Planetary and Space Science 214 (2022) 105433

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Geomorphological evidence of the internal geological activity of Sputnik Planitia, and its relationship with the surrounding terrains

Javier Eduardo Suárez Valencia [a,*], Luis Hernán Ochoa Gutiérrez [a], Camilo Delgado-Correal [b], Fabián Saavedra Daza [a]

[a] Universidad Nacional de Colombia, Bogotá, Colombia
[b] Universidad Distrital Francisco José de Caldas, Bogotá, Colombia

ARTICLE INFO

Keywords:
Pluto
Sputnik Planitia
Geomorphology
Icy bodies
Cryovolcanism

ABSTRACT

In this work, we made a geomorphological analysis of the surface of Pluto using LORRI data from the New Horizons flyby, to make an observational evaluation of a previously established convective model as the endogenic source of Sputnik Planitia geologic activity. With corrected high-resolution images and the Digital elevation model (DEM), we defined and described six geological terrains. Sputnik Planitia was examined in more detail using the higher quality images, and within it were defined eighteen geomorphological units. The link between the interpretation of the geoforms and the known composition of some of these units, provided key information to understand the geometries and distributions of the ices that make up the plain, including the classical cell patterns and the small H_2O blocks trapped in them. The analysis of Sputnik Planitia lead to interesting interpretations about the zone: The convective process is the best explanation for its current configuration; the glaciers of Sputnik Planitia have lost altitude over the last geological times, exhuming rocks of the Cthulhu Regio terrain; and it could be possible that the rough-looking Sputnik Highlands terrain is a degraded form of a previous zone similar to Sputnik Planitia.

1. Introduction

1.1. Previous work

On June fourteenth of 2015, New Horizons made a flyby over Pluto, taking high-resolution images and multispectral data of its surface (Stern et al., 2015). This information allowed a detailed geological analysis of an icy body that displays a wide variety of geological features (Moore and McKinnon, 2020). The most striking one is Sputnik Planitia (SP), a vast plain that covers 15% of the observed hemisphere of Pluto, which shows interesting patterns within it and has complex boundaries with its surroundings.

The first results of the flyby were analyzed by Stern et al. (2015) and Moore et al. (2016). These authors made an initial division of the observed regions of Pluto, establishing differences between the dark area Cthulhu Regio (CR), the Tombaugh Regio that contains Sputnik Planitia (SP), and other big-scale features. Since this early interpretation, it was evident that SP is younger than its surroundings, due to the lack of impact craters, and the possibility of this phenomenon being related to the cellular pattern dissecting it. White et al. (2017) made a more detailed analysis of Sputnik Planitia, identifying and describing geological units across the plain.

Before the arrival of New Horizons, CH_4, CO, and N_2 had been detected in spectral signatures (Cruikshank et al., 2015), and H_2O was believed to be a major component of the crust (Brown, 2002). The large abundance of water ice was confirmed after the flyby, as its spectral signature was detected in big areas across Pluto (Protopapa et al., 2017; Gabasova et al., 2021). These four components represent most of the surface of Pluto and probably of its crust. All of them, excluding H_2O, are present as ice on the surface and as gas in the atmosphere (Young et al., 2018).

The rheology of these materials plays a key role in the surface morphology of Pluto. The three volatiles shape solids that are joined by van der Waals forces (McKinnon et al., 2016). This results in weak rock bodies that are plastic to deformation, so the regions enriched in these volatiles have low topographies and accommodate stress by relaxation

* Corresponding author.
E-mail addresses: jaesuarezva@unal.edu.co (J.E. Suárez Valencia), lhochoag@unal.edu.co (L.H. Ochoa Gutiérrez), mcdelgadoc@udistrital.edu.co (C. Delgado-Correal), fsaavedrada@unal.edu.co (F.S. Daza).

https://doi.org/10.1016/j.pss.2022.105433
Received 12 February 2021; Received in revised form 16 December 2021; Accepted 1 February 2022
Available online 3 February 2022

instead of fracture (Yamashita et al., 2010). On the other hand, H_2O ices are solids joined by hydrogen bonds, creating strong hexagonal structures, and resulting in rock bodies that are fragile to deformation and landscapes dominated by fractures and resistant topographies (Moore et al., 2016). As a result, N_2, CH_4, and CO make plastic glaciers that span across the surface, and H_2O ices are the prime material of the bedrock in the crust of Pluto (Howard et al., 2017). Ice density is an important factor to understand SP dynamics, both N_2 and CO have densities around 1 gm/cm^3, H_2O has a density of 0,91 gr/cm^3 and CH_4 has 0,5 g/cm^3 (Luna et al., 2012).

1.2. Convection

SP origin is a primary topic in the investigations of Pluto, there is currently a strong hypothesis suggesting that SP geoforms are the external signature of several convective cells working under the plain (McKinnon et al., 2016; Trowbridge et al., 2016). These authors made numerical simulations of SP considering the rheology and viscosity of a CH_4:N_2:CO mix, and proposed that convection could be achieved if the deep of the basin exceeds 1 km and the basal temperature is at least 63 K (McKinnon et al., 2016). In the present study, we analyze the surface geomorphology and processes interactions that could support this convective model from a geological point of view.

2. Materials and methods

All the imagery data was downloaded from the Planetary Data System (PDS) in the node of small bodies. We used the 2.0 version, the most up-to-date at the time this work started. LORRI data consists of panchromatic images, each one with 1024 x 1024 pixels. A total of 78 images ranging from 500 m/pixel to 76m/pixel were used. These images were geometrically corrected creating four Transverse Mercator projections with four origins and using the Pluto 2000 datum. A color modulation was made to homogenize image illuminations. The preparation of the images and the interpretations were made in the ArcGIS 10.5 software. We used a 300 m/pixel resolution DEM created by the New Horizons team, published by the Johns Hopkins University Applied Physics Laboratory, and obtained on the USGS webpage. We conducted two steps of processing to the original DEM. We used the Fill tool of ArcGIS to eliminate holes and discontinuities, then the Focal Statistics tool was run to reduce the noise in the data, by creating a 6x6 pixel homogenization window. At this point, the DEM was ready to be used for measures of altitude and in morphometrical descriptions (Fig. 1a). After the prior treatment, we decided to apply the Filter tool only to the data of SP, as it was possible to recognize a trend in the topography, but it was heavily masked by noise. This function reduces the presence of small-scale extreme variations of altitude, and thus allows the recognition of the underlying features (Fig. 1b).

The units defined in this work are geomorphological, but we connected them to the geology of the zone as best as possible. The interpretation of the units meets the criteria established by Tanaka et al. (2010) and Wilhelms (1972): the defined bodies are discrete, follow the superposition principle and the crosscut laws can be applied to them. The names of the units are generally informal and descriptive of their geomorphology. Some names such as “Cthulhu Regio (CR)” or “Venera Terra (VT)” are maintained in this study, as they are widely used by previous

