REVISITING ICE STREAMING IN KASEI VALLES: A FLUID DYNAMICS PERSPECTIVE. A. Grau Galofre[1], A. Huff[2], and A. Noblet[1,3] [1]Laboratoire de Planétologie et Géosciences, CNRS UMR 6112, Nantes, France (anna.graugalofre@univ-nantes.fr), [2]School of Earth and Space Exploration, Arizona State University, Tempe, United States [3] Dept. of Earth Sciences, Univ. of Western Ontario, London, Canada.

Introduction: Outflow channels are among the largest, most arresting erosive landforms of Mars [1]. Up to two dozen systems of these large scoured megacanyons have been identified on Mars, spanning hundreds of kilometers in width, thousands of kilometers in length, and up to kilometers in depth. Activity in most outflow channels has been dated from the Hesperian period (~3.5-3 Byr ago) [1-3], with some channels displaying younger [2] and/or later [3] erosive episodes. Channel headwaters typically originate in collapsed chaotic terrains, are deepest at the head and decrease downflow, and rarely have tributaries [1]. Within the channels there are landforms indicative of the flow of massive amounts of fluid, including streamlined islands and longitudinal grooves and ridges, often seen diverging around obstacles.

Owing to the similar landforms carved by the Missoula megafloods observed in the Channeled Scablands on Earth [1,4], these martian outflow channels are analogously interpreted to be the result of ancient massive outburst floods [1-3], with calculated releasing discharges even larger than the terrestrial Missoula megafloods sourced by the collapse of glacial lake Missoula at the end of the last ice age [1,4]. Support for this hypothesis includes the presence and morphology of streamlined islands, the sheer scales of outflow channels, the presence of regularly spaced longitudinal ridges, and the presence of hanging valleys and U-shaped valleys [1,4,5,7]. Debate ensues, however, regarding the near surface stability and availability of liquid water during the Hesperian period required to produce erosion at the scales of observed outflow channels. Alternative hypotheses that could explain outflow channel formation include ice streaming [5-6] or regional construction and local erosion by turbulent lava flows [8-9].

Kasei Valles: Among the martian outflow channels, Kasei Valles stands out for its scale [7]. It is located in the Mare Acidalium and Lunae Palus quadrangles, flowing from the south in Echus Chasma (NW Valles Marineris) northward and then eastward into NW Chryse Planitia in a system of canyons spanning more than 2500 km long, 300 km wide, and 2 km deep at its largest [2-3]. Whereas Kasei Valles is interpreted to be the result of the catastrophic release of a subsurface aquifer located in Echus Chasma, past discussions have raised the possibility of an ice stream, *i.e.*, a fast-flowing megaglacier, playing a role in its formation [5-6]. An ice stream is the only erosive process on Earth known to cause megacanyons at a scale comparable to Kasei, with the currently active NE Greenland ice stream (Fig.1) being ~100 km wide, 600 km long, and with ice thicknesses ~1 km [10], in comparison with the Grand Canyon (446 km long, 29 km wide), or the Cheney-Palouse tract, the largest channel in the Channeled Scablands (~ 170 km long, ~60 km wide) [4].

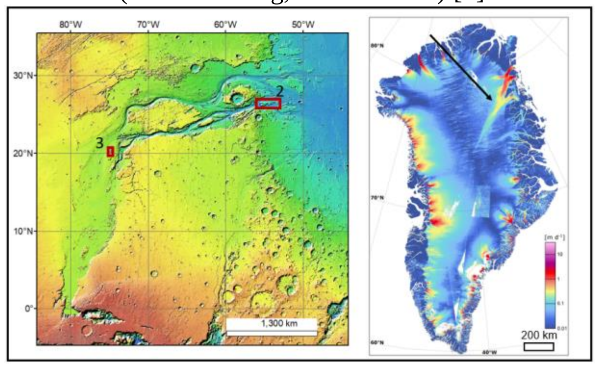

Figure 1: Kasei Valles (left, data from MOLA, MGS) showing the location of two streamlined features for analysis (2 and 3), displayed in figures 2 and 3. Greenland (right, data from ESA) showing the currently active NE Greenland ice stream (arrow), which displays a scale and planform more similar to Kasei than the Missoula megafloods.

