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Mass Movements on Venus: Preliminary Results from Magellan Cycle I Observations

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ABSTRACT

Mass movements on Venus, seen in radar images acquired by the Magellan spacecraft during its first mapping cycle, are easily interpreted within the scheme commonly used to classify terrestrial landslides. Rock slumps, rock and/or block slides, rock avalanches, debris avalanches, and possibly debris flows are seen in areas of high relief and steep slope gradients, and are most abundant in the tectonic troughs that crisscross much of the equatorial region of Venus. Many classes of regolith and sediment movements are not seen; such features might be too small to resolve in the 75 meter per picture element radar images, or their absence may reflect the relatively thin cover of fine sediments inferred from emissivity measurements and other observations. Venusian landslides, like those found within the Valles Marineris on Mars, tend to come from escarpments typically higher than those on Earth. They appear to fall between the terrestrial and martian height to length trends--they are also somewhat larger (using length as a surrogate for volume) than terrestrial subaerial landslides but smaller than their martian counterparts. Good morphologic analogs can be found in terrestrial volcanic slides (both subaerial and submarine)--oversteepening of volcanic edifices by intrusion and subsequent lateral collapse appears responsible for shaping a number of large, isolated volcanos on Venus. Faulting and seismically-induced accelerations are probably responsible for the majority of non-volcanic mass movements. The atmosphere may participate in promoting the movement of some of the landslide debris, but environmental factors (e.g., rainfall, temperature cycling) do not appear to play as dominant a role as they do on Earth. Based on the types and locations of landslides seen in the Magellan data it is possible to scale the terrestrial occurrence rate to Venus: if Venus is as seismically and volcanically active as the Earth, than of order one major landslide (i.e., discernable in Magellan images or ~5-10 km in runout distance) should occur per year, which careful re-examination of Magellan images acquired during later mapping cycles may be able to detect.

INTRODUCTION

Analysis of Magellan radar images of the surface of Venus suggest that gradational processes on that planet are relatively weak, with estimates of re-working rates of crater ejecta by eolian processes, for example, being $<10^{-2}$ micron/yr [Arvidson et al., 1991; Arvidson et al., 1992], nearly two orders of magnitude smaller than the comparable rate on Mars [Arvidson et al., 1979]. Reflectivity measurements suggest much of Venus is covered by at most a relatively thin veneer of unconsolidated material. Contemporary environmental geomorphic processes thus seem, for the most part, to be of little consequence on Venus.

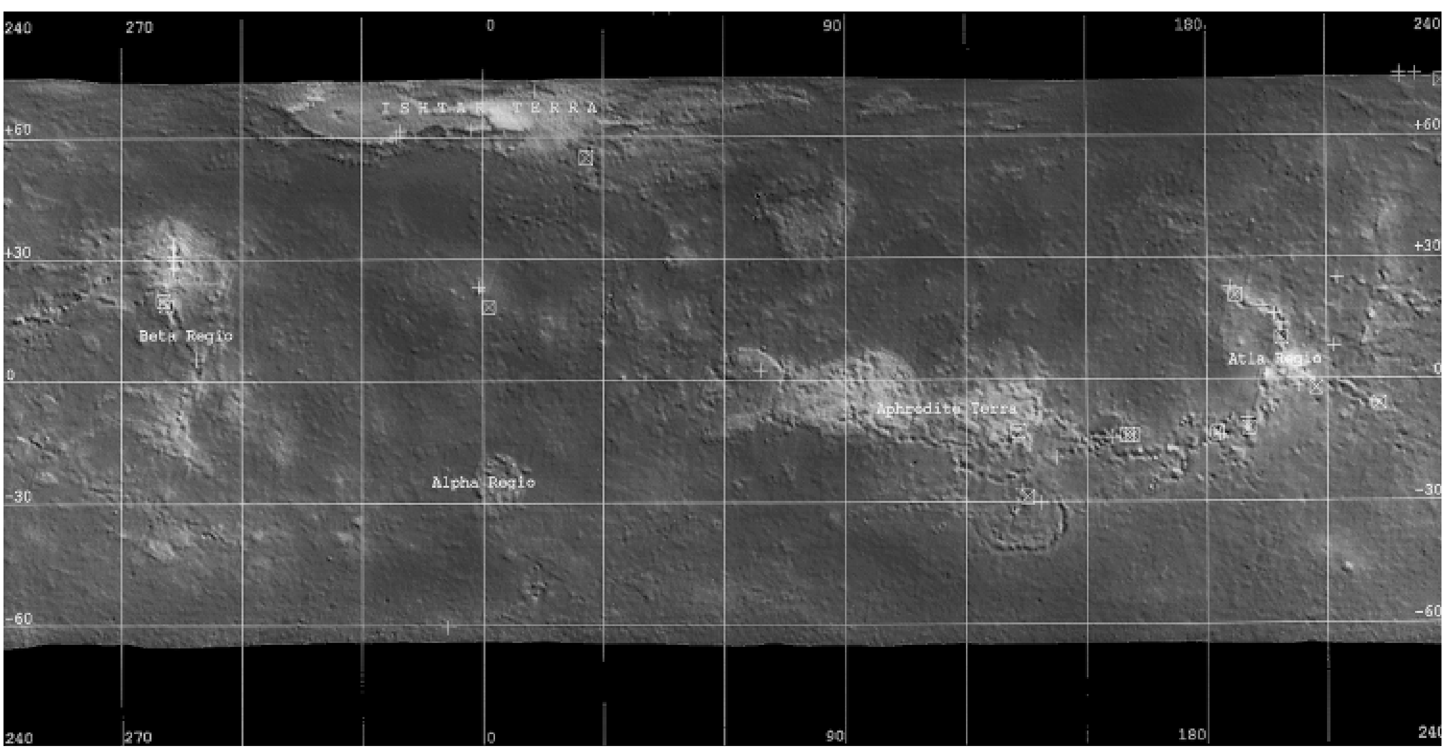


Figure 1: Map of Landslide Locations. Cylindrical equal angular projection of a shaded relief map produced from Pioneer Venus radar altimetry. Boxed crosses indicate the positions of mass movements used to illustrate this paper. Isolated crosses indicate other examined mass movements.

Tectonic processes, on the other hand, appear to be extremely effective in creating significant relief, and many local- to regional-scale slopes show evidence for formation of escarpments by displacement across faults or other bedrock fractures [e.g., Saunders et al., 1991; Solomon et al., 1991]. Given the locally high slope gradients found by Magellan [e.g., Ford and Pettengill, 1992], for example, in the mountain belts surrounding Lakshmi Planum, and previous interpretations of the relationships between RMS slope, radar reflectivity, radar scattering, and kilometer- scale morphology that suggest "tectonic weathering" in tesserae regions [Bindshadler and Head, 1989], it would not be unreasonable to anticipate evidence of mass movements in the Magellan data in these areas, despite the relatively low resolution (75 m/pixel) of such data. However, this is not the case. Although mass movement scars are found in the mountainous areas of Ishtar Terra, their occurrence is relatively limited, and there is little evidence of downslope mass movement within the tesserae. Mass movements in general appear to occur more abundantly in other localized areas (Figure 1), again with steep local slopes, which must in addition be distinguished by other characteristics.

This work describes a preliminary assessment of mass movements and their geomorphic characteristics as determined from visual inspection of Magellan Cycle 1 synthetic aperture radar images [Pettengill et al., 1991, Saunders and Pettengill, 1991]. For a few locations, local relief relationships were also derived from Magellan altimeter measurements [P. Ford, personal communication; Pettengill et al., 1991). Access to the digital altimetry products is limited by the additional processing steps involved in their production, and their location remote from the Jet Propulsion Laboratory analysis facility; thus the results presented here represent only a fraction of what may eventually be accomplished with these data.

The primary data set examined during this study was a catalog of somewhat over 200 ten-inch square photographic prints of full-resolution mosaic image data records (F-MIDRs), each covering approximately 330,000 km^2 (6 degrees in longitude by 5 degrees in latitude at the equator) at 0.075 km/pixel and reproduced at a scale of about 1:3M. These F-MIDRs cover approximately 15% of Venus. High-standing areas of intense tectonic disruption (Maxwell Montes, Alpha Regio, Ovda Regio, Beta Regio, etc.), being the most obvious places to look, were scrutinized with an 8X magnifying ocular, as were all areas that appeared to show, at the photographic scale of these prints, locally steep slopes (e.g., the opposing walls of troughs). Compact disc read-only memory (CD-ROM) versions of about 1/3 of the images became available just prior to completion of this initial analysis; the results of inspection of volatile displays of eight previously identified mass movements are also included here. Figure 1 shows the distribution of mass movements examined during this study. As expected, mass movements were found in areas of greatest topographic gradient (which, however, were not always in elevated regions). As on Mars, the walls of tectonic troughs are the richest sites of landsliding.

Owing to the geometry of radar observations, the study of steep slopes on Venus is significantly more difficult than the study of shallow slopes. Strong viewing asymmetries are apparent in the Magellan data. Slopes oriented approximately perpendicular to the radar viewing direction display foreslope shortening and/or layover, and backslope lengthening (relative to orthographic, planimetric views). These radar viewing effects act to exaggerate features both geometrically and in brightness such that longitudinal (downslope) features are seen primarily on the darker, viewing- geometry elongated slopes facing away from the radar. Features transverse to the slope (parallel to contours) are enhanced in this viewing geometry. On slopes oriented parallel to the radar, longitudinal features display characteristic ">" shapes, pointing away from the radar for depressions and towards the radar for ridges. Cross-slope forms are nearly invisible in this latter viewing geometry.