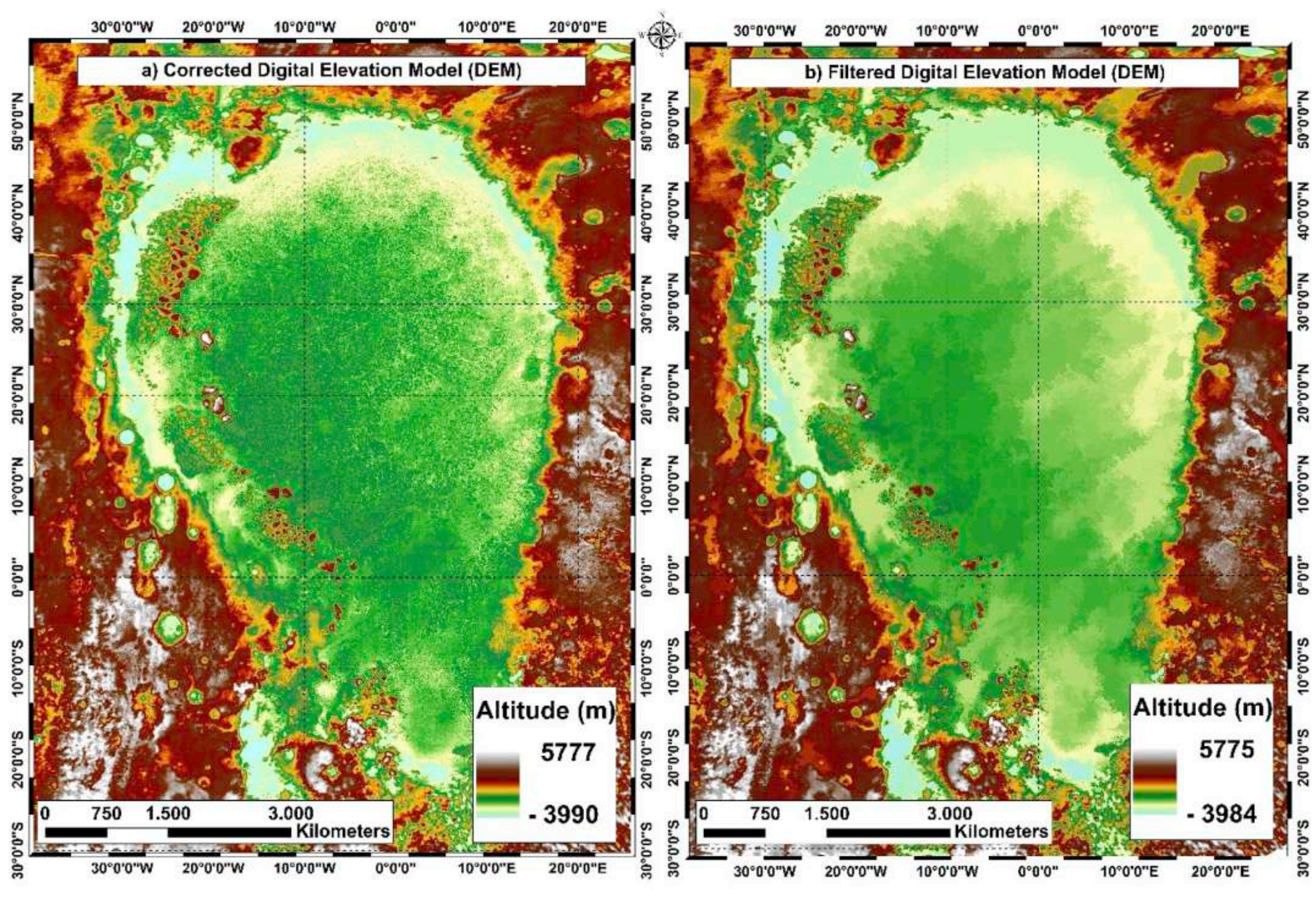

Fig. 1. Digital elevation model (DEM) of the zone. a) This is the DEM after running a focal statistic and a low-filter process to the original data, this model was used to measure heights and to make the geomorphological interpretations. b) This is the DEM obtained after several filters of the same data, it shows a continued decrease in altitude from the center to the edges of SP.

authors. We made an analysis in two different spatial scales. In a regional one, the area surrounding SP was divided into terrains, macro features that enclosures a series of characteristics that differs them from other terrains. On a detailed scale, SP was divided into eighteen geomorphological units, differentiated by the same criteria as the terrains, but adding the surface morphology variation as the main factor. The interpretation was carried out using the georeferenced orthoimages, the DEM, and 3D scenes resulting from the combination of the elements mentioned above.

3. Results

3.1. Surrounding terrains

Fig. 2 shows the terrains defined for the studied zone, centered in Sputnik Planitia. SP itself is the most particular feature in Pluto, as it is on average 2.000 m below its surroundings and is almost flat, except for some mountain ranges scattered in the plain borders. All the terrains are described in Fig. 2, but as only two of them play a major role in explaining SP geologic configuration, and the other ones have been previously studied by other authors (Howard et al., 2017; White et al., 2018, 2021), we focused our interpretations on Cthulhu Regio, Sputnik Planitia and Sputnik Highlands (SH).

After SP, CR is the most striking terrain. It is a vast brown region that extends more than 500.000 km^2 west of SP. As their limits are not visible, it may cover the south pole of Pluto and other areas not observed. Crater count is important in CR. We counted 20 craters with a diameter of 20 km or more in an area of 40.000 km^2, more than in other terrains in Pluto. It has an albedo close to 10%, which is well below the average of Pluto. Stern et al. (2015) and Protopapa et al. (2020) attribute this to a mix between water ice and tholins. Some areas in CR have higher albedos, especially in the border of the craters and in the transition to Venera Terra (VT) (Fig. 2). This may indicate that the dark material is shallow, and the ices in deep are clear of tholins. Water ice has been identified as the only major compound in CR (Protopapa et al., 2017), this controls the topography of the terrain and its brittle behavior (Fig. 3a and c). A particular interaction is observed between CR and SP in the southern part of the zone, several CR lands are partially covered or separated from the main terrain by SP light and plastic material. There are two possible explanations for this phenomenon, either it represents an atmospheric deposition of N_2 or the glaciers of SP had higher levels in the past. We believe that the second scenario is correct, as the covered craters have similar local altitudes and the higher craters around are not covered in light material. If this were the result of atmospheric deposition a homogeneous covering would be expected. An example is presented in Fig. 3b, where two nearby-equally-low craters are fulfilled with SP ices, and the surrounding-higher craters are not. The filling altitude varies over the west margin of CR, but in all cases, the light materials in these craters are disconnected from the main glacier of SP. This relationship shows that SP is superimposed to CR at least in this margin and that their glaciers levels have decreased over time.

The SH terrain is located east of SP. This terrain corresponds to the eastern side of the Tombaugh Regio, defined by Stern et al. (2015) and Moore et al. (2016). For this study, we separated this zone in SP and SH

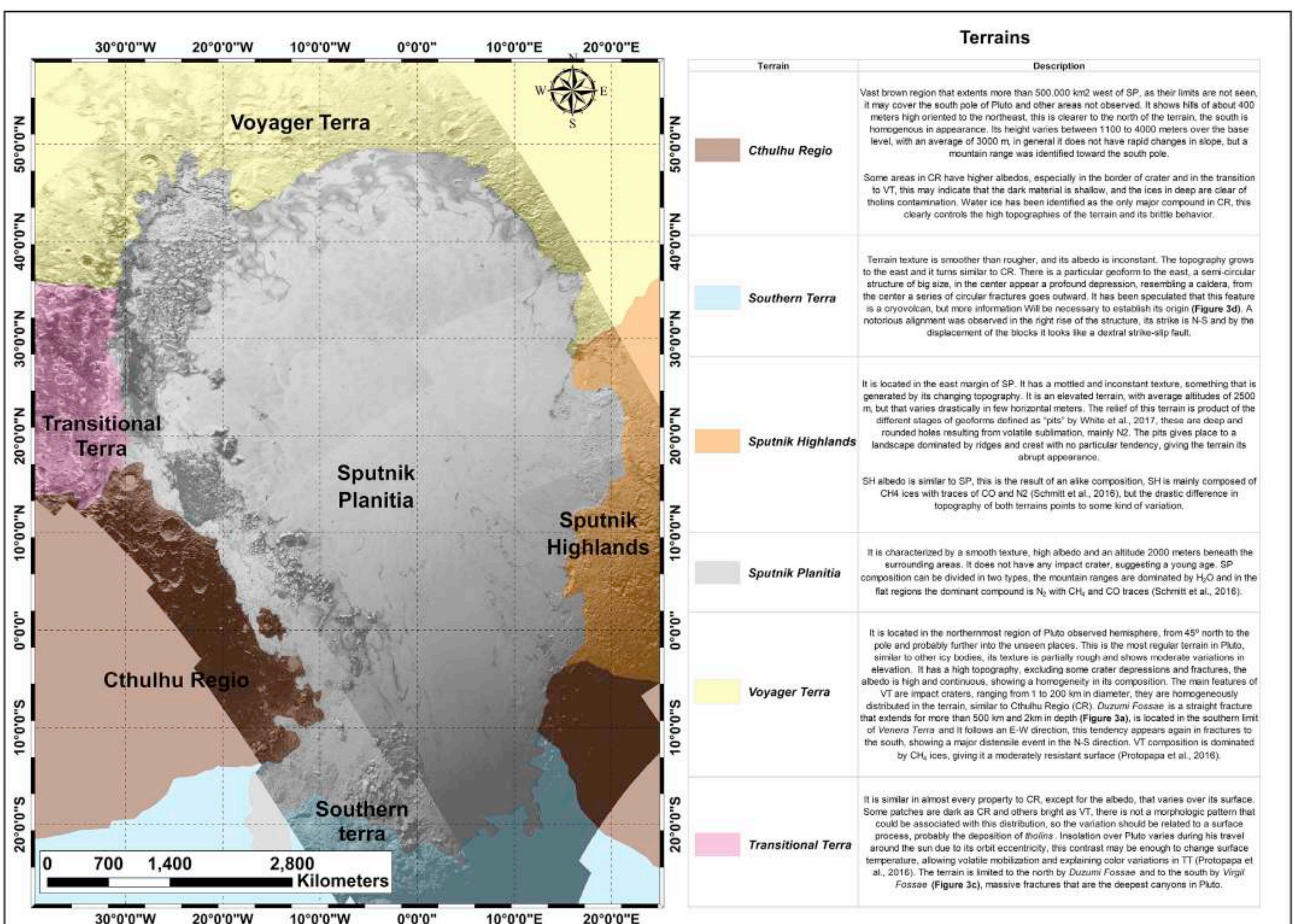

Fig. 2. Map of terrains in the studied zone.

