Mars

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Abstract We use orbital SHAllow RADar (SHARAD) sounder data to three-dimensionally visualize the subsurface structure of Elysium Planitia, the youngest volcanic province on Mars. Our results reveal an emplacement history consisting of multiple groups of overlapping lava flow units, originating from different sources. The uniquely complex "radar stratigraphy" of Elysium Planitia, relative to other volcanic regions, requires a distinct mechanism to generate the numerous reflectors observed in SHARAD data. Sedimentary deposits interbedded with successive batches of lava flows could account for the elaborate pattern of reflectors. We infer that widespread, rapidly emplaced material sourced from the enigmatic Medusae Fossae Formation (MFF) creates these sedimentary layers. This implies that episodes of atmospheric activity, perhaps linked with the obliquity of Mars, periodically erode and redeposit material from the MFF across a large region.

1. Introduction

Elysium Planitia (see Figure 1) is the youngest volcanic plain on Mars. Recent crater counts on individual lava units argue for multiple phases of activity over the last 230 Myr, with the most recent volcanic features dating to just ~2 Ma [*Vaucher et al.*, 2009]. The surface displays a complex history involving geologically recent fluvial [*Berman and Hartmann*, 2002; *Burr et al.*, 2002; *Plescia*, 2003; *Morgan et al.*, 2013], tectonic [e.g., *Head et al.*, 2003], and aeolian [*Kerber and Head*, 2010] activity in addition to the burial of preexisting Noachian/Hesperian crust by $>$100 m thicknesses of basaltic flows [*Vaucher et al.*, 2009]. To the south is situated the Medusae Fossae Formation (MFF), consisting of mountainous sedimentary deposits ($>$3 km of relief). Elysium Planitia has thus acted as a natural repository of geologic materials, offering a rare insight to processes operating throughout the Amazonian epoch, a period of Martian history otherwise considered cold and dry [e.g., *Bibring et al.*, 2006].

The study of Elysium Planitia from orbit has largely been restricted to investigations of the surface [*Berman and Hartmann*, 2002; *Burr et al.*, 2002; *Plescia*, 2003; *Jaeger et al.*, 2010] with the most recent eruptions obscuring the previous geologic history. However, on Earth, such extrusive volcanism has been shown to also preserve preexisting features such as the dune forms of the Cretaceous erg fossilized by the Paranã-Etendeka flood basalts in Namibia and Brazil [see *Jerram et al.*, 2000; *Scherer*, 2002].

Here with data collected by the SHAllow RADar (SHARAD) on the Mars Reconnaissance Orbiter, we are able to exploit the preservation potential of the Elysium lavas and penetrate over 100 m into the subsurface to visualize the underlying structure. After 9 years of SHARAD operations and data analysis, Elysium Planitia is unique in being the only volcanic province where areally extensive, multilayered subsurface structures can be identified [*Morgan et al.*, 2013]. In this study we three-dimensionally characterize central Elysium volcanic units in the region of deepest SHARAD penetration and then explore mechanisms responsible for generating the distinct pattern of subsurface reflectors.

2. Data Set and Methodology

The SHARAD sounder transmits a 10 MHz bandwidth signal centered on 20 MHz frequency, providing a range (vertical) resolution of 5–10 m in most silicate geologic substrates. The along-track resolution achieved through Doppler processing is 300–500 m [see *Seu et al.*, 2004]. SHARAD data are presented as radargrams (Figure 2),

