DSGSDs on Mars

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Deep-Seated Gravitational Slope Deformations (DSGSDs) are a set of slow and complex gravity-driven deformational processes, involving entire slopes (or large portions of them) over long time intervals. These phenomena have been identified on Mars since the early 2000s, and several detailed studies were conducted on them.

Keywords: DSGSDs ; Mars ; Landslides

1. Introduction

Evidence for slope phenomena such as landslides and other mass movements have been identified on Mars since the 1970s [1][2][3][4][5][6][7][8][9][10][11][12][13]. A particular type of slope phenomenon, well known on Earth, is represented by large-scale and slow-moving gravitational deformation and is generally known as Deep-Seated Gravitational Slope Deformation (DSGSDs).

DSGSDs are a set of slow and complex gravity-driven deformational processes, involving entire slopes (or large portions of them) over long time intervals [14][15]. These phenomena are generally characterized by deformation rates on the order of millimeter per years [15][16][17][18][19][20][21], very small if compared with their enormous dimensions [14]. Large-scale gravity-induced deformations are widespread in various morpho-structural conditions and are recognized all over the world [20]. DSGSDs are characterized by many morphological features distributed along the entire ridge-slope-valley floor system (Figure 1), such as double ridges, ridge top depressions, trenches, scarps, uphill-facing scarps, tension cracks, and toe bulging [15][17][19][22][23][24][25].

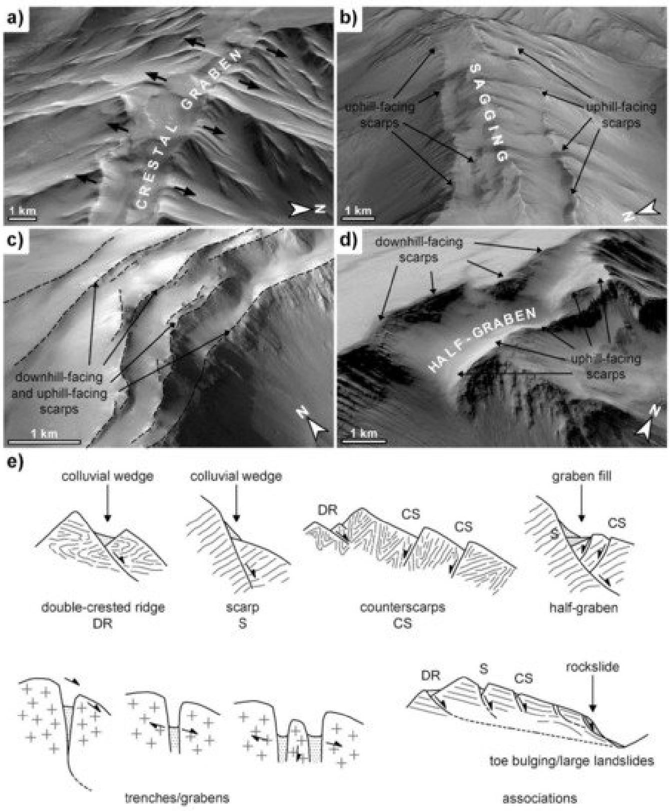

Figure 1. Examples of morphological features related to Deep-Seated Gravitational Slope Deformations (DSGSDs) on Mars: (**a**) crestal graben along the ridge at Candor-Ophir boundary; (**b**) sagging of crest line due to opposite systems of uphill-facing scarps along the inner ridge of Candor Chaos; (**c**) multiple scarps transverse to the ridge of the Melas-Candor boundary, downhill-facing along the southern margin and uphill-facing along the northern margin; (**d**) half-graben

in the upper sector of the western slope of Hebes Chasma, defined by downhill- and uphill-facing scarps; (**e**) morpho-structural features characteristics of DSGSDs, redrawn after Agliardi et al. [15]. All the Mars images were produced with Google Mars based on the MOLA gridded elevation data and CTX images.