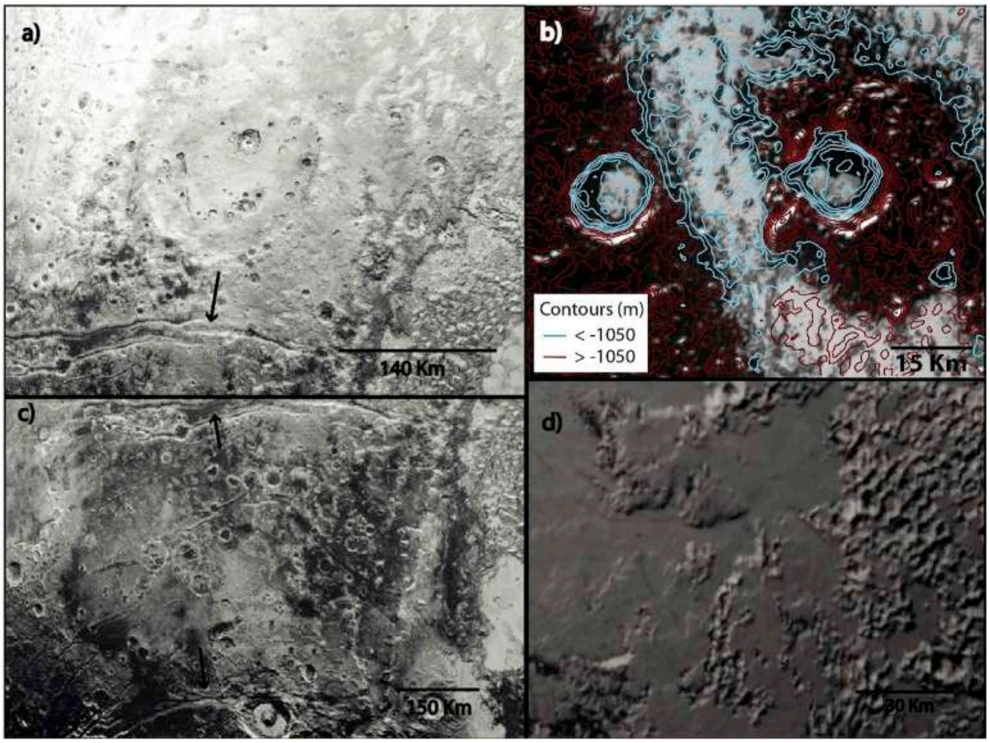

Fig. 3. Main structures of the terrains. a) *Duzumi Fossae* in VT and CR boundary, b) Two typical craters of CR fulfilled with SP light ices, the relation between filled craters and altitude implies that the level of SP glaciers was higher in the past, c) *Duzumi Fossae* at the north and *Virgil Fossae* to the south in CR, d) Transitional limit between smooth SP and rough SH.

(Fig. 2), as the interaction between them is important. The texture of SH is unique, it is mottled and variable, due to its changing topography. It is an elevated terrain, with average altitudes of 2.500 m that can vary drastically in a few horizontal meters. The topography of this terrain is the product of volatile sublimation, glacial erosion, and tectonic activity. Sublimation is evidenced in the different stages of geoforms defined by White et al. (2017) as pits, they are deep and rounded holes resulting from volatile ices turning into gas, mainly from N_2. When the sublimation process becomes more extensive, the pits give place to a landscape dominated by ridges and crests. The prior action of the pits, combined with a widespread glacial erosion gives the terrain its abrupt appearance (Umurhan et al., 2017). Some structural trends have been identified by McGovern et al. (2019), who detected pit chains that are aligned in a NE-SW direction. The authors suggest that this could be the result of extensional stress beneath the terrain, which would increase the size of the pits and the overall degradation of the zone.

The albedo of SH is similar to the one of SP, as a result of their similar composition, enriched in volatiles. SH is mainly composed of CH_4 ices with traces of CO and N_2 (Schmitt et al., 2017). However, the drastic difference in the topography of both terrains points to some kind of variation. We did not encounter an important number of craters in SH, just a few of them in the northern regions. This lack of impact craters is shared with SP and can be attributed to a recent or ongoing process that is changing the surface, probably related to sublimation and glacial activity (Umurhan et al., 2017; Howard et al., 2017). SH has a complex and transitional interaction with SP, being opposite to the one with CR. Glaciers flow from SH to SP in features resembling *u valleys*, connecting reservoirs in high topographies with the Planitia (Fig. 3d) (Howard et al., 2017). Some glaciers appear to have lost their connection to SP, probably due to uplift or to the lack of flowing material. A few of them are located deeper in SH, but their surfaces are degraded and surrounded by crests and valleys.

3.2. *Sputnik Planitia*

As SP was the primary target of this mission, the best data is in this terrain. We used fifteen images with a resolution up to 76 m/pixel in one narrow band, plus several images of lower resolutions. SP is characterized by a smooth texture, high albedo, and being on average 2.000 m below the surrounding areas. Here, the lack of craters suggests a young age. SP composition can be divided into two types, the first are mountain ranges dominated by H_2O, and the second are flat regions made up of N_2, with CH_4 and CO traces (Schmitt et al., 2017). We defined eighteen geomorphological units inside SP, all of them are described in Fig. 4, and the most relevant ones for understanding SP internal activity and interactions with other terrains are discussed in deep below.

3.2.1. *West margin*

This zone shows the major variability in SP, changing periodically in a N–S direction. Hillary Montes (HM, SHM) is a unit that contrasts with the rest of SP, it is a mountain range with low albedo, rough texture, and high topographies, surpassing the 3.000 m in altitude above the plain. The mountain range follows an N–S direction and is thicker in the E-W axis, with a maximum of 150 km in wide (Fig. 5a). The mountain range is made of single quasi-triangular or quasi-squared blocks. Each block has an average length of 20 km, but to the west, they become smaller. The blocks are separated from each other by SP glaciers, giving the unit the appearance of a chaotic terrain (Skjetne et al., 2021). The albedos of the blocks vary, but they are mainly low, similar to CR. The texture and resistance of the blocks also resemble the ices of CR. Therefore, we think that this unit has a similar genesis to CR, something that is further evidenced by the H_2O signals of the blocks (Schmitt et al., 2017). The strike of HM changes toward the northeast at 35° N, possibly due to thrusts from SP glaciers. Several signals of glacier regression are scattered throughout the mountain range, as block groups are exhumed from

