LANDSLIDES AS INDICATORS OF THE PAST EXTENT OF INTERIOR LAYERED DEPOSITS IN VALLES MARINERIS. P. M. Grindrod[1,2] and N. H. Warner[3], [1]Earth and Planetary Sciences, Birkbeck, University of London, UK, [2] Centre for Planetary Sciences, UCL, London, UK, [3]Jet Propulsion Laboratory, Caltech, Pasadena, USA. (p.grindrod@ucl.ac.uk)

Introduction: Mounds of layered deposits, often several kilometers in height, are common in the canyons of Valles Marineris. These interior layered deposits (ILDs) are important because they not only potentially preserve long sequences of Mars' stratigraphic record, but also because the common presence of abundant hydrous mineral phases implies aqueous activity crucial to studies of habitability and life. Despite their importance, no consensus exists regarding how ILDs form, with hypotheses including tectonic, volcanic, fluvial, aeolian, and mass wasting processes [e.g. 1-4]. Recent studies have suggested that erosion, ice and alteration could all play important roles in a combined ILD formation mechanism [5,6], and indeed throughout the whole of Valles Marineris [7,8]. In this study we use landslides in Valles Marineris to gain insight into the previous extent of two large-scale ILDs.

Data and Methods: Using visible wavelength images we identified three major occurrences of landslide deposits in Ophir Chasma, Valles Marineris, which are indicative of diversion or obstruction by material that is no longer present. We used MRO CTX images (5 – 6 m/px) and stereo-derived DTMs [9] (20 m/px) to map and characterize the terminal edges of long runout landslides. In one location, where CTX stereo coverage was insufficient, we used a lower resolution HRSC DTM (50 m/px).

Observations: The landslides in this study differ from most other landslides by increasing in height towards their front edges, showing distinctive concave scarp faces that are up to 500 m above the base level, and up to 400 m higher than the preceding part of the landslide deposit. These scarps are 1 – 2 km from, and mimic the shape of, the current extent of the ILD outer boundaries (Fig. 1). Although not continuous throughout Ophir Chasma, the scarps extend between 20 and 50 km in length at different landslides, suggesting a common boundary at the northern edge of Ophir/Baetis Mensae.

Typical Valles Marineris landslide topographic profiles consist of a steep headwall in the source region, with the landslide flowing sometimes large distances downslope before gradually toeing out onto the surrounding terrain [e.g. 10]. By comparison with other landslides in Valles Marineris, it is evident that the frontal scarps that we have identified have an elevation profile that is too great to be the natural leading edge of a landslide deposit without the flow having been obstructed and piling up. The scarps are also unlikely to be depositional mounds made from material from the ILDs as they have a different geomorphic expression and have a surface texture that forms part of the landslides deposits [e.g. 11].

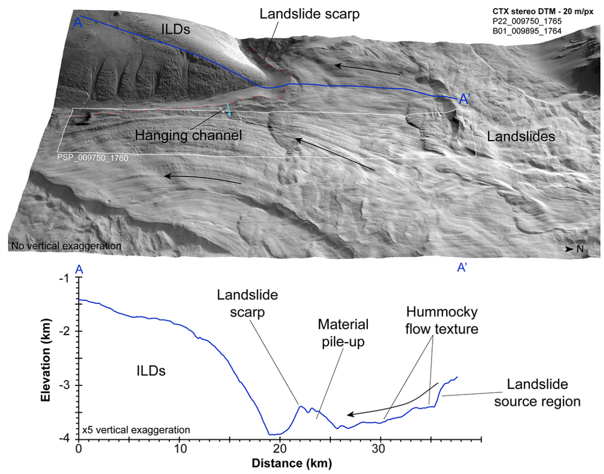

Figure 1. Example of obstruction of landslide deposits. Top: Perspective view of landslide scarp surrounding ILDs in Ophir Chasma. Bottom: Profile showing frontal scarp.

Interpretation: The most likely explanation for the formation of these scarps is that the leading edge of a landslide has piled up in front of an obstacle that has since been removed. The plausibility of this mechanism is demonstrated elsewhere in Valles Marineris, where landslides have ridden up between 500 and 800 m in height against bedrock material in the center of Coprates Chasma that has not been subsequently removed. Given that the landslide scarps mimic the outline of the ILDs, it is most likely that the landslide obstacles were ILDs that were larger in the past and have since reduced in size, effectively pulling away from the landslide front edges. This interpretation is supported by the identification of a hanging channel that begins at a landslide scarp, which must have formed when the ILD was in contact with the landslide leading edge. The channel has subsequently been cut-off at the distal end by burial by a later landslide deposit.