In addition to the previously described characteristics (e.g., dimensions, low deformation rates, and assemblage of morphological features), DSGSDs differ from “conventional” landslides for some elements, such as diffuse or not well-defined boundaries [15][17][26][27], complex viscous and plastic deformations [17][28][29][30], and large space-time scale factors [14][15][19][20]. Some authors identified the absence of continuous sliding surface or basal shear zone as a typical feature of DSGSDs, thus considering them as discriminating elements with respect to “conventional” landslides [14]. Notwithstanding, these features have been recognized or inferred in many DSGSDs [15][17][18][31][32][33][34][35] and so they have lost their value as discriminating element.

DSGSDs are controlled by time-dependent deformation [21][22][28][29][36][37][38][39][40][41][42][43], acting on very long time periods [14][15][21], on the order of thousands up to hundreds of thousands years. Rock mass strain is mainly due to viscous deformation connected to deep-seated creep [22][24][36][39][44][45][46] and secondarily to ductile and viscoplastic deformation along shear planes or sliding surface [17][18][19].

Generally speaking, large-scale gravitational deformations are controlled by pre-existing and inherited geological structures, such as folds, faults, bedding planes, and schistosity [17][19][21][30][35][39][42][47][48], which act as a kinematic release and directly affect the geomechanical and rheological characteristics of rock mass at the slope scale [18][21][49][50][51]. Not infrequently, these deformations can have a paroxysmal evolution and evolve into large landslides and slope collapses [20][52][53][54].

As was the case for landslides, this type of phenomena was recently identified on Mars by various studies conducted since the early 2000s (Figure 2), when the newly available data allowed a more efficient and complete analysis of geomorphological elements that characterized the planet. In the present work, descriptions of all known existing studies of DSGSDs hypothesized on Mars are given in order to provide a complete and comprehensive picture. The main characteristics of phenomena reported in these studies are reviewed and compared with ones on Earth, to highlight similarities and differences with their terrestrial counterparts. Finally, the main open issues that emerge from the comparative analysis of these works are discussed.

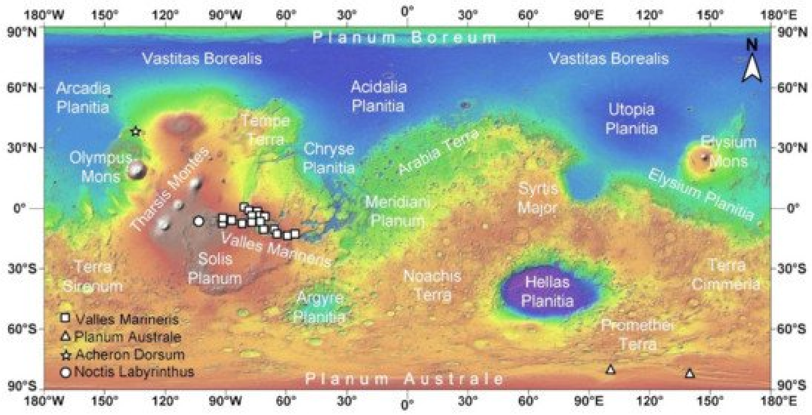

Figure 2. Locations of hypothesized major DSGSDs on Mars based on literature studies, distinct with reference to the four geographical areas described in text (Valles Marineris, Planum Australe, Acheron Dorsum, and Noctis Labyrinthus). Refer to the text for the literature of each area. The Mars image was produced with MOLA colorized hillshade.

2. State of Art

Large landslides and mass movements were discovered in Valles Marineris on Mars in the early 1970s through the first images acquired by Mariner 9 [1]. In the following years, more detailed images by the Viking missions [55] allowed realization of the first general study on Martian landslides [56] and the first analysis of related large collapse features in Gangis Chasma [57]. In the following year, a basic summary work on Martian landslides was published [2], which described 35 large-scale phenomena in Valles Marineris. Due to its topographic characteristics with the presence of large and steep slopes, this area is the region with the largest number of landslides identified on Mars [2][3][5][6][7][10][13].

Despite the numerous studies conducted on gravitational phenomena, it was necessary to wait until the early 2000s to find the first evidence for DSGSD phenomena on Mars. These deformational processes were identified on Viking images in Valles Marineris by Peulvast et al. [58], although they were not analyzed in detail. In the study of these authors, which concerns the morphology and the evolution of the slopes bordering the chasmata system, it is suggested that the ridge-top splitting may indicate slow mass movements that contribute to the wasting process.