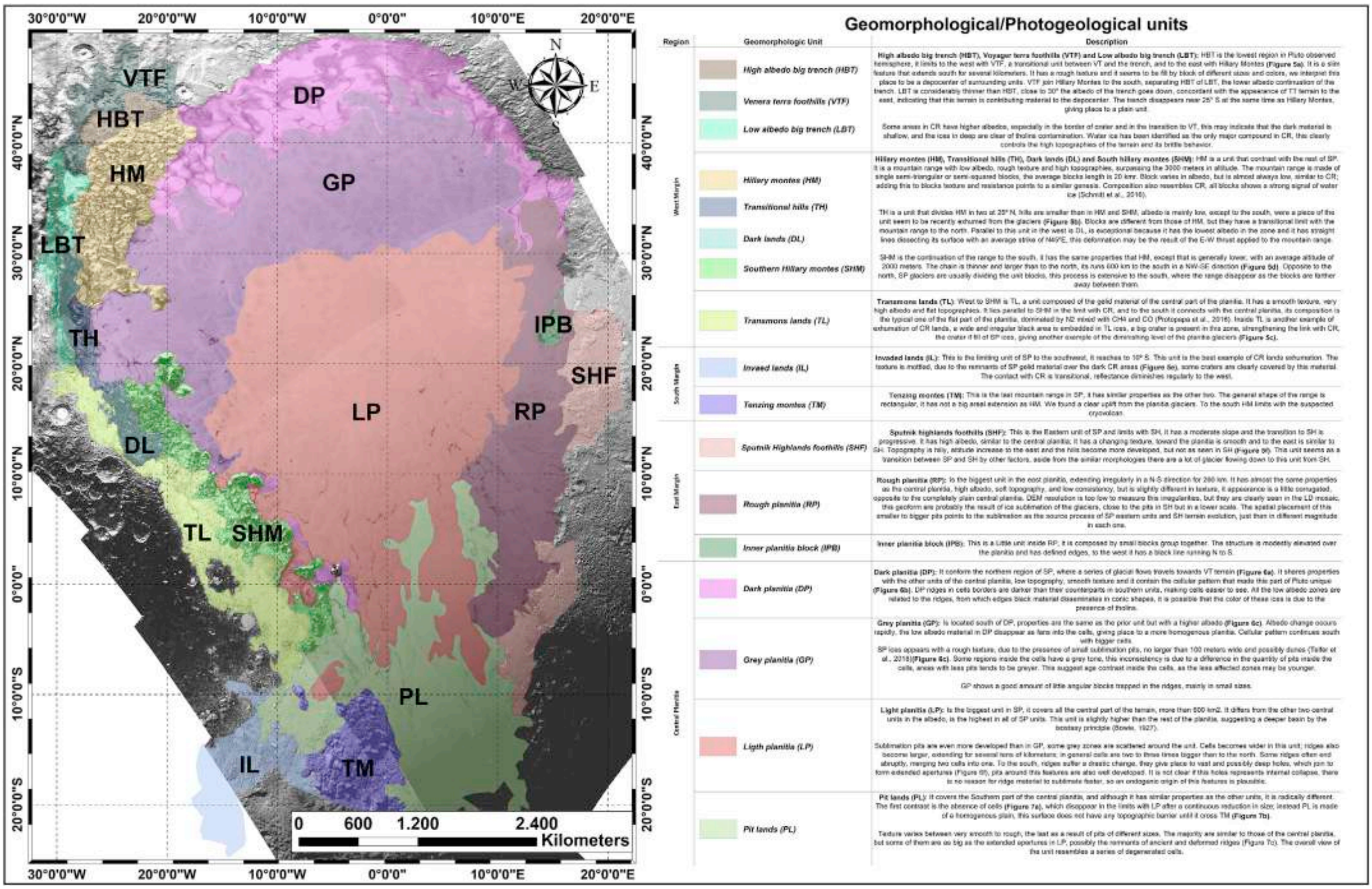

Fig. 4. Map of Geomorphological/Photogeological units of Sputnik Planitia.

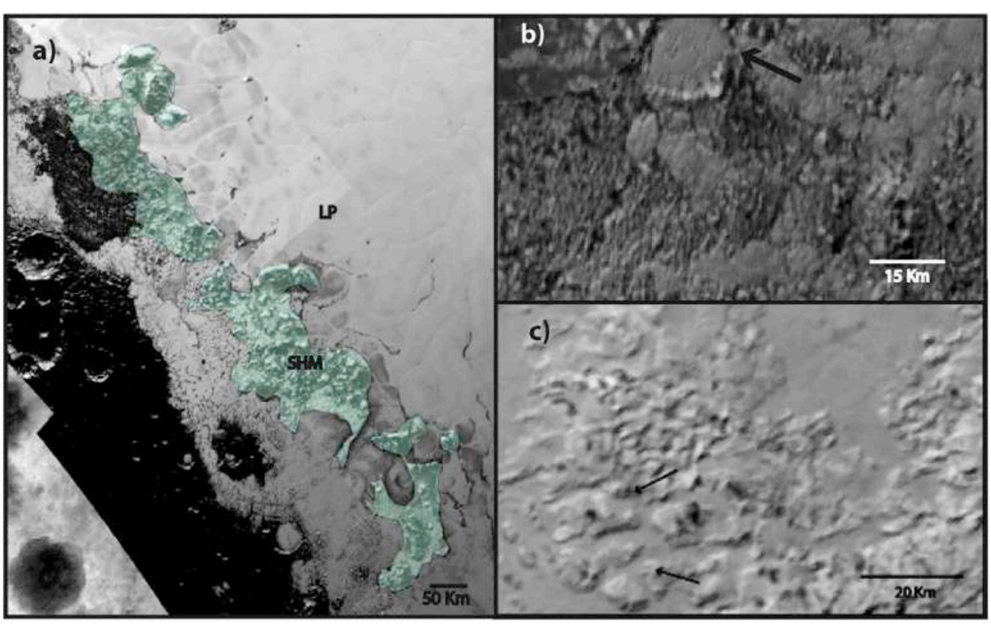

Fig. 5. Principal geoforms of Sputnik Planitia. a) Hillary Montes (HM), b) CR terrain exhumed from SP glaciers, c) Typical transitional terrain of Sputnik Highlands foothills (SHF).

previously glacier-covered zones, these zones can be identified by their higher albedo and relatively low topography (Fig. 5b). The exhumed blocks are common in the south of the Transitional Hills unit (TH), as this zone is a low point in the mountain range and was probably under the plastic material of the plain not long ago.

3.2.2. East margin

Opposite to the west margin of SP, this region is poorly variated, we interpreted three units that represent different stages of the same geologic process. The zone has a moderate slope and the transition to SH is progressive. The albedo of these units is high, similar to the one of the central planitia. The texture changes gradually, it is smooth on the Rough Planitia (RP) unit, towards the central planitia, while to the east, in the Sputnik Highlands foothills (SHF), it becomes similar to SH. The topography of this zone is hilly, altitude increase to the east and the hills become more developed (Fig. 5c), but they are not as steep as the ones seen in SH. This region looks like a transition between SP and SH, they have similar morphologies and several glaciers are flowing down towards this unit from SH.

3.2.3. Central planitia

The units at the center of SP constitute the largest part of the plain, covering nearly 80% of the surface of SP. All of these units have a seemingly plain topography, and their composition is dominated by N_2 (Schmitt et al., 2017), supporting the strong relation of this component with endogenic processes in SP (Trowbridge et al., 2016).

The northernmost part of the plain is covered by the Dark planitia (DP) unit, it shares properties with the other units of the central planitia: It has a low topography, a smooth texture, and it contains the cellular patterns that made this part of Pluto unique (Fig. 6b). The cellular patterns were first described by Stern et al. (2015), these intricate mosaics are made of cells with both regular and irregular shapes. Most of them have well-defined and self-closed edges, but sometimes the edges are open, allowing two or more cells to be connected (Bottom-right of