Hypothesis: Here we revisit the hypothesis that an ice stream contributed to the erosion of Kasei Valles [5-6], being specifically responsible for the longitudinal grooves found at its bed, currently interpreted to be the result of flooding [2-4].

Methods: Landforms produced by megafloods, lava floods, and ice streams may be hard to tell apart, including longitudinal ridges and streamlined islands, making geomorphologic criteria alone insufficient to tell these processes apart [2,4,6]. However, observing how the longitudinal grooves curve around obstacles we are able to obtain an estimation of the flow Reynolds number, a measure of the fluid inertia compared to its viscosity, allowing to quantitatively differentiate between a megaflood of Missoula proportions ($Re{\sim}10^{10}$ [11]), a lava flood ($Re{\sim}\ 10^2$-10^3) and a glacier or ice stream ($Re{\sim}10^{-8}$), yielding a difference in 18 orders of magnitude in Re between the ice and the flood extremes. *Our key assumption therefore considers that the longitudinal grooves at the bed of Kasei Valles map the ancient velocity field of the fluid that carved them.*

To proceed, we use image and topographic data from CTX (6 m/pixel and 18 m/pixel respectively) and CaSSIS (4.6 m/pixel) to analyze the direction and curvature of longitudinal grooves when diverging around obstacles, as shown in figures 2 and 3. We use the Matlab Computational Fluid Dynamics (CFD) toolbox to model the flow of fluids of different Re number around obstacles. We use CTX images and derived DEM data to measure and reconstruct the morphology of the streamlined islands shown in figures

2 and 3 into finite element meshes (e.g., white/red squares in fig. 3). We then analyze how the flow paths and velocity fields compare to the geological record of longitudinal grooves for fluids of different Re number. We test this method in different streamlined islands along the Kasei Valles system, including Sacra Sulci and the Chryse Planitia fan.

Preliminary Results: Results to this point have considered flows at Re~ 0, Re~ 100, and Re~ 10^{-8}, corresponding to steady water or lava flows and ice streams, flowing around two different obstacles: an island at 26.44N, 54.69W (Chryse Planitia fan, fig. 2), and one at 20.16N, 74.82W (Sacra Sulci, fig. 3). Whereas at the time of this abstract we are working on highly turbulent flows (Re>10^6), results make apparent that higher Re numbers tend to reduce flow line curvature, whereas small Re number flows are capable to readily deform just before an obstacle and converge shortly after. This is to be expected, given the difficulty to bend flow lines in high inertia flows.

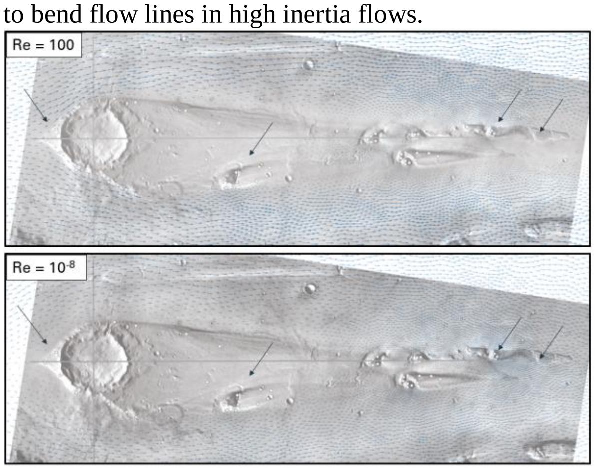

Figure 2: Streamlined obstacle on the Kasei Valles fan (indicated in fig.1) observed in THEMIS daytime infrared data (NASA/ASU), with overlying arrows showing the direction and magnitude of the fluid moving past the obstacle. Compare the sites highlighted with black arrows, and note how higher Re numbers match better the geological record than low Re.