DSGSDs on Mars have been discovered recently in many areas and then described by various studies following the work of Peulvast et al. [58]. In the following sections, all the existing studies explicitly concerning the DSGSD phenomena are described with reference to the specific geographical area (Figure 3).

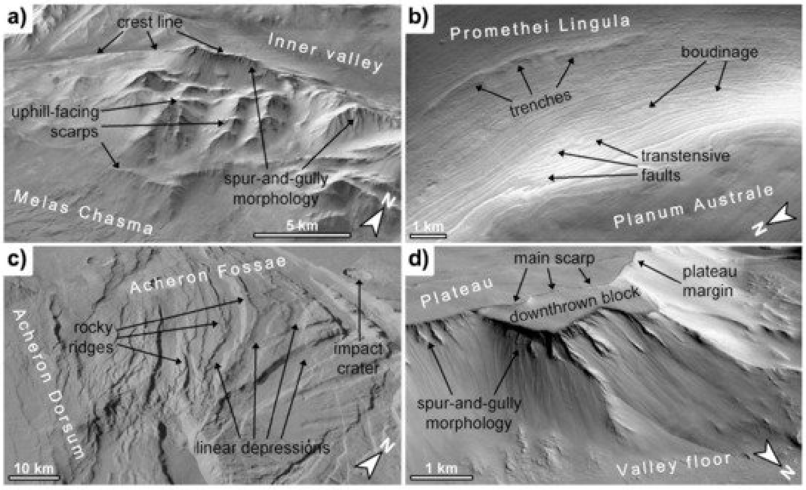

Figure 3. Examples of DSGSDs in different geographical areas of Mars: (**a**) large-scale gravitational deformation in Valles Marineris, on the southern slope of the Melas-Candor boundary; (**b**) gravity-induced deformation in Planum Australe, on the external sector of Promethei Lingula; (**c**) DSGSD in northern sector of Acheron Dorsum, involving the Acheron Fossae area; (**d**) gravity-induced deformation in the central sector of Noctis Labyrinthus, along the southern margin of E-W chasma. All the Mars images were produced with Google Mars, based on the MOLA gridded elevation data, combined with a CTX mosaic of The Murray Lab, California Institute of Technology for (**a**), and with CTX images for (**b**–**d**).

2.1. Valles Marineris

Bulmer and Zimmerman [[59]] analyzed the landslides in Coprates, Candor, and Ganges Chasmata to determine the values of H/L ratio versus volume. In the upper portion of a dislocated mass by a large landslide on the southern wall of Ganges Chasma, they identified some geomorphological features (terraces, ridges, double ridges, depressions, troughs, and uphill-facing scarps), which suggest a slow movement of the landslide body related to deep-seated gravitational creep. The multitudes of small lobes, which constitute the main landslide accumulation, therefore, would be due to many secondary phenomena favored by the development of sackung on the main landslide body. This study, while identifying a DSGSD, did not analyze in detail the characteristics of the process and possible control factors.

These aspects have been better described some years later in the following work on the Valles Marineris case. Mège and Bourgeois [60] represents the pivotal work summarizing the large-scale gravitational processes on Mars. The study focuses on possible past glaciations in Valles Marineris and on the presence of many DSGSDs, highlighted by widespread crestal graben and uphill-facing scarps along slopes and ridges in this chasma system. Like many terrestrial counterparts, the sackung in Valles Marineris appears to be connected to the ridge/slope unloading after valley deglaciation and are guided by pre-existing discontinuities, such as stratification planes, faults, joints, and schistosity. Additional factors favoring the development of sackung are wallslope height, chemical alteration by groundwater flow and hydraulic fracturing. The best examples of DSGSDs are found in Ius, Coprates, Candor Chasmata, and also at the Candor-Ophir and Melas-Candor boundaries (Figure 3a).