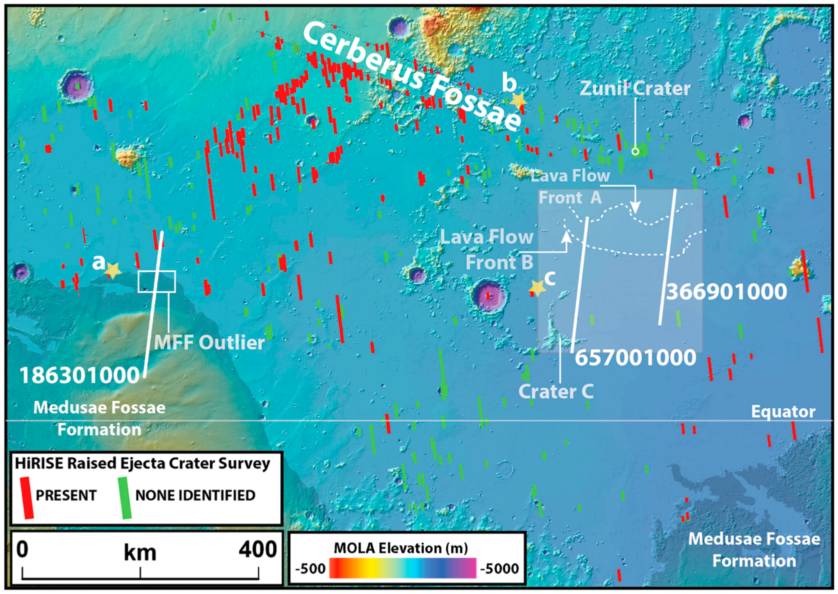

Figure 1. Elysium Planitia highlighting the central study region and the results of our survey of HiRISE images that contain craters with raised ejecta. The three white lines represent the SHARAD tracks displayed in Figure 2 and the three stars mark the locations of images in Figure 4. The background is MOLA gridded data. Highlighted MFF units are derived from mapping presented in *Vaucher et al*. [2009].

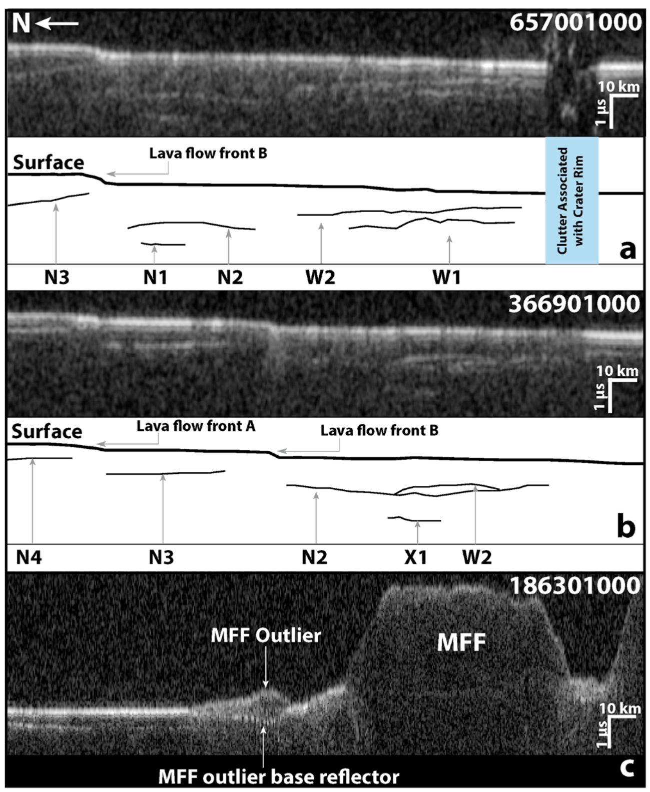

Figure 2. Examples of radargrams with corresponding sketch maps highlighting (a and b) the seven identified reflector groups in central Elysium and (c) the reflector below the reworked MFF outliner used to estimate the dielectric constant of the overlying material. The presence of reworked MFF on top of young Elysium flows demonstrates that processes have operated to transport MFF material across the region.

displaying round-trip delay time on the vertical axis and along-track distance on the horizontal axis. SHARAD coverage of central Elysium consists of 83 orbits, all of which contain evidence of at least one subsurface reflector. The majority reveal multiple, tens to hundreds of kilometers long reflectors at different depths, suggesting a complex subsurface structure (Figures 2a and 2b).

