MODELLING INVESTIGATION OF TSUNAMIS ON MARS. F. Costard[1], A. Séjourné[1], K. Kelfoun[2], S. Clifford[3], F. Lavigne[4], I. Di Pietro[5] and S. Bouley[1], [1]GEOPS-Géosciences Paris Sud, Université Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bâtiment 509, 91405 Orsay, France. [2]Laboratoire Magmas et Volcans, OPGC, Clermont-Ferrand, France. [3]Lunar and Planetary Institut, Houston, Texas. Université Paris 1, [4]Laboratoire de Géographie Physique, Meudon, France. [5]Università G. Annunzio, Pescara, Italy. francois.costard@u-psud.fr.

Introduction: The possibility that a large ocean once occupied the Martian northern plains is one of the most important and controversial hypotheses to have originated from the exploration of Mars. Recently, the identification of lobate deposits, which appear to originate from within the plains and onlap the plains margin, have been interpreted as potential tsunami deposits associated with the existence of a former ocean [1, 2, 3]. Rodriguez et al. [3] argued that the deposits they identified were formed by two separate ocean impact events that occurred ~3.6–3.4 Ga, and that the location and morphological characteristics of the second event suggested a retreating shoreline and a significantly colder climate. Here we compare the geomorphologic characteristics of the Martian deposits with the predictions of well-validated terrestrial models (scaled to Mars) of tsunami wave height, propagation direction, runup elevation, and distance, for three potential sea levels. These deposits appear to have originated from one or more impact-generated tsunamis in a Martian northern ocean.

Thumbprint terrains: Arabia Terra (centered at 45°N and 10°E) encompasses part of the Vastitas Borealis Formation and shows numerous examples of thumbprint terrains. These landforms include curvilinear rides with pits, hills with concentric lobes of 10 to 20 m in thickness and individual mounds with pits. At their southern limit, thumbprint terrains exhibit peripheral pressure ridges in contact with topographic obstacles (such as knobs and mesas) which are diagnostic of viscous flows that propogated from north to south [1]. Thumprint terrains are localiszed along Contact 2 and have been interpreted as mudflows [4], mud volcanoes [5; 6], moraines, or ice-cored ridges associated with a former glacial environment [7, 8, 9], but their exact origin is still debated.

Here, we suggest that these lobate deposits were emplaced by sediments carried by one or more impact-generated tsunamis in a Martian northern ocean. Differences in the flow directions inferred from these deposits suggest that they resulted from multiple tsunami events [2]. Rodriguez et al. [3] argued that the deposits they identified were formed by two separate ocean impact events that occurred ~3.6–3.4 Ga, and that the location and morphological characteristics of the second event suggested a retreating shoreline and a significantly colder climate.

Numerical approach: Theoretical investigations of the potential generation and propagation of large tsunamis from meteorite impacts into a Martian northern ocean were previously conducted by Matsui et al. [10] and Iijima et al. [11] but no explicit geological evidence of tsunami-emplaced deposits were identified by these authors. Here we used the numerical model VolcFlow [12] to compare the propagation of an ocean impact-generated tsunami with the distribution of lobate deposits found along the dichotomy boundary [1, 2, 3].

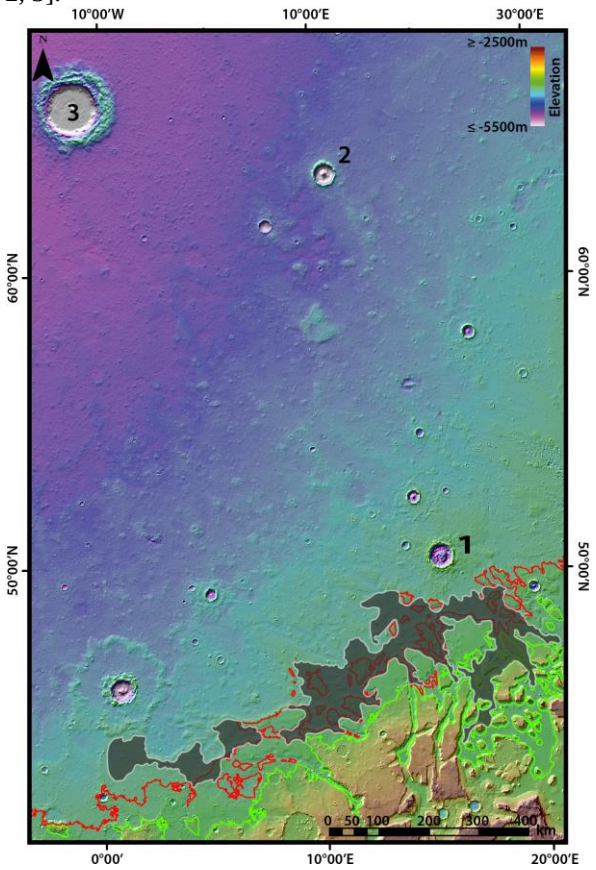

Fig. 1: The locations of the three impact craters in Acidalia Planitia considered as the potential sources of the tsunamis investigated in this study. The observed distribution of TT and terminal lobate deposits in Arabia Terra are depicted in grey. The -3940 m (red line) and -3760 m (Contact 2; green line) topographic contour lines represent the minimum and maximum elevations of the ocean shorelines considered in our numerical simulations. MOLA elevations are superimposed on a shaded relief map with Cassini projection. Courtesy of NASA/JPL/USGS. Crater 1: 50.52°N/16.39°E, crater 2: 63.70°N/10.98°E, crater 3: 64.88°N/09.15°W.