The role of deglaciation on the development of DSGSDs was better described in the following work of Gourronc et al. [61]. In this paper, the authors described a 3.5 Gy old glaciation in Valles Marineris and all the morphological elements that support this hypothesis. They provided further insights into the relationship between DSGSDs and post-glacial unloading. Once again, the large-scale gravitational processes founded in this area are concluded to be due to post-glacial debuttressing, while many large landslides would have occurred on glaciers and derived from the paraglacial evolution of sackung. The important insight of these works on the possible triggering mechanisms of large-scale gravitational deformation in Valles Marineris was mainly based on the geomorphological characteristics of the area but lacking quantitative analysis on the kinematics of the processes and on the post-glacial unloading of the slopes.

In those years, the quantitative study of DSGSDs had a notable boost as a result of numerical modelling of the phenomena involving the inner ridges of some chasmata in Valles Marineris. Makowska et al. [62] described the deep-seated gravitational spreading present in Coprates Chasma, performing a series of 2D numerical modelling to understand the role of destabilizing factors and the influence of slope angle and weak layers within the involved rock mass. Makowska et al. [63] conducted a similar and more accurate study for the DSGSD phenomenon affecting the horst of Geryon Montes, which well represents many gravity-induced deformations within Valles Marineris. In this later work, two series of models were examined to define the triggering of deformational phenomena: homogeneous rocks and rock masses with weak layers. In each model, the slope was destabilized through the unloading caused by glacial retreat. The two series were analyzed with different mechanical characteristics of rock masses and by varying the slope inclination between 20° and 35°. The results showed that the conditions with homogenous rock promotes the formation of bulging and uphill-facing scarps, while the conditions with weak layers favors the formations of sliding surface and slope collapse.

Other quantitative studies were produced in the same period by Kromuszczyńska et al. [64]. In this work, the authors described the geology of Valles Marineris, with particular emphasis on deep-seated gravitational spreading. They compared the offset of the gravitational uphill-facing normal faults of DSGSD phenomena on Earth and Mars highlighting at least one order of magnitude difference in dimensional scale. In addition to the morphological analysis, the work reports some 2D numerical modelling with different slope inclinations and friction angles of rock masses, which highlight how these parameters are among the most influential in the development of DSGSDs, favoring their combination for the growth of sliding surface and bulging. Kromuszczyńska and Dębniak [65] updated the morphological analysis on gravitational faults offset by introducing three dimensional parameters for the comparison between DSGSDs on Earth and Mars.

The preliminary morphological analyses carried out by some authors in the studies just described, were integrated and detailed in a subsequent work, which to date represents the latest study on DSGSDs on Mars. Kromuszczyńska et al. [66] summarized the previous studies on morphological and dimensional characteristics of Martian large-scale slope deformation. Three DSGSDs of Valles Marineris were analyzed, located in Coprates Montes, along the ridge separating Melas and Candor Chasmata and the ridge located between Candor and Ophir Chasmata. All the gravitational phenomena were considered inactive and of paraglacial origin, in accordance with many of the previous studies. The comparison of the gravitational uphill-facing normal faults offsets on Mars and Earth showed that the deformed Martian ridge are larger than the terrestrial counterparts by one or two orders of magnitude, but with similar height/width ratios. The morphological analyses suggest, therefore, that DSGSDs on Mars and Earth started under different conditions but reached the same final configuration.

2.2. Planum Australe

In the same period in which the studies on Valles Marineris were conducted, some authors analyzed different geographical locations of Mars. Regarding the Planum Australe of the southern polar region, Guallini et al. [67] analyzed brittle and ductile deformation structures within the South Polar Layered Deposits and identified DSGSD phenomena in two different external sectors of Promethei Lingula. The large-scale gravity-induced slope deformations, with different evolution grade and morphological characteristics, are devoid of clear head scarps and secondary landslides, and are probably related to climatic variation and impact events.