Similar though less debilitating problems are encountered in observing landslide masses subjacent to steep slopes. In general, these are distinguished by a

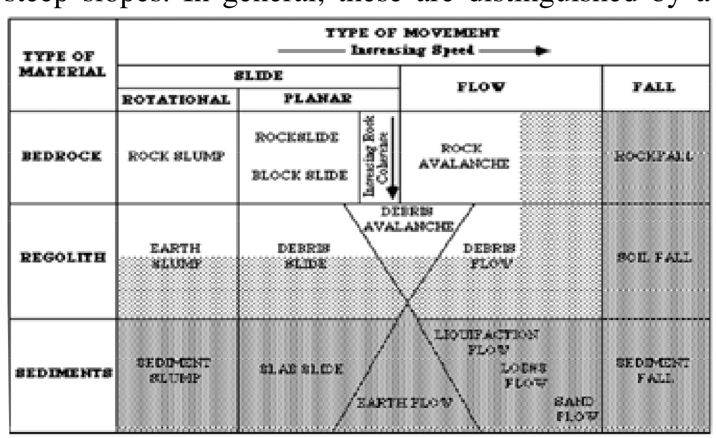


Figure 2: Classification of Mass Movements. Diagrammatic representation of mass movement classification, based on work of Sharpe [1939], Varnes [1958, 1978], and Coates [1977]. Unshaded types are inferred to occur on Venus based on morphologic observations. Light shading indicates possible occurrence on Venus. Dark shading indicates types not seen. (Modified from Coates [1977])

characteristic light, sometimes spotty pattern of surface brightness reflecting the jumbled surface topography of the landslide deposits.

OBSERVATIONS AND DESCRIPTIONS OF VENUSIAN MASS MOVEMENT FEATURES

Large mass movements on Venus are characterized by two attributes--the break-away scar left on the superjacent escarpment, and the landslide mass derived therefrom positioned at the base of the escarpment. A distinct landslide mass is typically not visible for the smallest mass movements; here the characteristic landform is the fluted or ribbed appearance of the upper slope beneath the escarpment brink and a relatively monotone and featureless surface below those ribs and flutes, reflecting the development of talus slopes.

There exists in the planetary science community a dichotomy of opinion regarding all classification schemes. One camp prefers to use non-genetic, sometimes descriptive names (e.g., Type 1 or Hilly and Lineated) while another prefers to use more traditional or terrestrially-oriented nomenclature despite the often strong genetic implications of such usage (e.g., calling a low, flat hill with lava flows a "shield volcano" or a circular, terraced depression with a central peak and raised rim an "impact crater"). Genetic implications are to be avoided in many cases, as when there is no well-understood mechanism to create a feature and to use a genetic term would be misleading, or when use of genetic terminology might lead to unfounded speculation by others. In choosing a nomenclature for venusian landslides, a relatively subjective test was used: what nomenclature would most promote effective communication while minimizing the risk of misinterpretation? After evaluating several alternatives, it was decided to use the terrestrial landslide classification scheme, as this seemed to fit the available morphological data well, was descriptive, and, although fraught with genetic implications, not without reasonable application to Venus. Thus, the classification scheme for venusian mass movements used in this work follows the conventions of Sharpe [1939], Varnes [1958; 1978], and Coates [1977], which are based on the type and coherence of material moving, and the nature and rapidity of motion. Figure 2 illustrates this classification, and highlights the range of types of mass movements observed on Venus to date.

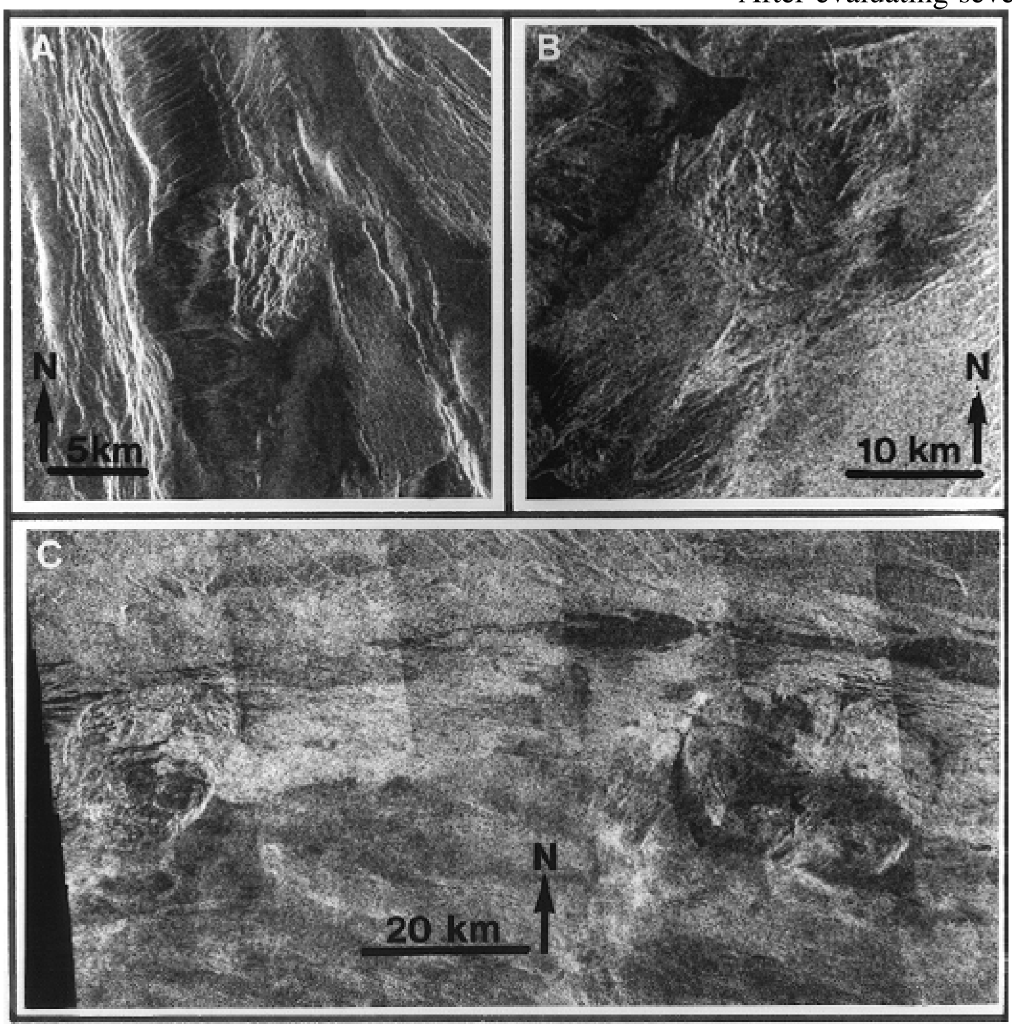


Figure 3: Rock Slumps and Rock/Block Slides.
A. Mass movement at 54.9 deg N,25.6 deg E, illuminated from the left at radar incidence angle (i) of 30 deg (enlargement from F-MIDR 55N023);
B. Possible slide at 11.4 deg S, 190.3 deg E, illuminated from left at i = 41.3 deg (enlargement from F-MIDR 10S188)
C. Three landslides located at 13.5 deg S between 159 deg E and 160 deg E; illuminated from left at i = 40.5 deg (enlargement from F-MIDR 15S157)

For venusian landslides, the application of the terrestrial classification scheme is clearly inferential, based principally upon analogous deposit morphology. Among the types of landslide deposits seen are compact, coherent masses (rock slumps and rock and/or block slides), aprons or cones of blocky material (block or rock slides and rock avalanches), relatively featureless, homogeneous slopes of high to medium radar brightness (rock and debris avalanches), and small, thin, lobate units of relatively low radar brightness (debris avalanches and flows). In the following sections, examples of each of these types are presented along with descriptions of specific features of note.