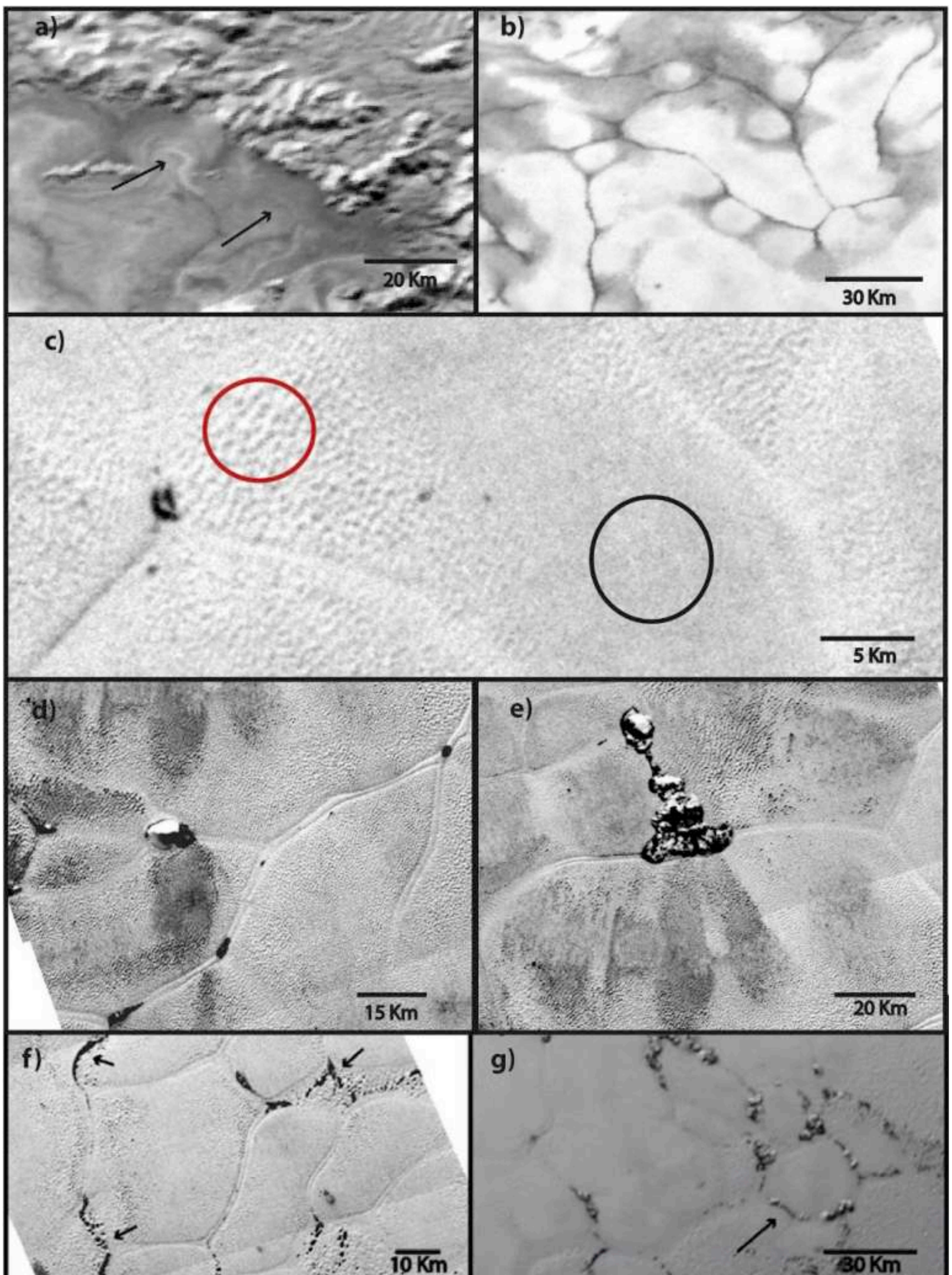

Fig. 6. Principal geoforms of the central planitia units. a) Flow patterns, these structures show the motion of the glaciers from SP to VT. b) Typical tonality of Dark planitia ridges, possibly due to an enrichment in tholins. c) Interior of a cell in Grey planitia, the left circle shows a zone with numerous sublimation pits, the right circle encloses a more central place with a lower number of pits. d) Little H_2O block related to ridges, e) Anomalous block, f) Deep holes appear instead of ridges, as cells disappear south of Light planitia unit, g) Blocks following the contour of a polygonal cell, showing the relation between the two.

Fig. 6d). Their size varies between 7 to 40 km, and their limits are straight or curved lines. We found that the limits of the cells are made of complex structures; a depression with a central ridge appears between the cells (Fig. 6d), however, it was not possible to measure the proper altitude of these structures due to the limit of the vertical resolution of the DEM. The ridges of DP are darker than their counterparts in southern units, making cells easier to differentiate. All the low albedo zones are related to the ridges, from where black material disseminates in conic shapes. The color of these ices may be also related to the presence of tholins.

Across the west margin of this unit, cells intersect perpendicularly with the HM blocks, and to the north, cells gradually become more curved until they disappear inside the glaciers flowing towards VT (Fig. 6a). The limit of SP with VT is characterized by a gentle negative slope, where the glaciers travel continuously to the north and no exhumation features are interpreted on this side. This evidence, as well as the ones discussed in Umurhan et al. (2017), suggests that VT is the basement of SP in the northern zone, and that the level of the glaciers has been stable or progressive.

The Grey planitia (GP) unit is located south of DP, it differentiates from the prior unit by its higher albedo (Fig. 6c). The albedo change occurs rapidly, as the low albedo material in DP disappears as fans into the cells, giving place to a more homogenous planitia. The cellular patterns continue to the south with bigger cells. The better image resolution in this region led us to appreciate a change in texture as scale grows, here the glaciers appear with a rough texture, due to the presence of small sublimation pits (Fig. 6c), no larger than 100 m wide, and to the existence of eolic dunes (Telfer et al., 2018). Some regions inside the cells have a grayer tone than others, the change of color results from a difference in the number of pits inside the cells, as the areas with fewer pits tend to be grayer (White et al., 2017). This suggests an age contrast inside the cells, being the less affected zones younger than the rest. GP shows a good amount of little, angular, black blocks trapped in the ridges, mainly in small sizes. These small blocks resemble the ones shaping HM, so they could also be associated with CR material (Fig. 6e, g).

Light planitia (LP) is the biggest unit in SP, it covers the central part of the terrain, with an extension of more than 600 km^2. It differs from the other two central units in its albedo, being the highest of all the units of SP. This unit is slightly higher than the rest of the plain (Fig. 1b), suggesting a deeper basin by the isostasy principle (Bowie, 1922). Sublimation pits are even more developed than in GP, which also enables the appearance of some grey zones scattered around the unit. As cells become wider in this unit, ridges also become larger and extend for several tens of kilometers. In general, cells are two to three times larger than the ones present in the north. To the south, in the Pit Lands (PL) unit, ridges suffer a drastic change, they give place to large and possibly deep holes. These hollows join to form extended apertures (Fig. 6f). The sublimation pits around these features are also more developed than in any other place in SP. It is not clear if these holes represent internal collapse, but as there is no reason for ridge material to sublimate faster, an endogenic origin of these features is plausible. This phenomenon increases gradually to the south. The little black blocks keep appearing in this unit, especially to the east (Fig. 6g).

4. Discussion and conclusions

4.1. Composition and rheology

From our analysis, we conclude that the composition is the main controlling factor of the geology of Pluto, as evidenced in the response of the rock bodies to the few geologic processes acting in this dwarf planet. This seems to be the case for at least the last geological age of Pluto, due to the changing nature of its orbit and atmospheric conditions (Bertrand et al., 2018). Atmospheric events are mainly restricted to sublimation (Stern et al., 2015) and some wind-driven events (Telfer et al., 2018). However, the last ones seem local and not strong enough to constitute an important erosive agent in Pluto. The prior situation positions the next events as surface modifiers: impact craters, sublimation, condensation, glacial erosion, tectonic activity, and the endogenic processes inside SP.

CR and SP mountain ranges are dominated by H_2O compositions. In both cases morphologies are consistent and steep, responding in a fragile regime to stress, as exemplified in CR several slope breaks. This response is similar to glaciers in Europa, where H_2O is also the dominant compound (Collins et al., 2000). The little blocks inside SP are almost exact copies of the larger ones forming the mountain ranges (Fig. 6d), this leads us to infer that they are similar in composition, meaning they may share their origin with CR. The three volatile substances influence the geoforms as they dominate over the others, CH_4 is the less volatile by difference, their structures overcome time and do not sublimate as quickly as N_2 (Moore et al., 2017). The central planitia units in SP have the major concentrations of N_2 and CO in the observed hemisphere of Pluto, as a result, they do not show a rugged topography. These units also display a great number of sublimation pits even in their youngest zones, showing the incidence of N_2 volatile properties. SH terrain falls a little out of this interpretation, as its morphologies result from the combination of intensive sublimation, glacial erosion, and the extensional tectonic force that may be acting beneath SH (McGovern et al., 2019). Yet, the signals of N_2 and CO are weak in comparison to SP, another terrain with several sublimation pits. We suggest that SH is older than SP but similar in origin and that almost all its N_2 was lost during the sublimation process, letting behind the less volatile CH_4 ices (Tan and Kargel, 2017).

4.2. Relative ages

We made a simple crater count exercise in the terrains following Kneissl et al. (2015), measuring all craters bigger than 2 km in an area of 20.000 Km^2. As the relative age models of Pluto are not yet well established, we defined four big time-lapses using crater count densities and the development of sublimation features (Fig. 7). For crater density we found that the more impacted terrain is CR, Singer et al. (2019) had a similar result, estimating a 4 Gy age for this terrain. VT shows a similar crater abundance as CR, so both make up the first time-lapse and probably the basement of Pluto crust. Transitional Terra (TT) and Southern Terra (ST) seem to be transitional stages between CR, VT, and SP (Fig. 2). These two units belong to the second time-lapse but giving an age estimation is not possible. Both SP and SH share an important feature, they do not have craters, except for an eroded one in SH. This indicates that these two terrains are the youngest of the ones we defined and that they underwent resurfacing processes in the last 10 million years (Stern et al., 2015). As the crater count method is not useful to differentiate ages inside these two terrains, we took advantage of the extended sublimation. Volatile-rich glaciers with more developed sublimation pits are older, as

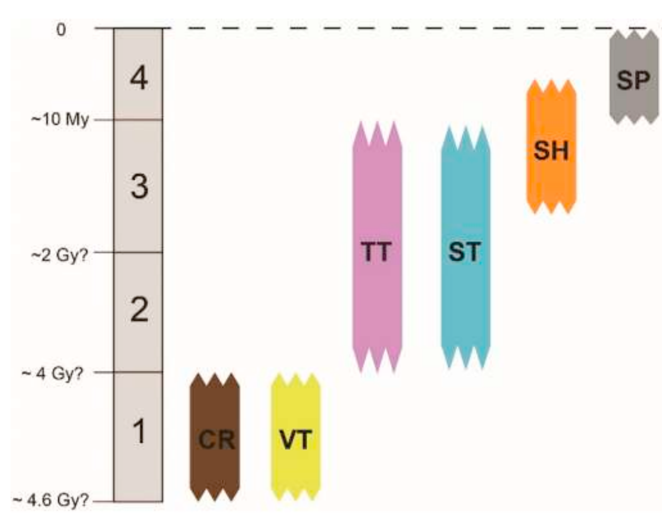

Fig. 7. Schematic relative ages of studied terrains.