The morphological and kinematic characteristics of the phenomena, only preliminarily described by Guallini et al. [67], were the subjects of a more extensive and detailed subsequent work of Guallini et al. [68]. This last paper accurately describes these two large-scale gravitational deformations, which represent the first evidence for DSGSDs within a polar ice cap of a planet. The two types of gravity-induced deformations, inactive and fossilized, are characterized by scarps and trenches systems in the upper portion of the slopes and by faults, folds, disrupted layers, and bulging at the toe (Figure 3b). An evolution model showed that the DSGSDs occurred after the first phase of shallow soft-sediment tectonics, leading to the gravitational reactivation of pre-existing structures, such as normal faults and detachment horizons. These structures are attributed to the partial melting/softening of icy components within some levels in the South Polar Layered Deposits and the outward movement of the ice sheet in response of climate heating. In particular, the detachment horizons follow the weak layers within the stratigraphic succession, outward dipping of about 5–10°, and drive the extensional gravitational processes.

The role of weak layers on the development of DSGSDs and the melting/softening of icy levels during warmer periods, hypothesized in the first works, was the subject of a subsequent quantitative study. Guallini et al. [69] conducted thermal and mechanical modelling to analyze one of the previous described deformation systems. The results showed that different layers of the South Polar Layered Deposits are probably composed of CO_2 ice, which melted or deformed when surface temperatures were higher than the present. These layers probably acted as preferential shear and/or detachment planes, playing an important role in the development of deformational processes that involves the external sectors of Promethei Lingula.

2.3. Acheron Dorsum

De Blasio and Martino [70] described the evolution of Acheron Dorsum, a volcanic ridge located about 800 km north of Olympus Mons. This structure is characterized by a series of deep and wide linear depressions (or fossae), stretch in E-W direction, commonly interpreted as grabens formed by local lithosphere stress. The authors suggest that these structures (Figure 3c) may be the superficial expression of a DSGSD phenomenon (or sackung) due to the presence of a rigid layer resting on a soft and viscous layer. The 2D numerical simulation of such a ridge, along two sections, showed that viscosity values of the weak layer between 7×10^{15} and 1×10^{17} Pa·s allow simulation of the graben formation sufficiently. The spatial variability of graben orientations can be explained through both the control of pre-existing tectonic structures and the different thickness of the viscous layer.

2.4. Noctis Labyrinthus

Based on a detailed topographic reconstruction of the Noctis Labyrinthus region utilizing the Colour and Stereo Surface Imaging System (CaSSIS) data [71], Massironi et al. [72] identified a DSGSD phenomenon along a slope characterized by a downthrown block (Figure 3d). The 3-dimensional geological reconstruction of this large-scale slope deformation allowed defining of the possible sliding surface, involved volumes, and kinematics of the phenomenon. The result shows a rotational slip surface and a maximum thickness of DSGSD of about 750 m. The upper portion of the deforming masses has the same orientation of the main normal fault that cut the plateau margin.

2.4. Martian Database

Crosta et al. [12] present a database of 3118 Martian landslides. This works is associated with the study of their mobility [13], and it reports the presence of 27 DSGSDs on Mars. Typical features of double ridge and sagging were recognized in the Valles Marineris area, especially in Tithonium and Candor Chasmata, Melas Labes, Geryon Montes, and Coprates Labes. The authors underline the difficulty of discriminating the morphological elements connected to DSGSDs from forms of structural origin, especially due to their extraordinary length and constant geometrical characteristics.

3. Discussion

In the following sections, the main aspects of large-scale deformational processes on Mars are described and discussed. The most important characteristics are described by comparing them with their terrestrial counterparts, which instead are widely studied and documented.

3.1. Spatial Distribution

The hypothesized DSGSDs are widespread in different areas of Mars and involve reliefs with extremely variable geological, structural, and geomorphological characteristics. This spatial distribution reflects what were observed on Earth, where gravitational deformations have been recognized almost in every area of the planet [20]. Most of the Martian DSGSDs were found in Valles Marineris, where high energies of relief, morphological characteristics of the slopes, and geological and climatic evolution of the area favor formation of extensive gravitational slope processes [58][60][61][63][64]. Not surprisingly, landslides and mass movements also show particular concentrations in this area [2][3][5][6][7][10][13].