Rock Slumps and Rock/Block Slides

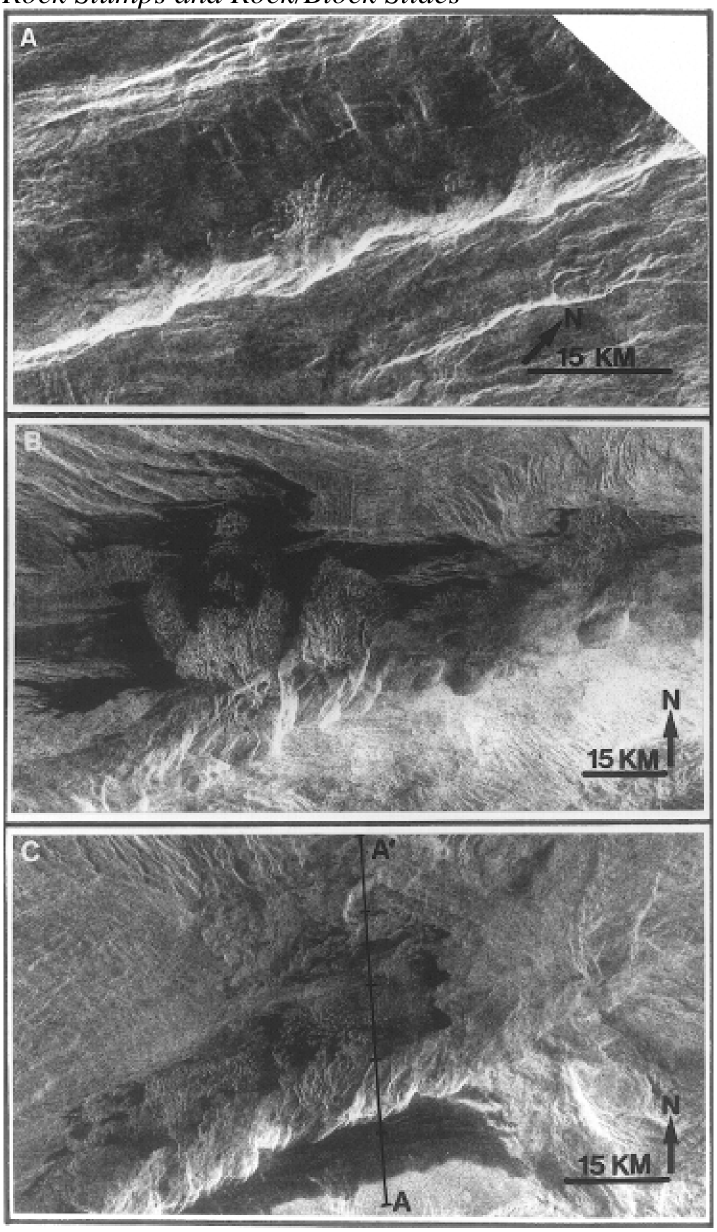


Figure 4: Rock/Block Slide- Avalanches. Note particularly the alcove-like head scarp, the distal progression from continuous, hummocky to isolated, blocky surfaces, and the dark (smooth) surface that is found on and adjacent to the most distal portions of the mass movement deposits.
A. Several slides located near 28.5 deg S, 135 deg E, illuminated from the upper left at i = 33.3 deg (portion of F-MIDR 30S136)
B. Several slides located near 13.4 deg S, 160.8 deg E, illuminated from left at i = 40.7 deg (portion of F- MIDR 15S163)
C. Several slides located near 12.4 deg S, 132.4 deg E, illuminated from left at i = 40.9 deg (portion of F- MIDR 10S132). Profile A-A' (from 12-12.5 deg S) is shown in portion of Figure 6. Marks on profile are spaced at 0.1 deg intervals. Radar altimeter resolution is about 0.07 deg (~7 km).

One form of large mass movement on Venus includes a broad headscarp theater, several subordinate units and scarps, transverse ridges, and a short, compact main body confined by well-defined, steep lateral and distal margins (Figure 3). These landslides give a strong visual impression of substantial thickness.

This form of mass movement is not particularly abundant on Venus: only five examples were found in the 200 Cycle 1 images examined in this study, and no Cycle 1 altimeter swaths passed over any of the slumps studied. Three of the five examples occur along a 120 km length of a 3.5 km high ridge at 13.5 deg N, 159.5 deg E. One of the other two occurrences (at ~11 deg S, 190 deg E) is clustered with several other types of mass movements. The remaining example (at 55 deg N, 25.5 deg E) occurs in isolation. All five are nearly as broad as they are long--the largest has a headscarp about 15 km across and a longitudinal extent of just under 25 km.

Rock/Block Slide- Avalanches

The most common form of large mass movement on Venus, illustrated in Figure 4, consists of a theater- like headscarp (concave outward and often compoundly cuspate), a relatively long, straight, steep, ridged and/ or channeled slope, and a subjacent cone or fan of material with its primary apex roughly along the longitudinal centerline extension downslope of the head theater. The lateral margins of the portion of the mass movement on the steep, upper slope are either dip- parallel or slightly convergent (channelized) downslope.

The landslide mass occurs at the base of the slope, and diverges and thins distally. A portion of the mass can at times be found superimposed on the lower portion of the slope. More often, however, the mass spreads out at the base of the slope in a fan or cone several times wider at its toe than at its head. The body of the mass is topographically more rugged than the immediately surrounding surface. Near the apex of the deposit the surface is hummocky, including both transverse and longitudinal ridges and troughs (or channels). The region of hummocks transitions distally into a zone of roughly equidimensional knobs several hundreds of meters across and larger. The knobs become smaller distally. Their areal concentration also decreases in that direction. The distal margins are often lobate or digitate. Larger examples of this type of mass movement show most of the features described above, but the smaller occurrences do not (Figure 5).

The lowland surface adjacent to the landslide mass is significantly darker (smoother) than the other surfaces

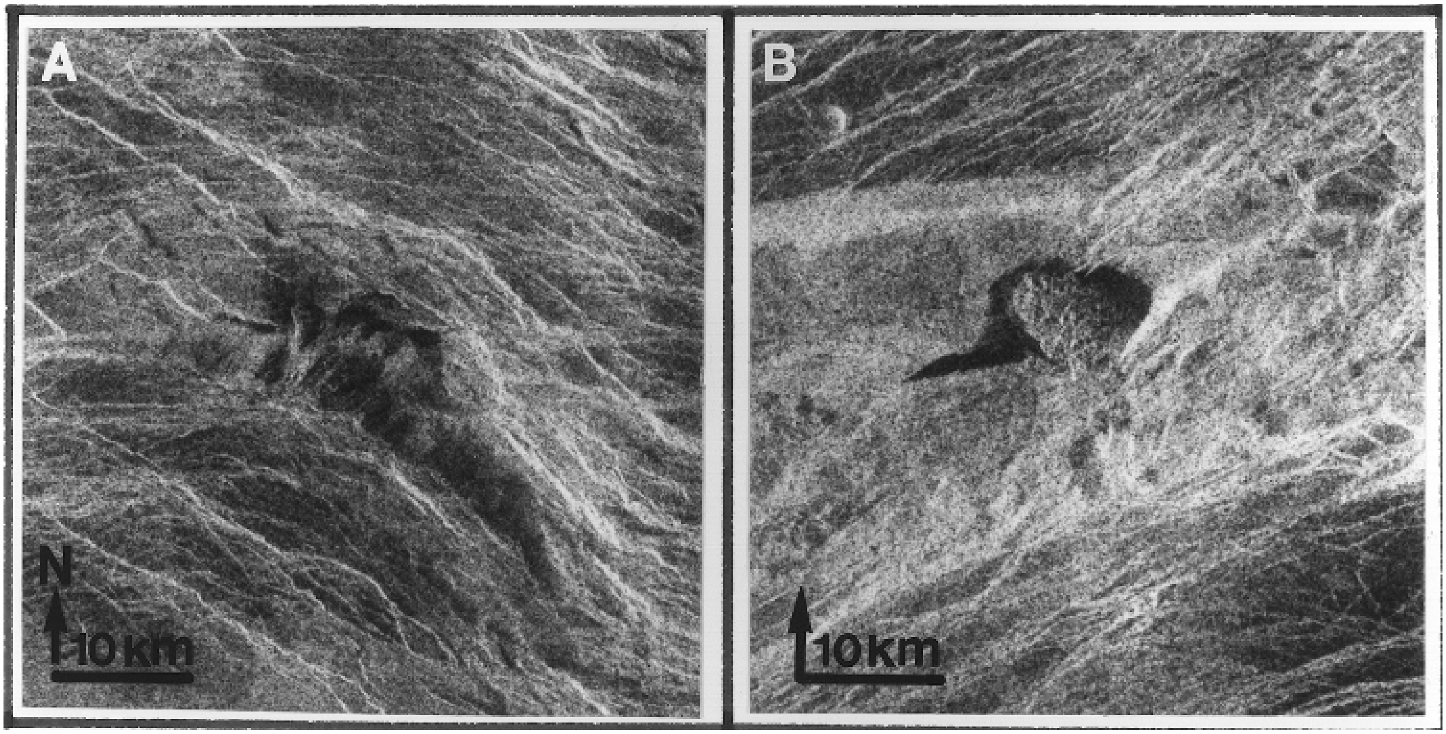


Figure 5: Small Rock Slide- Avalanches. Of particular interest for these smaller mass movements is the relationship they illustrate between the dark (smooth) surface that surrounds the hummocky/knobby portions of the landslide deposits. Their close association argues for cogenesis.

A. Several small rockslide avalanches near 2 deg S, 206.7 deg E, illuminated from left at i = 44.1 deg (portion of F-MIDR 00N205)

B. Small rockslide avalanche at 12.9 deg S, 181.9 deg E; illuminated from left at i = 40.8 deg (portion of F-MIDR 15S180)

in the near vicinity. The dark surface material in some areas embays the knobby unit, while in other areas the knobs appear superimposed on the dark unit. Similarly, in some instances the dark material appears confined to small, isolated depressions and channels, while in other instances the dark, smooth material defines a locally widespread surface.

Fortuitously, an altimeter profile passed directly over one of these mass movements (Figure 6). The horizontal resolution of the altimeter at the latitude of these observations is about 7 km, indicated by the X-axis "uncertainty bar" in Figure 6. The vertical precision of these altimetry data was about 50 m. As shown by the Y-axis "uncertainty bars", the altimeter returns were compact except for the single footprint directly over the hummocky/knobby portions of the mass movement, where the variegated small-scale topography resulted in an order-of-magnitude increase in the root-mean-square uncertainty. This uncertainty, although large, does not mask the apparent detection of the landslide deposit (approximately 500 m of relatively isolated large blocks and continuous interblock fill).