Estimates of Volume Loss: If we assume that the loss of ILD material evident at the front of the landslides is indicative of the loss elsewhere around the ILDs, then we can estimate the volume of material that has been removed. To prevent the landslides from overflowing the obstacle, there must have been at least 500 m depth of material removed. If material has just been lost from the northern slopes of the two ILDs, then the minimum volume removed is ~0.4 x 10^3 km^3; if however material has been lost from the entire circumference of the two ILDs then the minimum volume removed is ~1.2 x 10^3 km^3. If material has been removed from the entire ILD, rather than just at the base close to the landslide, then we can calculate maximum estimates of material loss. Again, if material has only been lost from the northern slopes of the two ILDs, then the maximum volume removed is ~1.5 x 10^5 km^3; if however material has been lost from the entire circumference of the two ILDs then the maximum volume removed is ~5.8 x 10^3 km^3.

Loss Mechanisms and Rates: There are two main ways in which the ILDs could have become smaller: by erosion or by sublimation of ice.

Aeolian Erosion. Erosion by wind has undoubtedly had an important effect on ILDs, accounting for significant surface texture modification and possibly material loss [12]. However, likely erosion rates on Mars are too low to account for such a large loss of material from the ILDs in the time since the landslides formed. Peak erosion rates on Mars are probably related to fluvial processes that occurred at the Noachian-Hesperian boundary [e.g. 13], which could remove 500 m of material in ~65 Ma. However, erosion rates have declined by at least several orders of magnitude during the Hesperian and Amazonian, when the ILDs likely formed [12], and even using the highest estimate of erosion rates during these periods would require ~5 Ga to remove 500 m of material. Thus since the formation of the ILDs in the Hesperian, and the subsequent formation of the landslides about 1 - 3 Ga later [14], erosion is even less able to account for the removal of ILD material. The lack of significant infilling by erosive products in the depression between the landslide scarps and ILDs also suggests that erosion was not the primary removal mechanism.

Ice Sublimation. Instead, the sublimation of ice from the ILDs is the most likely explanation for the removal of material that once blocked the landslides. Sublimation of ice on Mars is a complex process that depends heavily on parameters such as temperature, regolith diffusion properties, and wind [15], and so we estimate the likely minimum sublimation rate to give an upper bound on the time required to remove 500 m of ice. The likely range of temperatures experienced in Ophir Chasma [16] gives rise to sublimation rates that are up to five orders of magnitude greater than current erosion rates [17], resulting in a maximum time to remove 500 m of ice of ~57 Ma. The rate of ice sublimation is likely always several orders of magnitude greater than the erosion rate under a given environmental condition, meaning that ice sublimation is a more plausible method for removing material in the timeframe constrained by the timing of the landslides.

Implications: The ILDs that we have studied in Ophir Chasma are indicative of other ILDs in Valles Marineris, and also have similarities to ILDs in other regions such as Aeolis Mons in Gale Crater. It is well accepted that ILDs have undergone some erosion throughout their history, and therefore have probably been larger in the past, but the presence of abutting landslides in Ophir Chasma means that it is possible to quantify the material loss, which has implications further afield than this isolated canyon. Any model of ILD formation must be able to account for the significant removal of material from ILDs that we have identified. Moreover, the short timescale between landslide formation and the removal of the ILD obstacle material means that erosion alone is incapable of removing the material unless unrealistically high rates are assumed.

Instead ice sublimation processes are likely to have been the dominant removal method, which implies that a significant amount of ice was once present in the ILDs. This implication can fit with most ILD formation mechanisms if the ice is assumed to have accumulated after formation of the ILDs. However, given the large volumes of ice that must have been present over a wide range of different time periods, our results most strongly support those ILD formation mechanisms that involve ice depositional processes [5] and limited fluvial activity [6]. These observations also add weight to the growing evidence that suggests that Valles Marineris was once a huge glacial valley, with our results suggesting that terrestrial glacier-sized ice deposits were present at the equator on Mars [7,8].

References: [1] Chapman, M.G. and Tanaka, K.L. (2001) *JGR* 106, 10,087-10,100. [2] Peterson, C. (1981) *LPSC* 11, 1459-1471. [3] Lucchitta, B.K. et al. (1994) *JGR* 99, 3783-3798. [4] Nedell, S.S. et al. (1987) *Icarus* 70, 409-414. [5] Niles, P.B. and Michalski, J. (2009) *Nature Geosci.* 2, 215-220. [6] Kite, E.S. et al. (2013) *Geology* 41, 543-546. [7] Mege, D. and Bourgeois, O. (2011), *EPSL* 310, 182-191. [8] Gourannc, M. et al. (2014) *Geomorphol.* 204, 235–255. [9] Kirk, R.L. et al. (2008) *JGR* 113, E00A24. [10] Lucchitta, B.K. (1979) *JGR* 84, 8097-8113. [11] Quantin, C. et al. (2004), *PSS* 52, 1011-1022. [12] Andrews-Hanna, J.C. (2012) *JGR* 117, E06002. [13] Golombek, M.P. et al. (2006) *JGR* 111, E12S10. [14] Quantin, C. et al. (2004) *Icarus* 172, 555-572. [15] Williams, K.E. et al. (2008) *Icarus* 196, 565-577. [16] Millour, E. et al. (2012) *EPSC2012*, 302. [17] Chittendon, J.D. et al. (2008) *Icarus* 196, 477-487.