Further large-scale gravitational processes have been recognized in Acheron Dorsum [70], Noctis Labyrinthus [72], and Planum Australe [67][68][69]. The DSGSDs of Planum Australe are of particular interest, as they involve a succession mainly composed of an alternation of layers of dust and water–ice precipitates and represent the first evidence of large-scale gravity-induced deformation in the polar ice cap of a planet [68].

3.2. Morphological Characteristics

On Earth, there are many pieces of morphological traits characterizing DSGSDs, generally distributed along the entire ridge-slope-valley floor system, e.g., double ridges, ridge top depressions, trenches, scarps, uphill-facing scarps, tension cracks, toe bulging [15][17][19][22][23][24][25][29][38][39][45][46][73][74][75][76][77]. Often these morphological elements represent the gravitational re-activation of pre-existing tectonic structures [17][25]. On Mars, these types of phenomena show very similar morphological characteristics, although at least one order of magnitude larger due to the greater sizes of the slopes [64][65][66]. The typology of morphological elements found in the DSGSDs on Mars is comparable with those of the large-scale phenomena on Earth, as no peculiar elements have been found. The different dimensions in the Martian DSGSDs are probably due to the different conditions of the planet, where the lower gravity favors the formation of higher end extended slopes; these conditions imply the development of proportionally larger phenomena, as the greater volumes are necessary to achieve stresses that can favor the initiation and development of gravitational deformations.

In generally, there are notable differences in morphological characteristics according to the geological settings to which the DSGSDs belong: (*i*) in Valles Marineris the deformational processes are mainly characterized by double-ridges, crestal graben, and uphill-facing scarps [59][60][61][64][65][66], while the other morphological elements and especially the bulging are rarely observable due to the thick detrital covers [60][66]; (*ii*) in the other sectors, the deformations are mainly characterized by trenches, faults, and bulging [68][70][72]. This differentiation seems to be both due to the genetic characteristics of DSGSDs and the geological-structural setting of the relief.

The DSGSDs in Valles Marineris are among the most spectacular of Mars, both for their considerable size and for the specific geomorphological characteristics. Along the chasmata flanks, the gravity-induced deformations appear as single-sided phenomena, mainly characterized by scarp and uphill-facing scarp systems [60][66]. In correspondence of the internal ridges, on the other hands, the large-scale gravitational deformations appear as double-sided phenomena, mainly characterized by double-ridges and crestal graben due to uphill-facing scarp systems and sagging of crest lines [12][60][66]. A typical example is the phenomenon present along the inner ridge of Candor Chaos, north of Melas Labes, where uphill-facing scarps favor the development of sagging phenomena along the upper portion of the ridge.

3.3. Control Factors

The control factors of DSGSDs are numerous and mainly related to the characteristics of the relief and to the inherited and pre-existing structures [17][25]. Among them, of particular importance are tectonic structures such as folds and faults [17][19][26][30][35][39][42][47][48][76][78][79][80] and bedding planes or schistosity [21][35][48][51][81]. These structures act as preferential weakness planes (or zones) and affect the geomechanical and rheological properties of rock masses [18][21][49][50][51]. There are also locally karst processes [29][40][82][83] and dissolution [84][85], which can affect the DSGSDs. The large-scale gravitational processes on Mars have characteristics extremely similar to those on Earth, as they are controlled by various inherited and pre-existing structures.

These conditions are highlighted on the basis of geological and geomorphological studies for the DSGSDs in Valles Marineris [60][65], where gravitational processes are often driven by the numerous tectonic elements present along the relief and at the edges of chasmata [9][58]. The role of weak layers in the evolution and development of large-scale gravitational deformations involving the internal ridges of Valles Marineris were demonstrated through a series of 2D numerical modelling for the examples along Coprates Montes [62] and Ius Montes [63].

In the other regions, the importance of inherited structures was highlighted for all the described DSGSDs. The faults and the pre-existing tectonic structures show an evident control both on the trench systems of the deformational processes of Acheron Dorsum [70] and on the main scarp of the phenomenon in Noctis Labyrinthus [72]. From this point of view, characteristic DSGSDs are those of Promethei Lingula that not only reactivated pre-existing fault systems but were also guided by the presence of weak layers at the base of the stratigraphic sequence [68], as demonstrated by thermal and mechanical modelling [69].