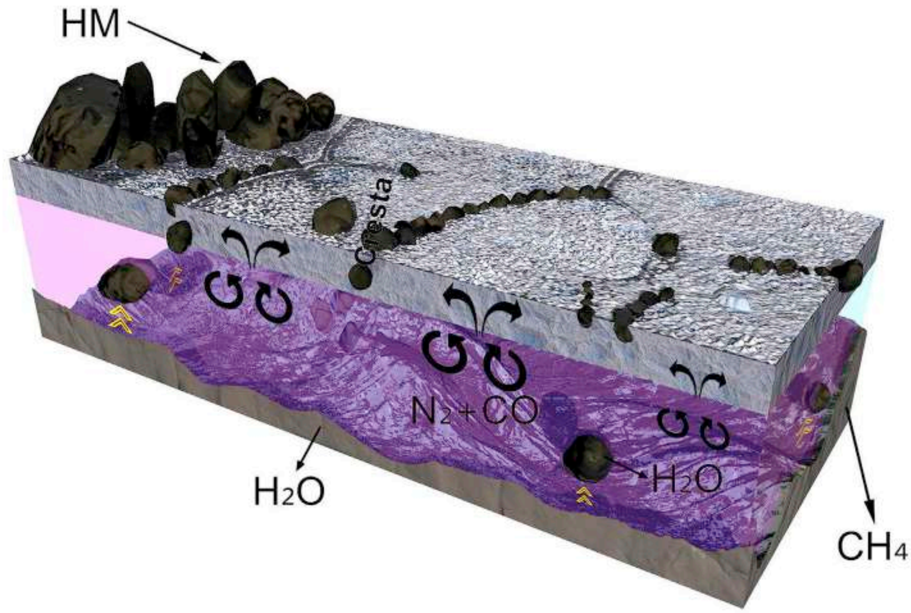

Fig. 8. Convective model of Sputnik Planitia. In-depth N_2:CH_4:CO mixtures are heated and give place to a convective process, cryomagmas are erupting from cell centers and carrying H_2O blocks from Cthulhu Regio basement.

prolonged exposure to the atmosphere of Pluto would allow them to grow bigger. With this principle is clear that SH is older than SP but younger than the other terrains, so it spans the third age stage. This method is also viable to determine ages inside SP, sublimation pits size increase to the east and south, pointing to a younger basin in the center of SP. This also implies a decrease of SP internal activity towards its edges, as bigger pits mean that there are no resurfacing processes happening in these locations.

4.3. Convection and signals

SP represented a geologic enigma since it was first seen, the factors controlling its topography and sublimation pits have been addressed, but the cellular pattern and associated geoforms remain unexplained. Understanding the dynamic of this process is difficult, and the absence of geophysical and multitemporal data is a barrier, so the interpretation of SP internal activity is provisional and cannot be solved until we have more data of Pluto. The geologic model for the formation of SP needs to satisfy some conditional observed in the data: 1) SP is younger than the surrounding terrains; 2) H_2O blocks could not form in phase with the volatile elements, and they share geological characteristics with CR; 3) N_2 Is the main compound in the plain, conditioning ice rheology; and 4) CR and VT are underlying SP and probably conform the crustal basement, and the interaction of SP with CR shows a reduction in the glaciers levels.

Only a few known geologic processes can explain the formation of cellular patterns. Desiccation processes causing clays to crack (Kindle, 1917), or columnar jointing in basalts due to thermal isolation (Mallet, 1875) are not possible ones. These comparisons were made mainly for the polygonal shapes produced by these processes, but they fail to explain SP configuration as cell proportions are much larger than Earth counterparts. Another option is that the cellular patterns are the surface expression of a complex structural setting, however, this is particularly difficult due to the ductile behavior of N_2 and the seemingly unorganized appearance of the cells. The third option is the most plausible, a convective process occurring inside SP is responsible for its surface configuration (McKinnon et al., 2016; Trowbridge et al., 2016). These authors established some necessary conditions to achieve convection: the composition inside of SP must be similar to the surface, the basin must be at least 1 km deep, and an energy source is needed to reach a certain heat gradient, that may be achieved by radiogenic decay of Pluto internal layers (Trowbridge et al., 2016).

We made a correlation of this hypothesis with the interpretation made in this work. The surface expression of such a process would be related to the cellular patterns. White et al. (2017), Trowbridge et al. (2016), and McKinnon et al. (2016) had proposed that the convective overturn occurs in the centers of the cells, and that subduction happens in the ridges defining the limits of the cell. This interpretation is supported by a measured decrease of 50 m in altitude from the center to the borders of the cells, and in the lesser concentration of pits in the center of them, suggesting younger ices in these locations. We share the interpretation made by these authors about the convection configuration, although we were not able to estimate an altitude gradient inside the cells with the available DEM. The difference in the concentration of sublimation pits is seen across the plain, additionally, SP morphology resembles Benard cells, which are hexagonal patterns resulting from a convective process of liquids with a plain surface (Demirel and Gerbaud, 2018; Manneville, n.d.). Although this interpretation is the more plausible (Fig. 8), there are some aspects, that if resolved, could strongly support the theory. There is no evidence of cryovolcanoes inside SP cells, probably due to a limitation in spatial resolution. If this is the case, the sources of cryomagmas should be smaller than 73 m wide, suggesting fissure magmatism. The second issue concerns the unit Dark Planitia, the ridges in the borders of the cells have a dark tonality, probably by the presence of tholins, indicating that they are not entering the subduction process and are accumulating in the edges of the cells (Scipioni et al., 2021). The last concern is about subduction, this process has not been seen in the solar system outside of Earth and Europa (Kattenhorn and Prockter, 2014), and in both cases, it is related to brittle and well-differentiated crusts, almost opposite to the situation in SP. We suggest the future study and integration of the above phenomena within the convective model, as it would be valuable to get a complete understanding of SP internal activity.

Aside from the cellular patterns, the H_2O blocks that form the mountain ranges and the little fragments scattered across SP are the biggest mysteries of the system. This can be elucidated by considering the density of the compounds. The glaciers enriched in N_2 and CO have a density close to 1 gr/cm^3, which would allow a less dense material to float in the mix. Such is the case for water ice at the environmental conditions of Pluto, as it crystallizes in the XI phase and has a density of

0,91 gr/cm^3 (Zhang et al., 2015; Liu et al., 2019). Taking this into consideration, it is possible to analyze the origin of the smaller blocks spread across SP. Most of them are confined to the edges of the cells, which means that they are being transported by the horizontal motion of the cells and that they cannot be subducted in the system due to their lower density. The only possible origin for these blocks is the underlying basement made of CR material, as little fragments of H_2O would be detached and lifted to the surface in the convective motion. It does not seem likely that the bigger blocks of the mountain ranges were transported by this mechanism due to their size and possibly deep roots. So we believe that the scenario proposed by Howard et al. (2017) is the most likely to happen, as they suggest that the blocks conforming Hillary Montes and other similar mountain ranges are detached fragments of CR, transported but not suspended in the glaciers of SP. This process could have been favored by previous high-energy events, as the proposed big impact that formed the basin containing SP (Hamilton et al., 2016).