Applying the techniques of *Morgan et al*. [2013], every subsurface reflector identified in the radargrams was individually traced, and the associated time delay relative to the overlying surface return was recorded. The latitude and longitude values for each point along the subsurface reflectors were extracted to derive a shapefile using the Mars_2000 geographic projection. The results of this mapping were then analyzed within a geographic information system environment. Due to the high density of SHARAD coverage in Elysium Planitia (Figure S1 in the supporting information), allowing continuous reflectors to be identified in adjacent tracks, interpolation routines were applied to three-dimensionally map the subsurface horizons (see Figure 3).

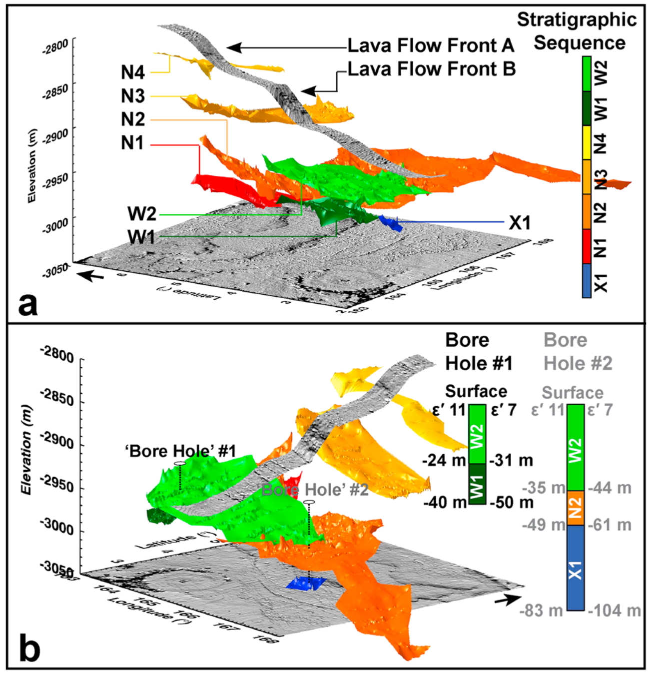

Figure 3. Three-dimensional reconstruction of the seven reflector surfaces present in central Elysium Planitia. (a and b) The same area from two different perspectives. Figure 3a includes a stratigraphic sequence of unit emplacement. Figure 3b shows two synthetic "boreholes" demonstrating the thickness estimates of different lava flows. Note that the grey strip is a 0.5° longitudinal strip of MOLA gridded data. Figure 3b shows a MOLA hillshade image for context. Reflector depth calculated using an ε' of 7. Black arrows point north.

3. Observations

Through our analysis, we have established that the reflectors identified in the radargrams can be attributed to seven subsurface interfaces in central Elysium, consisting of a western stratigraphic sequence, a northern stratigraphic sequence, and a single interface, denoted W1–W2, N1–N4, and X1, respectively (Figures 2 and 3). Reflector interfaces N3 and N4 end abruptly at the termini of lava flow units denoted A and B and likely represent the base of these flows (Figures 1, 2b, and 3). The bases of individual lava flows have also been observed in SHARAD data for eastern Elysium Planitia [*Morgan et al*., 2013] and west of Ascraeus Mons [*Carter et al*., 2009a]. Based on the similar radar behaviors and plan form morphology, we interpret the deeper reflector interfaces to also represent the base of lava flow units and thus delineate a stratigraphic sequence composed of either individual large flows or (more likely) flow fields.

Deriving thickness (h) estimates of the flow units from the round-trip delay time (Δt) of the reflectors is contingent on knowledge of the permittivity (ε') of the overlying material:

$$h = \frac{\Delta t \ c}{2\sqrt{\varepsilon'}} \tag{1}$$

where c is the speed of light in vacuum. Measurements of dry, dense terrestrial basaltic flows show a range in ε' from 7 to 11 [*Ulaby et al*., 1988; *Campbell and Ulrichs*, 1969], and bulk estimates for lava flows on Mars are in good agreement with these values [*Carter et al*., 2009a]. The thickness of the subsurface flows range from 16 to 50 m depending on the assumed ε' value (Figure 3b), and the average thickness is consistent with that of Mars Orbital Laser Altimeter (MOLA) measurements we have made of surface flows at ~ 30 m.