Rock- and block-slide-avalanches occur in groups (e.g., Figures 4, 15). Some of the best assemblages are found in the chasms of eastern Aphrodite Terra, where the numbers and morphologies of mass movements greatly resemble those associated with the Valles Marineris on Mars [Sharp, 1973; Blasius et al., 1977; Lucchitta, 1978, 1979, 1987], although they are somewhat smaller than their martian counterparts (see discussion of size relationships, below). In these locations, as well as at several others, there appear to be rich local histories of mass movement, with clear stratigraphic relationships between adjacent deposits.

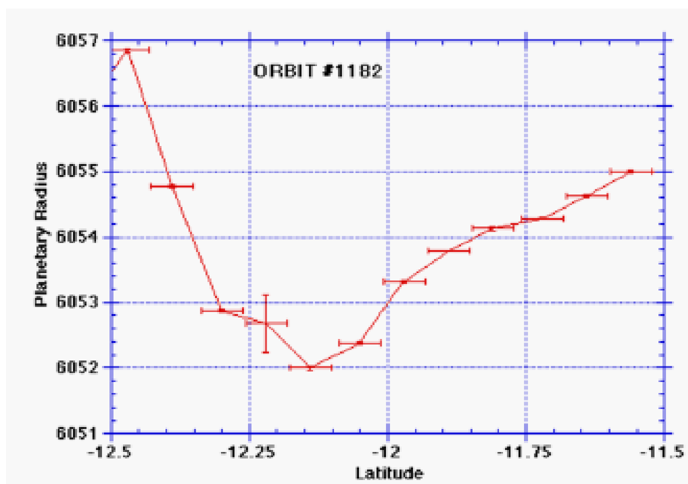
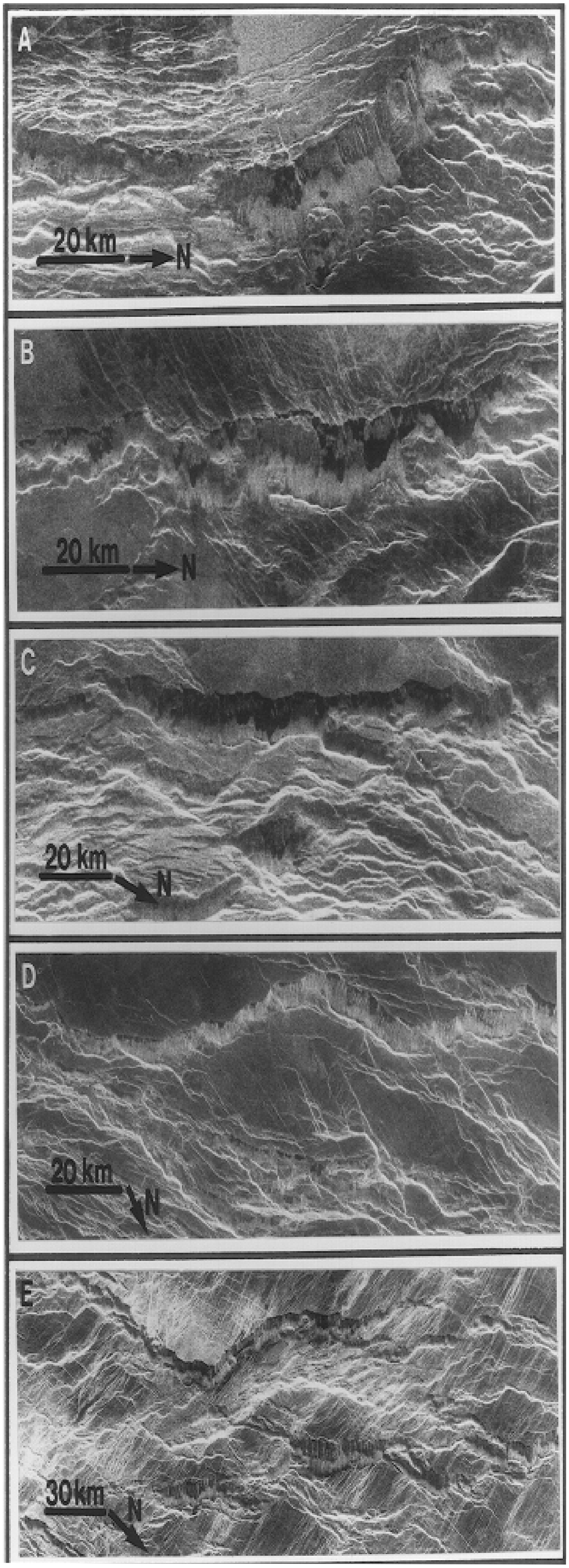


Figure 6: Topographic Profile over Rock-Slide-Avalanche. Topography across easternmost landslide in Figure 4C (Profile A-A'). Latitude "uncertainty" bars represent footprint size of altimeter (~0.07 deg or 7 km); Planetary Radius "uncertainty" bar indicates RMS variation within return, and are small except over the landslide mass itself. Landslide thickness can be estimated from this profile to be about 0.5 km (Portion of orbit profile 1182).



Rock/Debris Avalanches

Talus accumulations beneath steep, ridged and channeled slopes are the most abundant form of small mass movement on Venus. Such features are common throughout the chasmata associated with the Central Highlands. Figure 7 shows several representative examples.

As noted above, features on radar-facing slopes are difficult to see; thus, the best examples of talus slopes are those that face away from the radar, usually striking obliquely to the radar look direction and spacecraft orbit groundtrack. For such mass movement features, the slope immediately beneath the abrupt brink of the escarpment is typically fluted and ribbed with alternating chutes and spurs that extend as much as halfway down the slope. Beneath these chutes and spurs is a relatively brighter, smoother slope that is shallower in declivity. Occasionally, this lower portion of the slope is defined by subtle, side-lapping debris cones.

One of the more unusual aspects of these slopes are sharply-defined, monotonal dark areas that occur in some areas, some near the slope brink and others partway downslope. Two possible explanations for these features are that they are deposits of unusually fine material, or that they are shadows. As has been noted above, and will be discussed shortly, there is evidence elsewhere of fine material occasionally forming deposits on or subjacent to slopes. However, as the features under consideration here are found mostly in radar images taken at high radar incidence angles (typically above 40 deg), it is plausible that they are true radar shadows cast by portions of the slope that are steeper than the complement of the incidence angle (i.e., slopes between 45 and

Figure 7: Rock/Debris Avalanches in Rift Canyons. Very dark areas beneath the sharp brinks and along the slopes in several of these examples are most likely radar shadows cast by slopes steeper than the compliment of the incidence angles. In the cases where these occur partway downslope from the brink, a compound or stairstepped slope is inferred.

A. Ridged and channeled slopes and talus deposits in Devana Chasma in Beta Regio (18.8 deg N, 281.3 deg E); illuminated from top at i = 44.6 deg (enlargement from F-MIDR 20N280)

B. Ridged and channeled slopes and talus deposits in Devana Chasma in Beta Regio (20 deg N, 280.5 deg E); illuminated from top at i = 44.4 deg (enlargement from F-MIDR 20N280)

C. Slopes in Ganis Chasma (10.2 deg N, 198 deg E); illuminated from top right at i = 45.4 deg (enlargement from F-MIDR 10N200)

D. Trough near Gula Mons at 18.4 deg N, 1.2 deg E, illuminated from right (top) at i = 44.5 deg (enlargement from F-MIDR 20N003)

E. Tough near Nokomis Montes at 20.9 deg N, 186.5 deg E, illuminated from top right at i = 44.0 deg (enlargement from F-MIDR 20N186)

50 deg). That they often occur at locations beneath the brink suggest that the slope profile is stepped. A similar phenomena is found in many locations in the Valles Marineris, and may be attributed to episodic formation and modification of the troughs.

Debris Avalanches and Flows (?)

In one location, an unusual slope form was seen in close proximity to several other mass movements (Figure 8). This unusual form consists of several areas of radar dark material covering portions of a slope and the subjacent surface. The dark areas have lobate or digitate margins. They show no clearly visible relief. They are not monotonal; rather, they show downslope and distal streaking and patchiness.

Owing to their limited occurrence and the small size of their characteristic landforms (approaching the limit of resolution of the radar images), it is not possible to determine with any confidence the mode of formation of these features. Their planimetric configuration is suggestive of debris flows, although on Venus water is not available to fluidize debris. Thus, if these are flows, an alternative mechanism promoting fluid-like behavior is required. Iversen et al. [1976] noted that the venusian atmosphere has properties that place its sediment transport capabilities roughly halfway between terrestrial subaerial and submarine environments. If atmospheric gas can be ingested into moving debris, a dense flow may be generated akin to submarine turbidity flows.