The VolcFlow model was initially developed to simulate volcanic flows such as dense pyroclastic flows and debris avalanches [13].

Given the uncertainty in the location of the impacts responsible for the generation of the tsunamis and the corresponding sea level of the paleo-ocean, we have modeled the propagation of tsunamis associated with several nearby impact craters and three shoreline elevations (-3780 m, -3860 m and -3940 m). The transient cavity produced by the impact of an asteroid into an ocean is modelled by reconstructing the pre-impact bathymetry by removing the crater and its ejecta from the present-day MOLA topography. We then modeled the topography of the transient cavity (diameter and depth) based on the ratio of the final crater diameter to the transient cavity diameter (referred to as the collapse factor) which has an average value of 1.6 in rock [14].

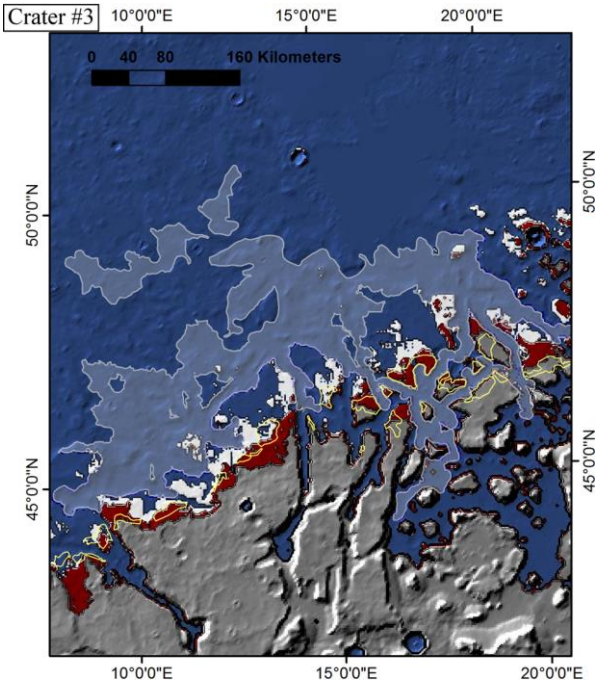

Fig.2: Numerical simulations of the propagation of a tsunami generated by the impact crater #3, assuming a sea level of -3760 m (ocean in blue). The white outline corresponds to the observed lobate deposits (TT) with runups. The simulation shows the direction and distance of propagation of the tsunami wave and the resulting inundated area (red). The inundated backwash area are in white color for the simlation and in yellow outlines for the observation.

The initial tsunami wave heights, predicted by our models [2], were on the order of 300 m at the rim of the impact transient cavity and declined to ~75 m by the time the waves reached the -3940 m shoreline, along the dichotomy boundary. The waves then continued to propagate as much as 150 km further inland (Figure 2).

Discussion: We did a comparison between the geomorphologic characteristics of the Martian thumbprint terrain, determined from a previous GIS mapping [1], with the predictions of tsunami wave height, propagation direction, runup elevation, and distance, for three potential sea levels, using our Volcflow [13] tsunami models, scaled to Mars.

Three impact craters in Acidalia Planitia were considered (Figure 1) based on their apparent age/state of degradation and locations, relative to the proposed shorelines. The crater #3 seems to be the best single candidate because the inundated areas and backwashed areas from the modelling show the best spatial correlation to the observed TT distribution (Figure 2).

Our simulations indicate that, when the initial tsunami collided with the complex topography along the dichotomy boundary, it gave rise to multiple reflected and refracted waves that propagated back out to sea creating the depositional conditions responsible for the characteristic arcuate pattern of the TT.

Conclusion: The tsunami hypothesis can explain the origin and location of the previously enigmatic TT of northern Arabia Terra which our models suggests were formed by the interaction of the refracted tsunami waves with those reflected by the shore and offshore islands/obstacles.

The detection of potential impact-generated tsunami deposits on Mars provides evidence of the existence of Martian ocean as recently as Early Amazonian, which has implications for understanding the volatile inventory Mars, its hydrologic and climatic evolution, and the potential for the origin of survival of life.

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References: [1] Costard F. et al. (2015) *EGU abstr*act n°3842. [2] Costard, F. et al. (2017) *JGR Planet*, in review. [3] Rodriguez J.A.P. et al. (2016) *Scientific Reports*, 6, 25106-1788. [4] Jöns H.P. (1986) *LPS XXVII*, 404-405. [5] Tanaka K.et al. (2014) *Geologic map of Mars* 3292. [6] Salvatore M. R. and Christensen P.R. (2014) *Geology* 42(5), 423-426. [7] Lucchitta B. K. (1981) *Icarus*, *45*, 264–303. [8] Rossbacher L.A. and Judson S. (1981) *Icarus*, *45*, 39–59. [9] Guidat G.S. et al. (2015) *EPSL*, *411*, 253-267. [10] Matsui T.I. et al (2001) *LPS XXXII*, 1716-1717. [11] Iijima, Y. K. et al. (2014) *Physical Processes in Geology*, 576. [12] Kelfoun, K. and Druitt T. H. (2005) *J. Geophys. Res.*, *110*, B12202. [13] http://lmv.univ-bpclermont.fr/volcflow/. [14] Melosh, H. J. (1989) *Impact Cratering: A Geologic Process*, 245 p.