Subtracting the converted depth values of the reflector surfaces from the MOLA gridded data provides a clear view of the subsurface structure relative to the surface topography, enabling a full 3-D reconstruction of the flow stratigraphy (Figure 3). As the reflectors represent paleosurfaces over which subsequent lava flowed, we can infer the origin of the flows from the interfaces in the 3-D reconstruction. This reveals two separate vertical sequences of reflectors, with potentially common sources: one originating from the north composed of four reflectors (N1–N4, Figures 2 and 3) and the other from the west consisting of two reflectors (W1 and W2).

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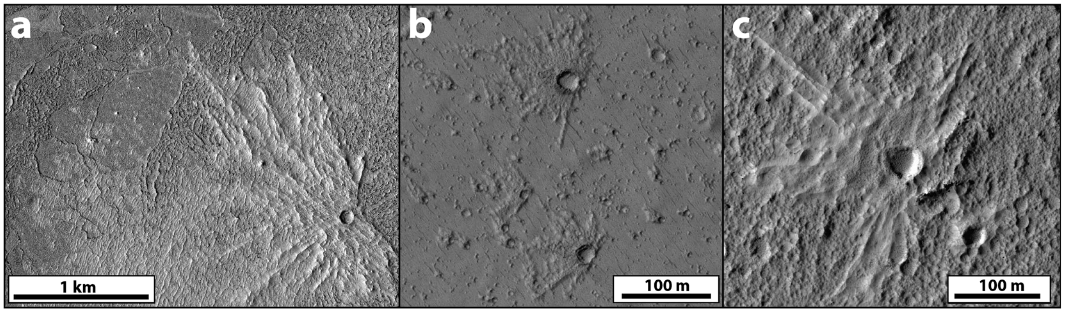

Figure 4. HiRISE examples of craters with raised ejecta. (a) Pedestal crater within MFF material overlying young west Elysium Planitia lavas. HiRISE image: ESP_017218_1890. (b) Examples of raised-ejecta craters 400 km north of Figure 4a. HiRISE image: PSP_002358_1840. (c) Raised-ejecta crater within central Elysium. HiRISE image: ESP_019209_1835.

The largest unit (N2) covers about one fifth of the areal extent of the youngest surface flow unit (2.5×10^5 km^2) mapped by *Jaeger et al*. [2010], indicating a wide range in areal extent for the Elysium flow complexes. The west group completely occupies and extends to the east of an 80 km diameter crater (crater c, Figure 1), representing the final phases of lava to fill the basin. The deepest reflector (X1, Figure 3) is more spatially limited, and it is not possible to constrain its origin. However, the maximum depth estimate of 104 m for reflector X1 is in good agreement with the minimum mean thickness estimate for the Amazonian lavas that flooded the central Elysium basin [*Vaucher et al*., 2009]. X1 may therefore represent the top of the underlying Hesperian/Noachian basement.

The order of emplacement of flow units that originate from the same direction, if not the same volcanic source, can be derived from their relative positions within the vertical sequence (Figure 3). The eruptive history of Central Elysium Planitia can therefore be appreciated from the stratigraphic relationships between the different groups (Figure 3a). For example, the uppermost western flow (W2) overlies both the deeper flow (W1) and the most areally extensive of the northern reflector group (N2, Figure 3b), indicating that it is the youngest of these three reflectors. This is supported by crater statistics that estimate at least a 24 Myr difference between the surface of lava flow unit B and the surface directly above W2 [*Vaucher et al*., 2009].

4. Origin of the Radar Reflectors

The radar-reflecting horizons in Elysium Planitia require relatively significant, laterally extensive (hundreds of kilometers), and generally contiguous contrasts in dielectric permittivity. Such shifts could be achieved by compacted sediments interleaved within a stack of lava units or through density differences, such as vesicular cooling zones, between succeeding layers of lava. Due to the high temporal frequency ($<$20 Ma) of Elysium eruptions over the late Amazonian [*Vaucher et al*., 2009], regolith development through impact gardening may be negligible [*Hartmann et al*., 2001] and thus not a strong candidate for producing the SHARAD dielectric interfaces. If regolith horizons were responsible for the SHARAD reflections observed in Elysium, we would expect to find similar dielectric layering in many volcanic provinces of Mars. The fact that multiple subsurface horizons have thus far been mapped only in Elysium Planitia argues strongly for a "local" explanation of the dielectric changes.