Statistical Relationships of Height and Length

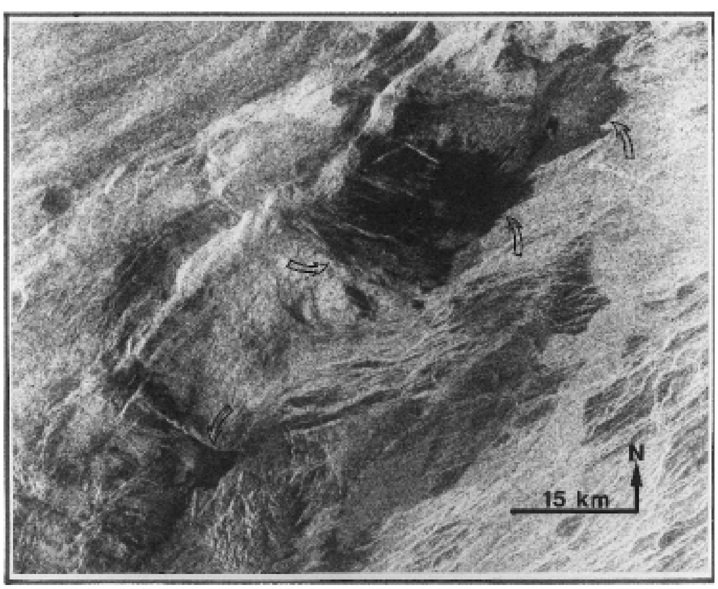


Figure 8: Possible Debris Flows. Open arrows indicate thin, dark surface deposits with lobate and digitate margins near 11.1 deg S, 190.3 deg E. Illuminated from left at i = 41.3 deg (enlargement from F-MIDR 10S188)

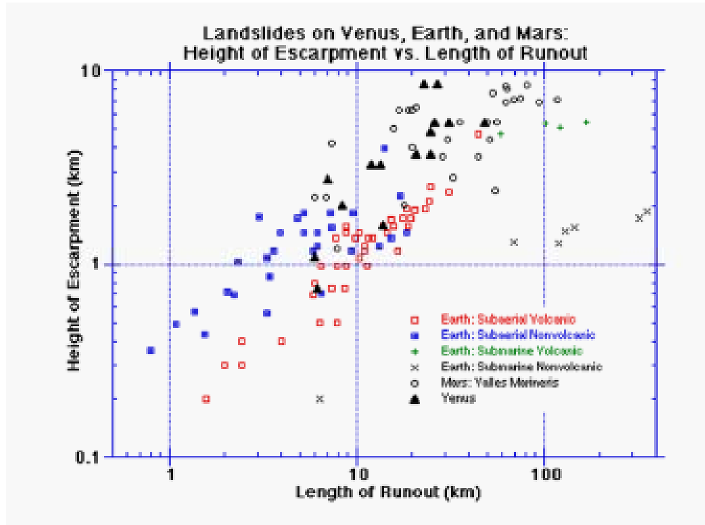


Figure 9: Graph of Head Escarpment Height and Length of Debris Runout. This graph shows that many different mass movements follow, in general, a power-law relationship between the height from which they start (their potential energy) and the distance at which they come to rest (the relative efficiency of flow). However, the range in power laws that fit the boundaries of these populations is quite large, permitting considerable variation from planet to planet.

Altimeter passes over or immediately adjacent to fifteen mass movements permit a preliminary assessment of their potential and kinetic energy relationships and efficiency of emplacement. Such analyses have been used since the pioneering work of Heim [e.g., Heim, 1932] to describe, for example, the increase in emplacement efficiency (as seen in greater runout distance) with increasing landslide mass.

Figure 9 illustrates the data available for this comparison. The height of the head escarpment relative to the position of the landslide toe, and the horizontal distance between the headscarp and toe, was measured for 15 mass movements. These values are compared to data for 40 terrestrial subaerial volcanic landslides, 29 terrestrial subaerial non-volcanic landslides, 4 terrestrial submarine volcanic landslides, 7 terrestrial submarine non-volcanic landslides, and 29 martian landslides. The terrestrial data were derived from Figure 14 of Lipman et al., [1988; see also references cited therein: Crandell et al., 1984; Hess et al., 1979; Jacobi, 1976; Moore, 1964; Moore et al., 1989; Normark and Gutmacher, 1988; Prior et al., 1984; Ui et al., 1986; and Voight et al., 1981]. The martian data were those compiled by McEwen [1989]. This particular form of display shows that terrestrial, martian, and venusian mass movements all generally follow the same trend, a power- law relationship, between the height from which they start (their potential energy) and the distance at which they come to rest (the relative efficiency of flow). Submarine non-volcanic slides, which consist of very fine-grained, unconsolidated debris, appear to travel farther for a given initial potential energy, suggesting that they are more efficient is flowing. Neither the venusian nor martian examples are distinguished from terrestrial mass movements in this plot, although both tend to fall at greater values on both axes than most terrestrial landslides.

McEwen [1989] noted that differences between terrestial and martian landslides could be seen in the power-law relationships between landslide height-to- length (H/L) ratio and volume (Figure 10). Unfortunately, it has not been possible to determine the volume of material involved in the venusian mass movements, both because of the limited topographic data and because distortions in the radar images preclude the derivation of volumes from geometry (e.g., the methods used by McEwen [1989] for the martian examples). Figure 10 is thus included here without venusian points for illustrative purposes. McEwen pointed out that the trend of the power law for martian landslides was parallel to but displaced from the terrestrial non- volcanic trend such that either a martian slide must be nearly two orders of magnitude more voluminous to achieve a given efficiency of movement (smaller H/L) or, for a given volume, martian landslide emplacement is half as efficient as emplacement on Earth. He concluded that the latter explanation probably was responsible for the observed offset, and speculated that gravitational effects on the yield strength of materials with Bingham rheology was responsible for the difference. McEwen did not include terrestrial submarine landslides in his Figure 1. He contends [McEwen, personal communication, 1992] that the occurrence of submarine volcanic slides along the trend of the subaerial terrestrial landslides is illusory, and that the submarine non-volcanic (fine-sediment-laden) slides are mudflow-like phenomena that are not comparable to the other landslides illustrated. His conclusions are controversial (see, e.g., Shaller, [1991], pg. 208-212).

Despite the absence of volumetric data, two additional plots of the available data do show interesting trends that may contribute to a better understanding of extraterrestrial mass movements. In Figure 11, H/L ratio is plotted against runout distance (L) and in Figure 12, H/L is plotted against height (H). In Figure 11, the martian landslides again appear to follow a trend separate from the terrestrial examples; the venusian landslides can be solely represented by neither the terrestrial nor martian trends. The implication of these relationships is that no single explanation has yet to describe the length and emplacement characteristics all three planets' land-

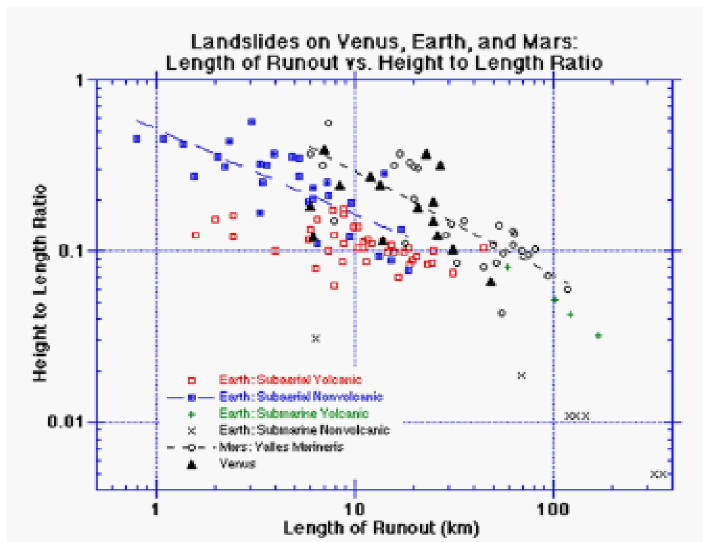


Figure 11: Graph of Height to Length Ratio versus Length. Venusian landslides appear to straddle the separate trends seen for terrestrial and martian landslides.

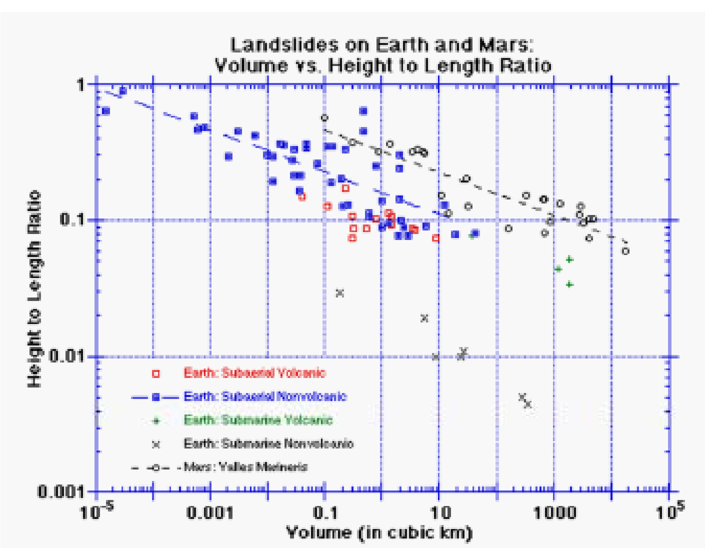


Figure 10: Graph of Height to Length Ratio versus Volume. (after Lipman et al. [1988] and McEwen [1989])

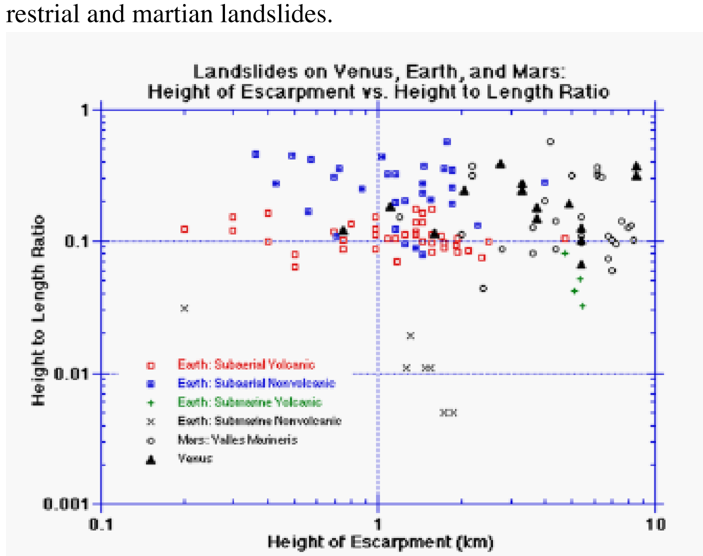


Figure 12: Graph of Height to Length Ratio versus Height. Venusian and martian mass movements appear to originate from greater heights than do their terrestrial counterparts.

