VOLUME MEASUREMENTS OF MARTIAN LANDSLIDES: ACCURACY ASSESSMENT AND IMPLICATIONS FOR DYNAMICS.

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Introduction: Valles Marineris on Mars is known as a place of numerous and well preserved large scale landslides due to the collapse of the huge canyon walls. The average drop height of these landslides is about 6.5 km and the average run-out length is about 40 km[1]. Their morphology reflects the dynamics of the emplacement of collapsed materials and is consider as indicator of the subsurface material properties. In particular, this study focuses on the long-standing debate about the role of subsurface volatiles (water ice, clathrates, ground water). First order examination based on Viking images considered the apparent friction coefficient. This parameter given by drop height divided by the maximum run-out length ranges from 0.05 to 0.2[2] which is quite smaller than the one for dry materials (e.g., 0.6 in [3]). To explain the low friction of such long run-out landslides, several fluidization models are proposed such as internal fluid (melt water or atmospheric gases), particles interaction, and/or acoustic fluidization[4,5]. On the other hand, the friction coefficient depends to the total volume of deposit, and is mostly independent on the drop height. Then, dry rock-avalanches comparable to their terrestrial counterparts are thought to be also plausible [6,7]. Several works based on the cross sectional shape or volume measurement were carried out[1,4,8] since MOLA digital terrain model were made available. However, the question whether the Martian landslides were wet or dry is still discussed.

Insights into the dynamics of landslides can be obtained from different measurements. In order to measure the dissipated energy during the flow, we have to substract the potential energy of the deposit mass from the potential energy of the displaced mass before the event. Then the rate of dissipation can be estimated from the drop height and run-out distance. We may also want to measure the volume difference of the displaced mass after and before the collapse event. Such estimations require accurate measurements of different geometric parameters, surfaces, and volumes. The volume of landslides in Valles Marineris were already measured [1] 5% to 70% of volume deficit in the deposit were found, suggesting a substantial amount of volatile in the wall which have been removed from the deposit. However, the presence of sublimation feature is not clear on the deposits. Despite of exciting results, the actual measurement method of the deposit has still space for improvement. In this study, we develop precise methods and evaluate them to discuss the error bars on volume measurements. In addition to volume measurements, the developed method is intended to estimate the location of the gravity center of the displaced mass after its collapse and for the present deposit. This work can be considered as a key prerequisite study to any statement about energy balance of material flow dynamics of Valles Marineris landslides.

Methodology: For the accurate estimation of the volume of landslide deposits, three topographic surfaces are defined (see Fig. 1 and 2).

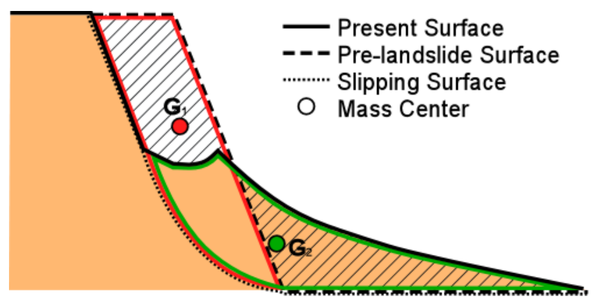

Fig.1 Schematic diagram of three surface definitions.

Extraction of the landslide surface. The present landslide surface (continuous line in Fig. 1) is defined from the present elevations of points belonging to the area which was affected by the modification (points inside the red line of the Fig. 3). The present landslide surface is obtained directly by MOLA digital terrain model.

Extraction of the pre-landslide surface. The pre-landslide surface (dashed line in Fig. 1) is defined by the reconstructed elevations before the mass flow event of the same points (inside the red line of the Fig. 3) belonging to the present landslide surface. To compute pre-landslide surface, we used linear interpolation method in a given direction from points surrounding (SP) the landslide which have been defined manually. For each desired interpolated point, we define a straight line in a given direction. The same direction is used for all the interpolated points and is usually parallel to the wall of the canyons. Then, the four closest points to the lines are selected from all the surrounding points. MOLA interpolates are excluded in the surrounding points, and only true MOLA measurements are considered. Surrounding points on local topographic changes such as mounts and crater rims have been also discarded. From the interpolation of the pre-landslide surface, we also define the region affected by displacement (moved area as defined on the Fig. 3). This surface includes the edges of deposit on the basal flat valley floor, the sides and the upper cliffs which have been modified by the mass flow. The pre-landslide surface was used to replace points inside the MOLA DTM to provide a view of the region before the landslide occurred (Fig. 4).