4.4. Sputnik Planitia prior and current state

There are striking similarities between SP and SH. These terrains have similar compositions, few to no craters are present on their surface, both are affected by the same sublimation and glacial processes, and both have several reservoirs of plastic material. Furthermore, a transitional change occurs from one terrain to another; as the sublimation and erosional structures in SP increase in size to the east, the planitia slowly gives place to the abrupt features of the highlands. This relation may suggest that both terrains share a similar origin. It is difficult to pull together a cohesive theory about the origin of SH due to the limitation of the data, but the similarities between SP and SH should be taken into consideration. We propose that regional sublimation and tectonic processes are and have been transforming SH, from a stage more similar to SP to its current appearance. Some features support this possibility: The remnant glaciers in SH, the abundant connections between both terrains, and the sublimation geoforms controlled by glaciers enriched in N_2. In this scenario, SH can be considered as an evolved form of SH. It has been established that when the cellular patterns disappear, the sublimation features become more intense, from this we can infer that convection regulates sublimation, thus controlling surface degradation. As no convection cells have been detected in SH, there is no regenerative process of the surface, so the continuous sublimation of ices and the erosion done by glaciers have molded the current appearance of SH over millions of years. However, there are some problems with this interpretation, it is not easy to explain why SH is several hundreds of meters higher than SP. Although it is possible that compressive tectonic processes have been acting strongly near SH, in Tartarus Dorsa (McGovern et al., 2019), and could be the source of regional uplift, the true origin of SH is not clear. We consider this to be an interesting topic for further research.

The southern central planitia units also point to a remarkable process. Cells become smaller towards the south until they disappear. Trowbridge et al. (2016) show that a smaller cell on the surface also means a small cell in-depth, so the basin must be getting shallower to the west, east, and south. If the current configuration of convective cells remained unchanged over time, this zone should look similar to SH. As this is not the case, we can assume that convection stopped in this place not long ago and that the overall size of SP has decreased in the last geological times, a phenomenon that is also clear in the exhumed patches of CR along the west margin of SP. Other geophorms in the northern terrains suggest that the glacier levels were once higher, for example, the washboard and fluted surfaces described by White et al. (2018). It remains unclear if this regression will continue over time, as other aspects, such as Pluto orbit and insolation, may affect the N_2 cycle (Bertrand et al., 2018; Earle et al., 2017; Johnson et al., 2021).

CRediT authorship contribution statement

Javier Eduardo Suárez Valencia: Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Visualization. **Luis Hernán Ochoa Gutiérrez:** Conceptualization, Validation, Formal analysis, Resources, Data curation, Visualization, Writing – review & editing, Supervision. **Camilo Delgado-Correal:** Conceptualization, Validation, Formal analysis, Resources, Data curation, Visualization, Writing – review & editing, Supervision. **Fabián Saavedra Daza:** Conceptualization, Methodology, Validation, Formal analysis, Resources, Data curation, Visualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank Sofia Barragán Montilla for her valuable revision of the content and form of the manuscript.

References

Bertrand, T., Forget, F., Umurhan, O.M., Grundy, W.M., Schmitt, B., Protopapa, S., et al., 2018. The nitrogen cycles on Pluto over seasonal and astronomical timescales. Icarus 309, 277–296. https://doi.org/10.1016/j.icarus.2018.03.012.

Bowie, W., 1922. Theory of isostasy - a geological problem. Bull. Geol. Soc. Am. 33, 273–280. https://core.ac.uk/download/pdf/212069251.pdf.

Brown, M.E., 2002. Pluto and charon: formation, seasons, composition. Annu. Rev. Earth Planet Sci. 30 (1), 307–345. https://doi.org/10.1146/annurev.earth.30.090401.095213.

Collins, G.C., Head, J.W., Pappalardo, R.T., Spaun, N.A., 2000. Evaluation of models for the formation of chaotic terrain on Europa. J. Geophys. Res.: Planets 105 (E1), 1709–1716. https://doi.org/10.1029/1999je001143.

Cruikshank, D.P., Grundy, W.M., DeMeo, F.E., Buie, M.W., Binzel, R.P., Jennings, D.E., Olkin, C.B., Parker, J.W., Reuter, D.C., Spencer, J.R., Stern, S.A., Young, L.A., Weaver, H.A., 2015. The surface compositions of Pluto and Charon. Icarus 246, 82–92. https://doi.org/10.1016/j.icarus.2014.05.023.

Demirel, Y., Gerbaud, V., 2018. Nonequilibrium Thermodynamics: Transport and Rate Processes in Physical, Chemical and Biological Systems, fourth ed. Elsevier.

Earle, A.M., Binzel, R.P., Young, L.A., Stern, S.A., Ennico, K., Grundy, W., et al., 2017. Long-term surface temperature modeling of Pluto. Icarus 287, 37–46. https://doi.org/10.1016/j.icarus.2016.09.036.

Gabasova, L.R., Schmitt, B., Grundy, W., Bertrand, T., Olkin, C.B., Spencer, J.R., et al., 2021. Global compositional cartography of Pluto from intensity-based registration of LEISA data. Icarus 356, 113833. https://doi.org/10.1016/j.icarus.2020.113833.

Hamilton, D.P., Stern, S.A., Moore, J.M., Young, L.A., 2016. The rapid formation of Sputnik Planitia early in Pluto's history. Nature 540 (7631), 97–99. https://doi.org/10.1038/nature20586.

Howard, A.D., Moore, J.M., Umurhan, O.M., White, O.L., Anderson, R.S., McKinnon, W.B., Spencer, J.R., Schenk, P.M., Beyer, R.A., Stern, S.A., Ennico, K., Olkin, C.B., Weaver, H.A., Young, L.A., 2017. Present and past glaciation on Pluto. Icarus 287, 287–300. https://doi.org/10.1016/j.icarus.2016.07.006.

Johnson, P.E., Keane, J.T., Young, L.A., Matsuyama, I., 2021. New constraints on pluto's Sputnik planitia ice sheet from a coupled reorientation–climate model. The Planet. Sci. J. 2 (5), 194. https://doi.org/10.3847/psj/ac1d42.

Kattenhorn, S.A., Prockter, L.M., 2014. Evidence for subduction in the ice shell of Europa. Nat. Geosci. 7 (10), 762–767. https://doi.org/10.1038/ngeo2245.

Kindle, E.M., 1917. SOME FACTORS AFFECTING THE DEVELOPMENT OF MUD-CRACKS. Geological Survey of Canada (Published).

Kneissl, T., Michael, G.G., Platz, T., Walter, S.H.G., 2015. Age determination of linear surface features using the Buffered Crater Counting approach – case studies of the Sirenum and Fortuna Fossae graben systems on Mars. Icarus 250, 384–394. https://doi.org/10.1016/j.icarus.2014.12.008.

Liu, Y., Huang, Y., Zhu, C., Li, H., Zhao, J., Wang, L., Ojamäe, L., Francisco, J.S., Zeng, X.C., 2019. An ultralow-density porous ice with the largest internal cavity identified in the water phase diagram. Proc. Natl. Acad. Sci. Unit. States Am. 116 (26), 12684–12691. https://doi.org/10.1073/pnas.1900739116.

Luna, R., Satorre, M.Á., Domingo, M., Millán, C., Santonja, C., 2012. Density and refractive index of binary CH4, N2 and CO2 ice mixtures. Icarus 221 (1), 186–191. https://doi.org/10.1016/j.icarus.2012.07.016.

Manneville, P. (n.d.). Rayleigh-Bénard Convection: Thirty Years of Experimental, Theoretical, and Modeling Work (q ed.). Springer Fachmedien. https://link.springer.com/chapter/10.1007/978-0-387-25111-0_3.

Mallet, R., 1875. On the Origin and Mechanism of Production of the Prismatic (Or Columnar) Structure of Basalt. Royal Society Publishing, Published.

McKinnon, W.B., Nimmo, F., Wong, T., Schenk, P.M., White, O.L., Roberts, J.H., Moore, J.M., Spencer, J.R., Howard, A.D., Umurhan, O.M., Stern, S.A., Weaver, H.A., Olkin, C.B., Young, L.A., Smith, K.E., 2016. Convection in a volatile nitrogen-ice-rich layer drives Pluto's geological vigour. Nature 534 (7605), 82–85. https://doi.org/10.1038/nature18289.

McGovern, P.J., White, O.L., Schenk, P.M., 2019. TECTONISM across PLUTO: MAPPING and INTERPRETATIONS [Contribution]. Pluto System After New Horizons 2019, Maryland, United States enero.

Moore, J.M., McKinnon, W.B., 2020. Geologically diverse Pluto and charon: implications for the dwarf planets of the kuiper belt. Annu. Rev. Earth Planet Sci. 49 (1), 173–200. https://doi.org/10.1146/annurev-earth-071720-051448.