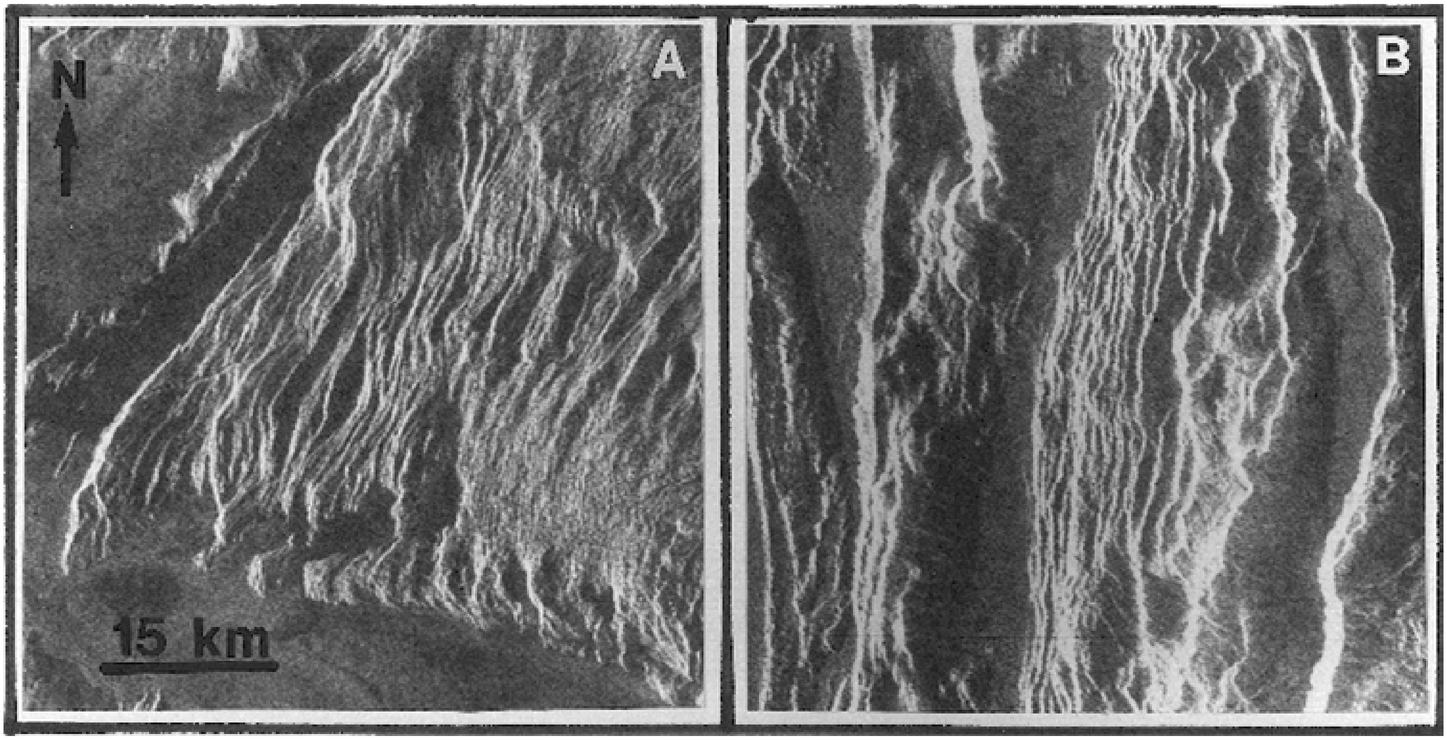


Figure 13: Multiple (Compound) Escarpments. Evidence of mass movements is generally rare in areas of mountain belts and tesserae, where closely spaced fractures accommodate topographic relief in series of small escarpments less prone to landsliding.
A. Mountains within the Akna Montes, western Ishtar Terra, at 69.4 deg N, 309.5 deg E; illuminated from left at i = 23.5 deg (portion of F-MIDR 70N310)
B. Mountains within the Akna Montes, western Ishtar Terra, at 71.5 deg N, 318.5 deg E; illuminated from left at i = 22.8 deg (portion of F-MIDR 70N310)

slides. Figure 12 shows that there is very little overlap in escarpment height between the Earth on the one hand, and Mars and Venus on the other. The majority of martian and venusian mass movements are associated with escarpments significantly higher than those found on Earth. This is in part an observational bias: most of the studies of terrestrial landslides involve field observation and the use of topographic maps that resolve the details of their morphology, while data for the martian and venusian cases involve only remote-sensing that excludes many smaller landforms not visible or difficult to observe. However, it may also be true that escarpments on Mars and Venus are typically larger than those on Earth because competing processes that reduce such slopes on Earth are not active on these other planets.

DISCUSSION

This discussion will focus on three main topics: the passive factors favoring landslides, the active factors initiating mass movements, and the timescales over which mass movements are occurring.

Passive Factors that Favor Mass Movements

On Earth, passive conditions favoring mass movements fall into five general categories: topographic (steep slopes created by erosion, intrusion, or tectonism), structural (dipping beds, faults, or joints; unrelieved stress created by tectonic deformation), lithologic (the occurrence of weak or unconsolidated materials, beds, and/or fracturing within areas of steep slopes), stratigraphic (the presence of incompetent beds within a sequence of competent materials), and environmental (the amount and rate of introduction of water onto and into the surface material).

Topography

On Venus, the creation of locally high relief is probably the most important factor in establishing the conditions necessary but not sufficient for mass movements to occur. The nature of the relief created by venusian tectonism, however, must be moderated by lithology and stratigraphy, as Venus displays a wide range in topographic conditions. For example, long, steep, high-relief escarpments in the mountain belts of Ishtar Terra, or within the tesserae, are rare. Where they do occur, such escarpments occasionally show good evidence for mass movements, including ridge and channel forms, repetitiously cuspate (adjacent) main scarps, and, occasionally, multiple block units and transverse ridges. However, typically such evidence of landslides is missing, there are few thick debris accumulations at the bases of the escarpments, and rare, faint albedo patterns are the only indication that debris is at times carried out onto the subjacent surfaces.

Why are there so few mass movements in these areas? The explanation may lie in the observation that much of the local and regional relief in these areas appears to be accommodated in compound sets of roughly parallel escarpments (Figure 13). Each scarp or ridge tends to be only a few hundreds of meters across and comparable in height (at most). Large variations in altitude often occur in the form of multiple escarpments superimposed on broader slopes, in a pattern reminiscent of terraces or stair-steps. The paucity of large, single escarpments in these areas, and the preponderance of compound or segmented slopes, argues for a weak near- surface layer (e.g., Solomon et al. [1991] discuss several examples where strain has been limited to a layer only a few hundred meters thick). Despite this layer's weakness at shallow depth, if the weight of material behind each small escarpment is not sufficient to overcome its strength, mass movements will not occur.

Conversely, as shown in this paper, landslides do occur in other areas, for example, within the chasmata that are found throughout the equatorial region, such as those in Atla and Beta Regii. It is clear that at these locations relief can be accommodated in large, single escarpments that experience a range of gravity-aided movement. What distinguishes these areas from the highland mountains and tesserae? One possibility is that the chasmata form exclusively by extension, while the mountain belts and portions of the tesserae form by compression and, to a much lesser extent, by extension [Solomon et al., 1991; Solomon et al., 1992; Bindshadler et al., 1992]. Speculation on the possible rock mechanical or thermophysical factors that would promote closely spaced fractures displaying limited differential vertical movement in areas of compression, and more broadly separated fractures displaying significant differential throw in areas of extension, is left to those more conversant in such matters.

Lithology and Environment

On Earth, many mass movements involve unconsolidated material. This does not seem to be the case on Venus. The simplest explanation for this difference is that Venus may not be mantled by much fragmental debris [Arvidson et al., 1991; Arvidson et al., 1992]. The absence of fine-grained mantling material is at least consistent with reflectivity observations, which suggest that, aside from scattering differences resulting from variations in the concentration of course fragments (i.e., those of the scale of the radar wavelength) on and near the surface, much of the surface of Venus is covered by, on average, a rock mantle or regolith only a few tens of centimeters thick [Pettengill et al., 1988; Bindshadler and Head, 1989; Tyler et al., 1991; Arvidson et al., 1991; Arvidson et al., 1992]. The downslope movement of this rock mantle would most likely be in the form of shallow debris runs. Such debris deposits are seen only associated with large escarpments--there is excellent evidence of such transport in the form of the fluted and/or scalloped scarp brinks, slope chutes and talus deposits illustrated in Figure 7.

Why does Venus lack a substantial unconsolidated surface layer? Probably because there are no globally effective weathering processes. Impact gardening, such as created the meters-thick lunar regolith, is precluded by the thick atmosphere. Physical weathering relies on temperature or pressure variations, neither of which occur at a given location on Venus because of the overpowering, moderating effects of the same thick atmosphere. Chemical weathering on Venus may also be less capable of producing unconsolidated surficial materials, because such weathering is not occurring, or because it does not create unconsolidated products (e.g., they may be bonded together).