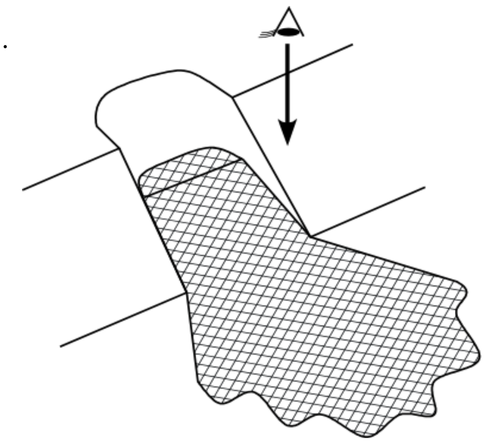

Fig.2 Birds-eye view of one landslide. Eye line suggests the view direction of fig.2.

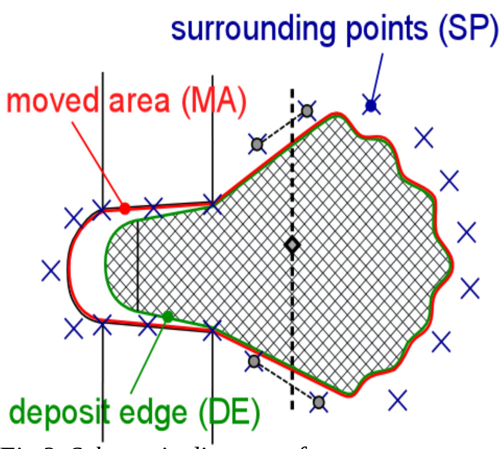

Fig.3 Schematic diagram of measurement method.

Extraction of the slipping surface. The slipping surface (dotted line in Fig. 1) is defined by the elevations of points corresponding to the subsurface boundary along which the mass flow occurred. One part of this surface is exposed at the upper cliff after the mass flow, while the other part is covered by deposited material.

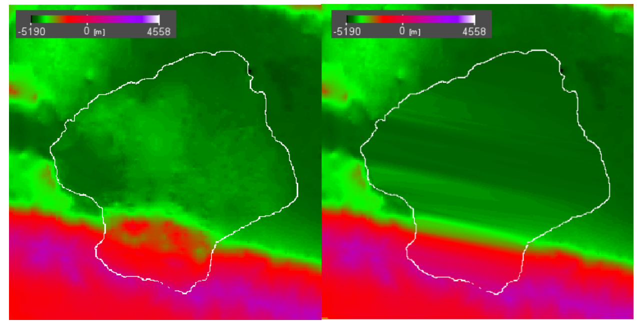

Fig.4 Present DEM from MOLA grid map of one sample site located at 11.7S, 292.2E (left) and computed pre-landslide surface (right). White line corresponds to the moved area (MA).

Slipping surface is composed from three parts; the basal flat area and the slope are which are covered by landslide deposit, and the exposed area on the upper cliff (surface belonging to MA but not to DE in Fig. 3). The exposed part is obtained by the extraction of the present landslide surface. The slipping surface on the floor is also given by the pre-landslide surface assuming for this first study little erosion of the valley floor by the landslide. The last part covered by the landslide deposit and along the wall is obtained by interpolation between the two other parts by both simple plane and minimum surface curvature [9] to check the influence of methods on the total volume estimation. Total volume estimation is important because it affects the measurement of the displacement of mass center and the volume deficit ratio given by the comparison with total volume. However, absolute value of the volume deficit or of the dissipated potential energy would not be affected by the slipping surface estimation. Indeed the common volume between the pre-landslide topography and topography after the landslide, which is bounded by the poorly defined slipping surface, cancels out in the volume difference estimation.

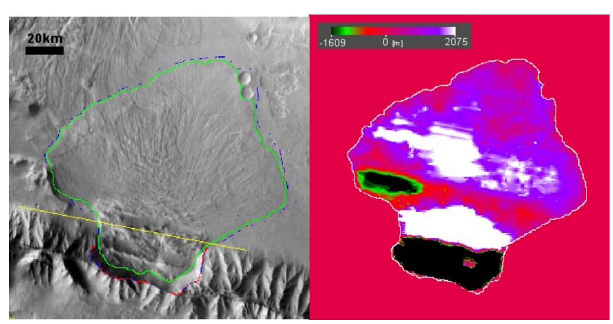

Fig.5 THEMIS IR-day mosaic image with all the data positions utilized in interpolation (left), and procedure result of "present DEM – pre-landslide surface" with deposit edge (right).