Moore, J.M., Howard, A.D., Umurhan, O.M., White, O.L., Schenk, P.M., Beyer, R.A., McKinnon, W.B., Spencer, J.R., Grundy, W.M., Lauer, T.R., Nimmo, F., Young, L.A., Stern, S.A., Weaver, H.A., Olkin, C.B., Ennico, K., 2017. Sublimation as a landform-shaping process on Pluto. Icarus 287, 320–333. https://doi.org/10.1016/j.icarus.2016.08.025.

Moore, J.M., McKinnon, W.B., Spencer, J.R., Howard, A.D., Schenk, P.M., Beyer, R.A., Nimmo, F., Singer, K.N., Umurhan, O.M., White, O.L., Stern, S.A., Ennico, K., Olkin, C.B., Weaver, H.A., Young, L.A., Binzel, R.P., Buie, M.W., Buratti, B.J., Cheng, A.F., Zirnstein, E., 2016. The geology of Pluto and charon through the eyes of New Horizons. Science 351 (6279), 1284–1293. https://doi.org/10.1126/science.aad7055.

Protopapa, S., Olkin, C.B., Grundy, W.M., Li, J.-Y., Verbiscer, A., Cruikshank, D.P., et al., 2020. Disk-resolved photometric properties of Pluto and the coloring materials across its surface. Astron. J. 159 (2), 74. https://doi.org/10.3847/1538-3881/ab5e82.

Protopapa, S., Grundy, W.M., Reuter, D.C., Hamilton, D.P., Dalle Ore, C.M., Cook, J.C., Cruikshank, D.P., Schmitt, B., Philippe, S., Quirico, E., Binzel, R.P., Earle, A.M., Ennico, K., Howett, C.J.A., Lunsford, A.W., Olkin, C.B., Parker, A., Singer, K.N., Stern, A., et al., 2017. Pluto's global surface composition through pixel-by-pixel Hapke modeling of New Horizons Ralph/LEISA data. Icarus 287, 218–228. https://doi.org/10.1016/j.icarus.2016.11.028.

Schmitt, B., Philippe, S., Grundy, W.M., Reuter, D.C., Côte, R., Quirico, E., Protopapa, S., Young, L.A., Binzel, R.P., Cook, J.C., Cruikshank, D.P., Dalle Ore, C.M., Earle, A.M., Ennico, K., Howett, C.J.A., Jennings, D.E., Linscott, I.R., Lunsford, A.W., Olkin, C.B., et al., 2017. Physical state and distribution of materials at the surface of Pluto from New Horizons LEISA imaging spectrometer. Icarus 287, 229–260. https://doi.org/10.1016/j.icarus.2016.12.025.

Scipioni, F., White, O., Cook, J.C., Bertrand, T., Cruikshank, D.P., Grundy, W.M., et al., 2021. Pluto's Sputnik Planitia: composition of geological units from infrared spectroscopy. Icarus 359, 114303. https://doi.org/10.1016/j.icarus.2021.114303.

Singer, K.N., McKinnon, W.B., Gladman, B., Greenstreet, S., Bierhaus, E.B., Stern, S.A., et al., 2019. Impact craters on Pluto and Charon indicate a deficit of small Kuiper belt objects. Science 363 (6430), 955–959. https://doi.org/10.1126/science.aap8628.

Skjetne, H.L., Singer, K.N., Hynek, B.M., Knight, K.I., Schenk, P.M., Olkin, C.B., et al., 2021. Morphological comparison of blocks in chaos terrains on Pluto, Europa, and Mars. Icarus 356, 113866. https://doi.org/10.1016/j.icarus.2020.113866.

Stern, S.A., Bagenal, F., Ennico, K., Gladstone, G.R., Grundy, W.M., McKinnon, W.B., Moore, J.M., Olkin, C.B., Spencer, J.R., Weaver, H.A., Young, L.A., Andert, T., Andrews, J., Banks, M., Bauer, B., Bauman, J., Barnouin, O.S., Bedini, P., Beisser, K., et al., 2015. The Pluto system: initial results from its exploration by New Horizons. Science 350 (6258), aad1815. https://doi.org/10.1126/science.aad1815.

Tan, S.P., Kargel, J.S., 2017. Solid-phase equilibria on Pluto's surface. Mon. Not. Roy. Astron. Soc. 474 (3), 4254–4263. https://doi.org/10.1093/mnras/stx3036.

Tanaka, K.L., Skinner, J.A., Hare, T.M., 2010. Planetary Geologic Mapping Handbook – 2010, 2010th ed. https://astropedia.astrogeology.usgs.gov/download/Docs/Mappers/pgm_handbook_2010.pdf.

Telfer, M.W., Parteli, E.J.R., Radebaugh, J., Beyer, R.A., Bertrand, T., Forget, F., Nimmo, F., Grundy, W.M., Moore, J.M., Stern, S.A., Spencer, J., Lauer, T.R., Earle, A.M., Binzel, R.P., Weaver, H.A., Olkin, C.B., Young, L.A., Ennico, K., Runyon, K., 2018. Dunes on Pluto. Science 360 (6392), 992–997. https://doi.org/10.1126/science.aao2975.

Trowbridge, A.J., Melosh, H.J., Steckloff, J.K., Freed, A.M., 2016. Vigorous convection as the explanation for Pluto's polygonal terrain. Nature 534 (7605), 79–81. https://doi.org/10.1038/nature18016.

Umurhan, O., Howard, A., Moore, J., Earle, A., White, O., Schenk, P., Binzel, R., Stern, S., Beyer, R., Nimmo, F., McKinnon, W., Ennico, K., Olkin, C., Weaver, H., Young, L., 2017. Modeling glacial flow on and onto pluto's Sputnik planitia. Icarus 287, 301–319. https://doi.org/10.1016/j.icarus.2017.01.017.

White, O.L., Singer, K.N., Williams, D.A., Moore, J.M., Lopes, R.M.C., 2021. A Global Geological Map of Pluto at 1:7M Scale [Contribution]. Planetary Geologic Mappers 2021, Virtual, Virtual junio.

White, O.L., Moore, J.M., Howard, A.D., McKinnon, W.B., Keane, J.T., Singer, K.N., Bertrand, T., Robbins, S.J., Schenk, P.M., Schmitt, B., Buratti, B.J., Stern, S.A., Ennico, K., Olkin, C.B., Weaver, H.A., Young, L.A., 2018. Washboard and fluted terrains on Pluto as evidence for ancient glaciation. Nat. Astron. 3 (1), 62–68. https://doi.org/10.1038/s41550-018-0592-z.

White, O.L., Moore, J.M., McKinnon, W.B., Spencer, J.R., Howard, A.D., Schenk, P.M., Beyer, R.A., Nimmo, F., Singer, K.N., Umurhan, O.M., Stern, S.A., Ennico, K., Olkin, C.B., Weaver, H.A., Young, L.A., Cheng, A.F., Bertrand, T., Binzel, R.P., Earle, A.M., et al., 2017. Geological mapping of Sputnik planitia on Pluto. Icarus 287, 261–286. https://doi.org/10.1016/j.icarus.2017.01.011.

Wilhelms, D.E., 1972, October. *Geologic Mapping of the Second Planet* (Astrogeology 55). https://www.lpi.usra.edu/resources/USGS-Reports/Astro-0055.pdf.

Yamashita, Y., Kato, M., Arakawa, M., 2010. Experimental study on the rheological properties of polycrystalline solid nitrogen and methane: implications for tectonic processes on Triton. Icarus 207 (2), 972–977. https://doi.org/10.1016/j.icarus.2009.11.032.

Young, L.A., Kammer, J.A., Steffl, A.J., Gladstone, G.R., Summers, M.E., Strobel, D.F., Hinson, D.P., Stern, S.A., Weaver, H.A., Olkin, C.B., Ennico, K., McComas, D.J., Cheng, A.F., Gao, P., Lavvas, P., Linscott, I.R., Wong, M.L., Yung, Y.L., Cunningham, N., et al., 2018. Structure and composition of Pluto's atmosphere from the New Horizons solar ultraviolet occultation. Icarus 300, 174–199. https://doi.org/10.1016/j.icarus.2017.09.006.

Zhang, X., Sun, P., Yan, T., Huang, Y., Ma, Z., Zou, B., Zheng, W., Zhou, J., Gong, Y., Sun, C.Q., 2015. Water's phase diagram: from the notion of thermodynamics to hydrogen-bond cooperativity. Prog. Solid State Chem. 43 (3), 71–81. https://doi.org/10.1016/j.progsolidstchem.2015.03.006.