Even where weathering creates altered material, it might not move conveniently downslope, either because the material is of an inconvenient size (too large or too small) or of a composition that doesn't promote movement within the surface layer (e.g., it doesn't create clays). The absence of fluids capable of increasing pore pressures in surficial materials may also contribute to the difficulty in moving granular materials.

Despite these negative factors, there is at least some evidence that fine materials participate in mass movement on Venus. The dark (smooth) surfaces that surround, and are sometimes found on top of, rock-slide avalanches (Figures 4, 5 , and 8) may be textural phenomena not associated with the transport of material. However, the ponding, embayment, and superposition relationships argue most strongly for some form of material redistribution, either of fine material elutriated from the body of the avalanche during movement or from the subjacent or adjacent surfaces by wind blasts generated by such movement.. These materials could form a dense cloud over the site of a landslide which, owing to low wind speeds in the dense venusian atmosphere, might settle locally and move not unlike ash clouds over volcanic pyroclastic flows (nuée ardentes). Alternatively, ingestion of gas from the thick atmosphere might permit, towards the end of movement, the sorting of materials between sizes that could be entrained within a density flow and those that could not, resulting in distal fining of deposits. Such a phenomena is believed responsible for the sedimentological characteristics of submarine landslide deposits, where smooth-surfaced, fine-grained aprons extend from and surround the knobby blocks found in the distal portions of such deposits. These aprons are mostly turbidites (materials that flowed across the ocean floor as dense suspensions of fines and water) believed to have been generated as the landslide material was sorted during emplacement [Lipman et al., 1988; Moore et al., 1989]. In either case, the thick venusian atmosphere would be responsible for contributing the "fluidizing" material. Thus, venusian atmospheric gases may play the same role as water does in terrestrial landslides; one might search for variations with atmospheric pressure.

Stratigraphy and Structure

Like Mars, Venus hides its rock stratigraphy well, revealing it only in those few locations where troughs have cut deeply into the upper crust. The Magellan data are not of sufficient resolution to clearly resolve rock units smaller than a few hundreds of meters in thickness, and there is no clear understanding of exactly what variations might occur in the physical properties of venusian rock columns. Also, the effects of radar viewing might obscure the more common forms such stratigraphic variations might take (e.g., albedo, topographic). In the mountains and tesserae, evidence of layering in the form of albedo variations or changes in slope would be difficult to see amid the closely- spaced ridges and valleys. Occasional evidence (e.g., the brightness banding on the slope above the block slide in Figure 3A) suggests, however, that stratigraphy may contribute to venusian landslides.

Structure is clearly important to establishing the conditions favorable to mass movements on Venus. Faults and joints exist, and most of the landslides studied occur in areas of intense faulting or jointing and are localized at specific faults. However, this preliminary study has not focussed on searching for evidence of, for example, dipping beds. Such evidence will be difficult to find owing to the absence of erosional processes that would expose such features to view.

Active Factors that Initiate Mass Movements

Although sometimes it appears that landslides occur spontaneously, they do not. They are precipitated by a change in one of a variety of conditions that led, up to that time, to slope stability and that subsequently changed to a condition of slope instability. Again, on Earth, such initiating causes include removal of basal support (erosion by running water or glacial ice, softening of subjacent ground by absorption of water, etc.), overloading (accumulation of material above a slope, ejecta around a crater, etc.), reduction of friction (lubrication of a slip plane), reduction of cohesion (liquefaction), prying or wedging (changes in volume owing to pressure or temperature changes), primary creation of oversteep slopes (igneous intrusion, thrust faulting), stresses (tides), and accelerations (earthquakes). Of these factors, some are unlikely to occur on Venus (reduction of friction or cohesion through lubrication or liquefaction) and others may occur only in specific locations (removal of basal support by erosion by, for example, a rapidly flowing lava flow). These will not be treated further here.

Some venusian landslides have very specific origins. Figure 14 shows excellent examples of landslides induced by the primary creation of oversteep slopes: two volcanos that exhibit avalanche caldera. Avalanche caldera are characterized by large, theater-shaped craters open in one direction, breaches as wide as the caldera with parallel or sub-parallel sidewalls, broad aprons of blocky or hummocky deposits extending out from the breach, and, often, resurgent volcanic activity within the crater [Siebert, 1984]. Terrestrial volcanos that experience such lateral collapse (e.g., Bezymianny [Gorshkov, 1959], Shiveluch [Gorshkov and Dubik, 1970], Mount St. Helens [Crandell and Mullineaux, 1978], Socompa [Francis et al., 1985], etc.) follow a distinct evolutionary track: Repeated eruption of interlayered lava and pyroclastic materials, and intrusion, create a weakly competent pile of volcanic material. Hydrothermal alteration and intrusion further weaken the pile. Finally, instrusion rapidly strains the edifice and a portion of the volcano collapses, often triggering a substantial eruption by the catastrophic release of confining pressure on the magma at depth. The eruption of Mount St. Helens in 1980 was, in fact, a geologically minor phenomena (i.e., one that will be hard to find in the geologic record of the future) involving about 0.1 km^3 of juvenile material that attended a much more geologically important landslide of significantly greater proportions (~ 2 km^3) [Voight et al., 1981]. A debate continues regarding the exact sequence of events at Mount St. Helens: did the weight of the oversteepened northern slope simply overcome the

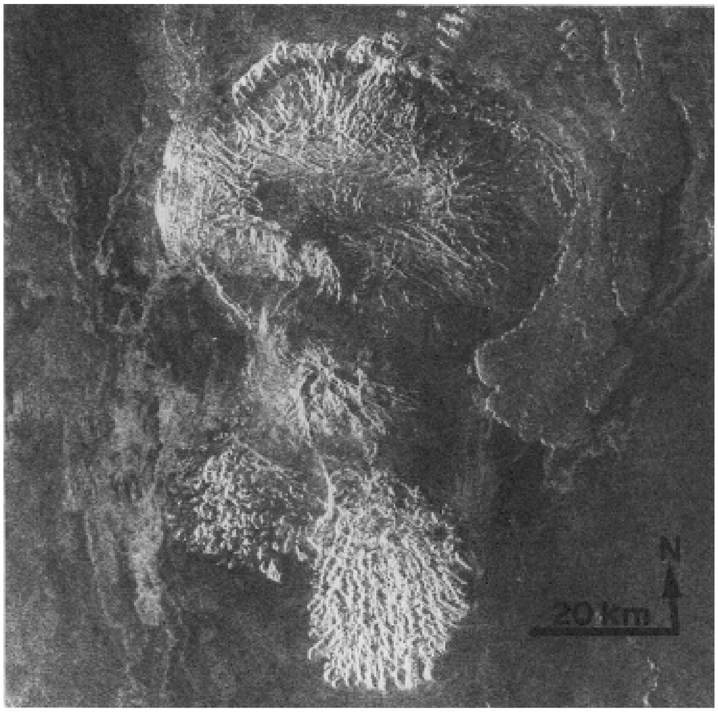


Figure 14: Volcanic Landslides. Two of several large volcanos with breached caldera and rugged avalanche deposits. These are located near 73.5 deg N, 238.5 deg E; illuminated from the left at i = 22.4 deg (portion of F-MIDR 75N237)

slope's strength, resulting in the mass movement whose acceleration mimicked a small earthquake [Kanamori and Given, 1982], and which initiated the eruption? Or did the acceleration of a small earthquake dislodge the oversteepened slope, causing the landslide and precipitating the eruption [e.g., Endo et al., 1981; Christiansen and Peterson, 1981; Voight, 1981]? Either mechanism could plausibly apply to the volcanos on Venus.

Other volcanos on Venus (see, e.g., F-MIDR 75N237, volcanos at 75.10 deg N, 232.00 deg E; 74.50 deg N, 228.00 deg E; and 75.50 deg N, 228.00 deg E) have experienced rockslide avalanches without the creation of breached caldera. These occurrences resemble the submarine landslides derived from the Hawaiian Islands [Lipman et al., 1988; Moore et al., 1989], and their genesis (through oversteepening by intrusion and overloading by extrusion) is probably similar.

Accelerations are the likely cause of most venusian mass movements. Two attributes that landslides on Venus share with their terrestrial counterparts support this contention. First, they are, for the most part, located in areas of intense tectonic deformation and associated with the largest slopes created by faulting. It is not reasonable to assume that such faulting occurs aseismically, and given the magnitude of the relief of these faults and the distances over which they extend, venusian earthquakes are likely to be more than sufficient to initiate landslides given the passive conditions discussed above. Second, many large mass movements on Venus appear in close proximity to one another (e.g., Figure 15). On Earth, groups of landslides in geologically active areas are often found to be more or less contemporaneous, presumably induced by occasional earthquakes (e.g., see Post, 1967) This may also be the case on Venus.

Time Relationships of Mass Movements

Time relationships for mass movements include the rate at which any individual movement occurs, the relative ages of adjacent landslides, the relative age of landslides with respect to other landforms, the absolute age of these features, and the present level of activity.