Results for the streamlined island in Chryse Planitia support the presence of a higher Re number fluid, quantitatively discarding the erosive action of an ice stream flowing around this obstacle at the fan of Kasei Valles (fig. 2). However, results shown in figure 3 indicate that an ice stream is not only compatible, but also likely the only geophysical fluid able to produce this highly curved flow pattern around the obstacle (compare black arrows for Re = 100 and Re = 10^{-8}), given the very low inertia required for the high curvatures observed in the longitudinal grooves.

Discussion: Observations of the curvature of flow lines around streamlined islands suggest a fundamental change in the dynamics of the erosive fluid, from very low to high inertia, as Kasei approaches its terminus. Two possible explanations include the release of meltwater at high pressure, high discharges at the terminal region of an ice stream, producing the two Re behaviors observed (and consistently with terrestrial analogues), and a different timing of events.

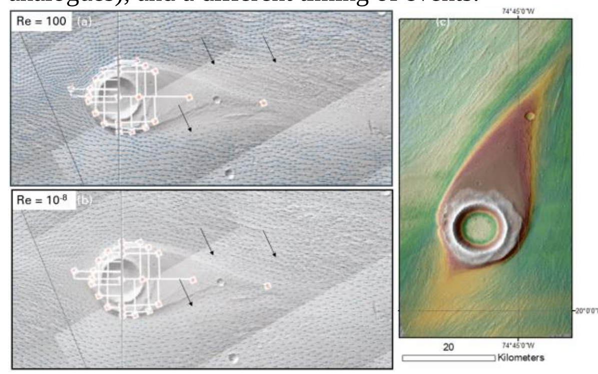

Figure 3: Left: Streamlined island in Sacra Sulci (site 3, Fig.1), represented with CTX data overlain with the fluid velocity field (arrows) at Re = 100 (steady water, lava) and Re = 10^{-8} (ice stream). The convergent and divergent groove pattern around the island is best matched by very low Re numbers, as highlighted by arrows. Right: CTX image D02_027868_2004_XN_20N074W overlain by a CTX DEM of the streamlined island.

More work is required to assess these hypotheses. Beside the longitudinal groove curvature and morphometry [5,6], Kasei Valles meets the current criteria to be considered an ice stream [12, *Grau Galofre et al., in prep.*, *Huff et al., in prep.*]: Characteristic scales, convergent flow patterns, bedforms with length-to-width> 10:1, abrupt lateral margins, and a terminal fan.

Conclusions: Fluid dynamic simulations matching longitudinal grooves at the bed of Kasei Valles show that the grooves were carved by a very low inertia flow (Re~0), which increased very significantly towards the outlet. These results are in line with the hypothesis that an ice stream played a role in the formation of Kasei Valles, being responsible for the longitudinal grooves.

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References: [1] Carr M.H. (2007) *C.U.P* (Vol.6). [2] Chapman M.G. et al. (2010a) *EPSL*, 294 (3-4). [3] Chapman M.G., et al. (2010b). [4] Baker, V.R. and Milton, D.J., (1974) *Icarus*, *23*(1), 27-41. [5] Lucchitta B.K. (1982) *JGR: Solid Earth 87*(B12). [6] Lucchitta B. K. (2001) *GRL*, 28(3), 403-406. [7] Gallagher C.J., and Bahia, R. (2021) *Elsevier* 13-40. [8] Leverington D.W. (2011) *Geomorphology 132*(3-4) [9] Dundas et al. (2019) *Icarus,* 321, 346-357. [10] Hvidberg, C. S. et al. (2020) *TC* 14(10). [11] Bohorquez, P., et al. (2019) *Earth Sci. Rev*. 193. [12] Stokes C.R. and Clark, C.D. (2001) *Quaternary Sci. Rev. 20*(13).