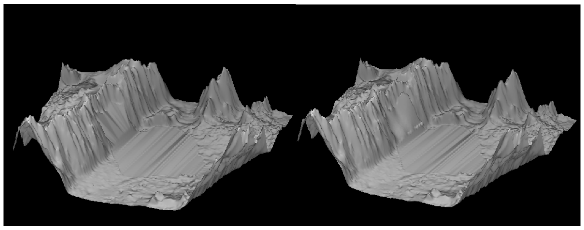

Fig.6 3D views of the slipping surfaces produced by simple plane interpolation (left) and minimum curve surface interpolation (right).

Estimation of the volume. By subtracting slipping surface from present landslide surface, we get the total volume of the deposit (moved and transported materials from their previous position). By subtracting pre-landslide surface from present landslide surface, we find negative and positive thicknesses of material. This corresponds to areas of mass removal and mass deposits. Summing all the volume within the landslide area gives the absolute value of volume change after displacement.

Result and Discussion: We measured 2 landslides along Valles Marineris as a preliminary test. Site1 and 2 is located around 11.7°S 292.2°E, 13.3°S 300.7°E respectively. Extracted present surface, pre-landslide surface, and slipping surface are shown in Fig. 4,5,6. The input data locations are shown in Fig. 5 left. Some regular noise parallel to the interpolation direction is usually found, especially on the deposit which covers the flat basal area. They are coming from bumps along the west edge of surrounding points. In the case the flowing material met obstacles such as mounds or another landslide deposit, the estimation of deposit thickness or deposit volume would be affected.

The remarkable point is that the volume changes in the two sites show opposite trend even if similar volume balance was measured in [1]. Site 2 shows slightly different value while site 1 shows larger differences when compared to [1]. The main difference is found in the total volume mass estimated before the landslide event. Topographically the site 1 shows a peculiar topography in comparison to other landslide sites. The upper part is not bounded by a plateau, so it is not possible to estimate the previous summit elevation of the landslide. In consequence, the reconstruction of the collapsed slope may underestimate the total volume of mass before it collapsed. We have also to consider a possible underestimation of the volume deposit in the case where a rough topography of the valley floor have lead to the inclusion of bumps in the estimation of this part of the pre-landslide surface. This interpretation means that the discussion of collapsed material based on the volume difference requires extremely careful measurements. The discussion of landslide mobility needs displacement of mass center which also needs careful mass distribution estimation.

	Site 1	**Site 2**
Total volume by minimum curve surface		
Before landslide [km^3]	249.08	1479.08
After landslide [km^3]	472.12	1081.56
Volume change [%]	189.55	73.12
Total volume by plane interpolation		
Before landslide [km^3]	215.52	1392.84
After landslide [km^3]	438.56	995.36
Volume change [%]	203.50	71.46
Upper shadow volume [km^3]	199.68	1347.00
Lower shadow volume [km^3]	422.76	949.48
Volume difference [km^3]	+223.05	-397.52
Dissipated potential energy [kJ]	9.7e+18	1.6e+20
Estimation of Quantin et al (2004)		
Initial Volume [km^3]	500.00	1583.46
Deposit Volume [km^3]	346.52	1021.61
Volume balance [%]	30.69	35.49
Volume difference [km^3]	-153.48	-561.85

Table.1 Result of estimated value in site1 and 2.

References: [1] Quantin C. P. et al. (2004) *Planetary and Space Sci.*, 52, 1011–1022. [2] Luccitta B. K. (1979) *JGR*, 84, 8097–8113. [3] Jaeger J. C. (1979) *London, Chapman and Hall*, 593. [4] Harrison K. P. and Grimm R. E. (2003) *Icarus*, 163, 347–362. [5] Collins G. S. and Melosh H. J. (2003) *JGR*, 108, B10, 2473. [6] McEwen A. S. (1989) *Geology*, 17, 1111–1114. [7] Soukhovitskaya V. and Manga M. (2006) *Icarus*, 180, 348–352. [8] Lajeunesse E. et al. (2006) *GRL*, 33, doi:10.1029/2005GL025168. [9] Franke R. (1982) *Comp. Math. Appls.*, 8, No. 4, 273–281.