There is little direct evidence of the rate of emplacement of the venusian mass movements. The resolution of the image and topographic data are not sufficient to show overtopped obstacles and other morphological indications of the speed of movement. However, the distance traveled by some slides across mostly flat terrain, the apparently thin deposits at some distance from the base of the superjacent slope, the broken, jumbled appearance of the main landslide body, and at least one possible set of features that appear to be diverted by topography (the putative debris avalanche/flows seen in Figure 8), suggest that many of the venusian mass movements studied were relatively rapid. Talus deposits below chute-like scars similarly imply initially rapid movement.

Slow movements may also occur, although what process might promote such movements is unclear. Thermal cycling appears to be an inefficient process on the Moon, which experiences considerably greater temperature changes than does Venus. Other mechanisms that induce slow creep (e.g., freeze/thaw, wetting/drying, vibration, etc.) require specific material types apparently in short supply on Venus (e.g., fine debris, rupture-surface lubricants, etc.). Even the slowest events, however, are likely to be very rapid on a geological time scale.

Although it was argued earlier that groups of landslides in geologically active areas are often the same age, spatial proximity need not necessarily imply contemporaneous formation. Other indications of the time sequence (superposition or cross-cutting relationships) are needed, although even these clues can fail: simultaneous landslides can create deposits that display clear stratigraphic relationships that in fact represent very small differences in arrival times for materials at particular locations. Thus, while it is possible to illustrate in a given location the relative time sequence of events, it

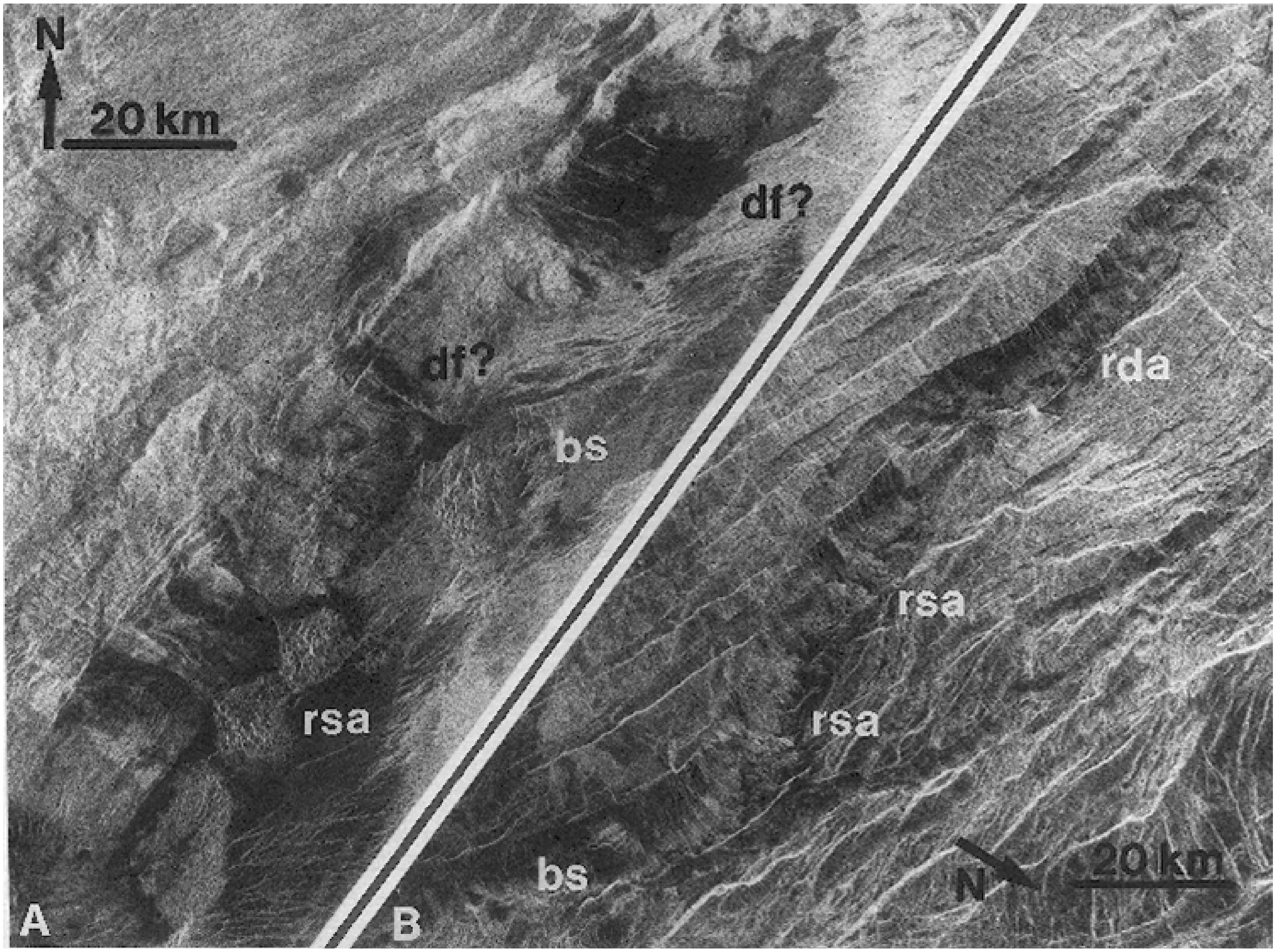


Figure 15: Grouped Landslides. rsa = rockslide avalanche; rda = rock/debris avalanche; bs = block slide; df? = possible debris flows
A. Group of several different types of landslides found near 11.5 deg S, 190.1 deg E; illuminated from left at i = 41.3 deg (portion of F-MIDR 10S188)
B. Group of several different types of landslides found near 5.8 deg S, 222.5 deg E; illuminated from upper right at i = 43.5 deg (portion of F-MIDR 05S222)

is not possible to tell whether the events occurred within a few hours or a few million years, and whether these features differ widely in age from their surroundings.

There are additional clues, however, to some of these time relationships. For example, most venusian landslides occur in areas where neighboring escarpments are as steep or steeper than those that failed. This suggests that inducing the failure is the "rate- limiting" factor. Either landslides occur at roughly the same time in a given location, or the phenomenon that induces the failure occurs repeatedly in a given area and not in immediately adjacent areas. Thus, the occurrence of mass movements may be useful in establishing the location, degree, and magnitude of seismic activity, and its relationship to building relief on Venus.

In areas of talus formation (e.g., the chasmata walls), two other time-dependent processes may be interacting to establish the limits of talus development--the rate of removal of debris from the talus slope (dependent on its rate of break-up and its rate of transport) or its redistribution at the base of the escarpment, and the rate of supply of debris from the superjacent slope (dependent on the slope-steepening rate and the weathering rate of in situ material). Obviously, if the supply rate is less than the removal rate, the slope appears denuded. If, on the other hand, the supply rate is greater than the removal rate, the process chokes in its own detritus and ceases to be effective (i.e., the talus cone extends nearly to the brink of the slope). On Earth and Mars, weathering and transport process effectiveness and slope-extension rates can be estimated from the position of the apex of the talus on the slope; similar analysis may establish these relationships for Venus.

What is the probability of observing a mass movement on Venus? Inspection of Cycle 1 images is a necessary prologue to searching for changes in later observations, but can itself not yield information on the present rate of activity. Despite the erroneous identification of an active mass movement in early Cycle 2 repeat coverage (see, e.g., Kerr [1991]), there is, at present, no clear evidence of contemporaneous activity. With data from only the first Cycle readily available, it is too early to establish a reasonable observational upper limit to the level of activity. On Earth, subaerial landslides large enough to be seen in satellite images are rare; those induced by large earthquakes (e.g., the Mt. Huascaran slides in 1962 and 1970 [e.g., Cluff, 1971; Plaker et al., 1971] or the Madison Canyon slide induced by the 1959 Hebgen Lake earthquake [Hadley, 1964]) occur, at most, a few times per decade. Volcanic avalanche craters have formed on Earth at a rate of about 4 per century [Siebert, 1984]. If Venus is as active as the Earth, and normalizing for the land surface difference, large landslides (i.e., those discernable in Magellan images or ~5-10 km in runout distance) would occur there about once a year. Magellan repeats its coverage of Venus every 240 days, so there is a finite possibility that it could observe a mass movement, provided appropriate imaging coverage is acquired.

CONCLUSIONS

Venus shows clear and unambiguous evidence of mass movements at a variety of scales. This is not unanticipated given its apparent level of tectonic activity and the seismicity that presumably accompanies this tectonism. Mass movements appear mostly in the form of block and rock movements; there is little evidence of regolith and sediment movements. Although this may reflect the relatively low resolution of Magellan data, it is also consistent with emissivity measurements that have been interpreted to indicate that much of Venus is covered by, at most, a very thin mantle of debris. This in turn is consistent with the view that Venus exhibits a relatively benign weathering environment.

Unique venusian conditions may play a role in the creation of some mass movement features. Dark (smooth) surfaces surrounding many rockslide avalanches are probably fine materials emplaced as part of the mass movement process, as airfall, surface-hugging density flows, or coarse-depleted debris flows. At least one example otherwise suggests flowing debris; if a fluidizing material is needed, atmospheric gas is the only plausible candidate.

The size and efficiency of emplacement of landslide deposits on Venus are comparable to those seen on Mars, which in turn generally resemble terrestrial occurrences. These landforms are generated on Venus, the Earth, and Mars primarily because these planets have processes that create the conditions favoring and initiating mass movements. Large landslides are not found on the Moon and Mercury, nor on the icy satellites of the outer solar system. Their existence is prima facie evidence for "active" geophysical processes on planets, and they may provide clues both to the magnitude and frequency of this activity.

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