3.4. Trigger Factors

Triggering factors for terrestrial DSGSDs are strictly connected with the morpho-dynamics of the relief [21] and are mainly represented by morpho-climatic evolution of the area [21][27][86], topographic and tectonic stresses [48][87], river erosion [43][88], changes in water table level [17][49], tectonic deformations [29], and earthquakes/seismic shaking [20][89][90][91][92]. One of the main triggering factors in the alpine environment seems to be the post-glacial effects (e.g., slope debuttressing, glacial rebound, stress redistribution, valleys erosion, changes in slope hydrology and rock jointing), as demonstrated by numerous studies that have linked the DSGSDs with the glacier retreat and the consequent stress state variation [27][76][86][92][93][94][95][96][97][98][99][100][101][102]. On Mars, the evaluation of these factors appears to be remarkably complex due to the difficulty in obtaining reliable data on the geological evolution of slopes, the climatic history of the area, and the geomorphological processes underway at the time of the development of the DSGSDs.

Most investigators identify post-glacial unloading as the main triggering factor for large-scale gravitational deformation on Mars [60][62][63][64][66]. In particular, on the basis of detailed geomorphological analyses, some authors hypothesized ancient vast glaciation existed in Valles Marineris during the late Noachian to early Hesperian [61], which would have led (among other things) to the development of the numerous DSGSDs observable today. Some others are against the hypothesis of such vast glaciation in this region of Mars [103] and, while not directly analyzing these phenomena in detail, underline that their formation is not necessarily connected to post-glacial debuttressing.

Regarding the DSGSDs in the external portions of Promethei Lingula, the triggering of the large-scale deformational processes could be connected to the outward movement of the ice cap during the warmer periods [68]. This movement would be favored by the presence of weak layers in the stratigraphic sequence, probably melted or deformed when surface temperatures were higher than today, which control the deformational processes and acted as basal detachment planes [69].

3.5. Landslides and Slope Collapses

On Earth, the DSGSDs are often associated with secondary landslides and large slope collapses [17][21][25][27][30][47][49][53][54][97][104][105][106][107][108][109][110][111][112] that can present slow to extremely rapid kinematics [20][52]. On Mars, landslides and slope collapses appear to be connected to the locations of DSGSD phenomena, even if though the few available data do not allow drawing of certain conclusions.

For large-scale gravitational deformation external to Valles Marineris (i.e., Acheron Dorsum, Noctis Labyrinthus, Promethei Lingula), no example of secondary landslides and large gravitational collapses has been reported. The reason for this absence could be sought in the geological settings of these areas and in the limited slope heights, although in some sectors, it is possible that landslides deposits may have been sublimated, eroded, or covered and not recognizable [67].

Instead, in Valles Marineris, the conditions are greatly different, as landslides are extensively widespread both along the slopes bordering the chasmata and the ridges within them [2][3][4][6][7][10][12][13]. For this area, several studies report the presence of large landslides and slope collapses directly associated with DSGSDs [59][60][61][66]. Passive control of these structures on large landslides is therefore very likely [12]. Given the considerable occurrences of instability phenomena in this area where landslides and DSGSDs are often superimposed, this condition makes it difficult to assess the real influence of large-scale gravitational deformation on slope collapses.

Numerical modelling conducted for some DSGSDs in Valles Marineris [62][63][64] shows that both the higher slope inclinations and the presence of weak layers favor development of large-scale shear planes and formation of large landslides by slope collapse. Their obtained results are congruent with the state of knowledge for terrestrial processes, for which the deep control of weak layers and inherited structures is well documented for several phenomena on Earth [25][49][108][112].

4. Open Issues

The scientific literature provides many and important indications on the large-scale gravitational deformations that have occurred on Mars. The highlighted characteristics are generally compatible to those of terrestrial phenomena, demonstrating a strong analogy between the geomorphological processes of Mars and those of the Earth. Despite this, the still limited number of conducted studies and the difficulty in obtaining specific geological, geomorphological, and paleo-climatic information for Mars leave many unsolved problems.