Given the heterogeneous nature of lava flow surfaces within Elysium Planitia over equivalent scales to that of the reflectors (hundreds of kilometers), it appears implausible that porosity differences within a stack of lava could produce distinct and contiguous subsurface horizons. A slab-like or rubbly zone, which might have a permittivity contrast with dense flows, would also tend to scatter the incident radar signal over a wide range of angles rather than behave as a smooth interface. Here again, the lack of other SHARAD detections of extensive, multiple subsurface reflectors in volcanic regions suggests that a geologic mechanism unique to Elysium Planitia is responsible for the contrasts in dielectric permittivity.

To generate a dielectric contrast through a sedimentary layer requires an emplacement mechanism that is both extensive, covering the $>10^4$ km^2 surface area of the mapped reflector surfaces, and dynamic enough to occur between successive eruptive phases. Is there evidence for such a process to have occurred within Elysium Planitia? *Jaeger et al*. [2010] documented the occurrence of Zunil secondaries with raised, optically bright ejecta near Cerberus Fossae, on the surface of the youngest lava flow in Elysium Planitia (Figure 4).

The authors attributed this to the deposition of sediments that have since been eroded, with only those deposits shielded by ejecta blankets remaining. Along the northern boundary of the Medusae Fossae Formation (MFF), 350 km to the south, *Kerber and Head* [2010] noted pedestal craters (Figure 4) with a very similar appearance to those documented by *Jaeger et al*. [2010].

We propose that the sediments shielded by small crater ejecta described by both authors represent remnants of a much larger expanse of material that once covered the region. To investigate this, we surveyed all High Resolution Imaging Science Experiment (HiRISE) images of the youngest Elysium Planitia lavas between Cerberus Fossae and the MFF (Figure 1). HiRISE data represent the highest resolution images available of the surface of Mars (<1 m/pixel). We found that 54% of the 227 images surveyed contained raised-ejecta craters. HiRISE coverage is sparse over central Elysium (Figure 1), but four HiRISE and least one Mars Reconnaissance Orbiter Context Camera image (G04_019710_1836_XN_03N193W) contain an example of raised-ejecta craters (Figure 4).

Volcanic ash derived from the same eruptions that produced the lava flows, or dust transported by the Martian winds, could account for material in the ejecta blankets of these craters, which (based on the extent of our survey) cover an area of $>6 \times 10^5$ km^2. It would take at least 3.4 Myr to accumulate a 1 m thick blanket of material at current dust deposition rates <0.4 g/m^2/yr [*Aharonson et al*., 2003] assuming a Martian dust particle density consistent with basalt and a conservative porosity of 50%. The deposition of volcanic ash, in contrast, would be relatively instantaneous. As all of the young volcanic provinces are potential dust sinks [*Christensen*, 1986], and their eruptions might generate substantial ash, accumulations related to these two mechanisms should not be limited to Elysium Planitia.

The thick, extensive MFF deposits provide a potential source of friable sediments directly south of Elysium Planitia and may offer the local explanation for the unique radar interface sequence. Outcrops of reworked MFF material are distributed across Elysium [*Tanaka et al*., 2005], and *Kerber and Head* [2010] argued that raised-ejecta craters shield remnant MFF debris. Stratigraphic investigations show that the MFF has been extensively reworked since at least the Hesperian period [*Kerber and Head*, 2010; *Zimbelman and Scheidt*, 2012], with material stripped from the deposits since before the first eruptions of Elysium Planitia lavas [*Vaucher et al*., 2009; *Tanaka et al*., 2005]. There are several examples in which the MFF is both buried by and superimposes young lavas [*Kerber and Head*, 2010, Figures 8–10; *Keszthelyi et al*., 2010, Figure 8] consistent with at least confined occurrences of MFF material between successive flows.

Some sense of the nature of these reworked outliers of MFF material can be obtained using radar sounding data to measure their bulk dielectric permittivity where the interface with underlying plains can be discerned. *Watters et al*. [2007] first achieved this by using Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS) data. SHARAD radargrams have finer vertical resolution than MARSIS data, so we can study even thin distal deposits that might be good analogs for the proposed interbedded sediments in Elysium. Our example MFF unit is superimposed on the youngest Elysium Planitia lava flow unit and situated to the west of the study area (Figures 1 and 2c). A reflecting interface is associated with the boundary between the base of the outlier and the underlying lava surface (Figure 2c). As this contact can be topographically constrained by extrapolating the MOLA surface elevation around the rim of the MFF material, an estimation of the permittivity of the overlying material can be derived from the round-trip delay time (equation (1)). The resulting estimate of ε' of ~2, with a range of 1.6–2.2 (see Figure S2), is low relative to the value estimated by *Watters et al*. [2007] using MARSIS data (2.9 ± 0.4) and those measured by SHARAD of ~3 [*Carter et al*., 2009b], 3.9 ± 0.6 [*Stillman and Grimm*, 2011], and 3 ± 0.5 [*Alberti et al*., 2012]. As ε' is a function of density for dry materials [*Ulaby et al*., 1988], this discrepancy can be attributed to significantly lower self-compaction within the outlying MFF deposit, which is an order of magnitude thinner than the main body of MFF measured in previous MARSIS/SHARAD studies. Applying a two-layered model to characterize the difference in power between the surface and subsurface reflections, we were able to demonstrate that the dielectric contrast between basalt and a thin layer of MFF material reproduced the strong subsurface reflections observed within the SHARAD data (see supporting information). We therefore argue that the reflectors correspond to older, thin northern expanses of MFF material that have been preserved in place by subsequent lava flows.

5. Conclusions

Prior studies argue that the surface of the MFF has been successively reworked through time [*Kerber et al*., 2012; *Kerber and Head*, 2010] and the relationships with Elysium Planitia volcanism shown here place further constraints on the nature and timing of this modification. The extensive blanket of sediments revealed by our survey of the surface of Elysium Planitia likely represents material derived from a recent period of MFF erosion. Lava flows interbedded with similar layers of MFF-derived sediments provide a plausible model to generate the complexity observed in SHARAD data for Elysium.

The processes operating to redistribute materials over areas in excess of those associated with the subsurface horizons mapped by SHARAD must be rapid in nature. This is demonstrated by the emplacement of sediments on the surface of lavas ~10 Ma [*Murray et al*., 2005; *Vaucher et al*., 2009; *Jaeger et al*., 2010] and their removal since the impact that formed Zunil, $<$ 2.7 Ma (assuming the impact was the source of the Shergottite Meteorites [*Nyquist et al*., 2001]). The removal and deposition of the MFF deposits has therefore not been continuous, and the widespread deposition of reworked MFF material must have been episodic over the late Amazonian. Only episodes of MFF emplacement that were followed relatively rapidly by lava flows would have been "fossilized" at depth. The episodic nature of MFF modification likely reflects short-term changes in climatic and geologic processes linked to Martian obliquity oscillations. Shifts in wind direction and strength are possible determining factors that could have initiated periods of MFF erosion and redeposition.

Acknowledgments
We wish to thank the four reviewers for their very helpful comments and suggestions. All the data used in this study are available through NASA's Planetary Data System. We gratefully acknowledge financial support provided by a grant from NASA's Mars Data Analysis program. The MFF map element incorporated within Figure 1 was reprinted from Vaucher, J., D. Baratoux, N. Mangold, P. Pinet, K. Kurita, and M. Gregoire, The volcanic history of central Elysium Planitia: Implications for Martian magmatism, Icarus, 204, 418–442 (2009) with permission from Elsevier.

The Editor thanks Colin Dundas, Victor Baker, and two anonymous reviewers for their assistance in evaluating this manuscript.

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