One of the most crucial aspects certainly concerns the identification of DSGSD phenomena and their detailed study. Many gravitational slope deformations have been discovered on Mars. Nevertheless, other relevant phenomena could be present on the planet's surface, both in Valles Marineris and in the other regions. In addition, the kinematic and morpho-evolutionary characteristics of large-scale gravitational processes have been poorly studied and analyzed, apart from a few examples, and more detailed studies are desirable in this regard.

Furthermore, detailed study of gravitational processes should allow recognition of DSGSDs overlapping other geological and geomorphological processes, as evidenced by some studies for landslide deformed blocks [59] or ice cap slow moving outward [68]. In this sense, it is important to highlight the cases of overlapping between large-scale gravitational processes and tectonic elements. The latter, as described above, often control the development of DSGSDs and, therefore, it is not always straightforward to discriminate between the two [15][19]. Precisely defining whether certain morphological elements (e.g., double ridges, graben, and uphill-facing scarps) are of gravitational or tectonic origin is not a simple task [12]. Solution in this regard can come from systematic and detailed study on individual phenomenon.

On Earth, DSGSDs have extremely slow deformation rates, on the order of millimeter per years [15][16][17][18][19][20][21], and develop over larger time spans [14][15], generally on the order of thousands up to hundreds of thousands years. In relation to the huge dimension of Martian gravity-induced deformations and the different gravity conditions of the planet, it will be interesting to understand if these phenomena have deformations rates and evolution time comparable with those of their terrestrial counterparts. The understanding of these aspects can help to better define the correlations existing between the Martian and terrestrial phenomena, through the identification of analogs that are able to represent not only the morphological characteristics of the DSGSDs on Mars but also the mechanical and kinematic aspects that govern their development. In this sense, the scaling of phenomena acting in such different conditions is complex and particularly important.

Regarding the state of activity, the difficulty of carrying out specific geomorphological analyzes or monitoring the phenomena makes understanding this aspect particularly complex. Some authors suggest that both DSGSDs in Valles Marineris [66] and Planum Australe [68] are today inactive and devoid of geomorphological evolutions. On the other hand, the reduced deformation rates and the creep processes that characterize these phenomena are difficult to analyze and, therefore, further data are necessary to confirm the evaluations made by these authors on the basis of geological and geomorphological analyses. Help in this regard could come from future missions on Mars, both through the study of minor Marsquakes (produced by the rock mass deformations) and the interferometric and satellite slopes monitoring (for surface deformations).

Regarding the control factors of DSGSDs, data on the pre-existing conditions indicate that they are very similar to the terrestrial ones, while less information is available for the real triggering factors. Especially for Valles Marineris, many studies have attributed the development of gravitational processes to post-glacial effects [60][62][63][64][66], a consequence of ancient vast glaciation [61], as commonly occurs for the phenomena in the alpine environment on Earth. Despite all these studies, the difficulty of finding concrete and certain data on the geological evolution of the planet and on past tectonic, morphological, and climatic events makes the study of these factors particularly complex.

It is likely that other triggering factors identified on Earth have had influence on the evolution of these phenomena on Mars as well, such as morpho-climatic evolution, topographic and tectonic stresses, erosional processes, changes in water table, tectonic deformations, and earthquakes/seismic shaking. Nonetheless there is currently little information about them for Mars. Considering the characteristics of Mars, it is presumed that an important role is played by seismic shaking caused by Marsquakes, meteoric impacts, and volcanic events, as hypothesized for many landslides [10][12][113][114].

Finally, the paroxysmal evolution of DSGSDs and the consequent development of large landslides and slope collapses has particular importance. Although the relationship between large-scale gravitational processes and landslide have been found on Mars [59][60][61][66], many further steps forward can still be made, also through numerical modelling [62][63][64]. In fact, while control factors are well studied, there is little information on triggering factors of slope collapse even on Earth, such as tertiary creep [30][51], variation of mechanical characteristics of rock mass [21][106][115], modification of slope topography [116][117], and sudden changes in stress conditions [54][112][118].

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