FORMATION OF GULLIES ON MARS: WHAT DO WE LEARN FROM EARTH? N. Mangold[1], F. Costard[1], F. Forget[2], D. Baratoux[3], [1]Orsay-Terre, FRE2566, CNRS et Université Paris-Sud, Bat. 509, 91405 ORSAY Cedex, France, mangold@geol.u-psud.fr. [2]LMD, Jussieu, Paris, France [3]Observ. Midi-Pyrénées, Toulouse, France.

Introduction: The observation of gullies on Mars indicates the presence of liquid water in recent times [1]. They have been proposed to result of subsurface seepage of water [1], geothermal activity [2] or brines [3], near-surface ice melting at recent periods of high obliquity [4], snowmelt in more recent periods [5] or liquid CO_2 breakout [6]. In this study, we describe how terrestrial studies help to understand better the formation of Martian gullies. We show that all characteristics of Martian gullies are consistent with some external process triggered by seasonal melting at high obliquity.

Debris flows in French Alps: Best analogs to Martian gullies are debris flows from Greenland [4] and Canada [7] which occur over a permafrost. Debris flows in the Alps sometimes occur over a permafrost but this is not the case usually. They nevertheless consist of good analogs for the properties of the flow and the geometry. The two examples shown fit the association of alcove at the gully head and channel with levees. They have been triggered by snow melting in the springtime or strong showers in summer, thus external processes only. The debris flows of the Izoard do not show any springs at the head (Fig. 1). One spring has been observed in the valley 400m in elevation under the gully head and no debris flows alcove is observed at this location. The debris flows of Izoard formed in 1985 and they have overflow the road located at mid-slope. They are typically 10 m large with 2 m high levees.

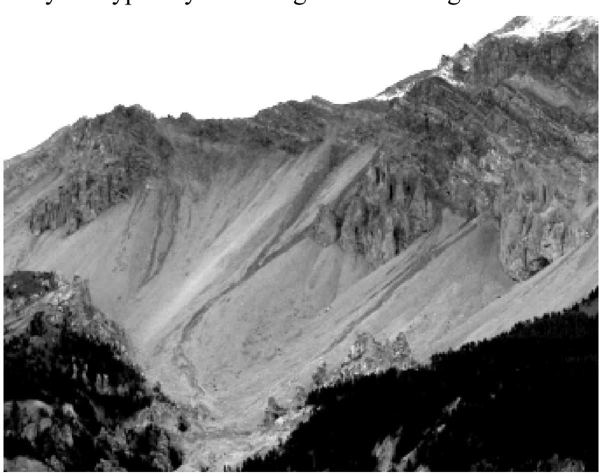

Fig. 1: Debris flows in Izoard location named "Casse déserte" in Queyras, French Alps. The length of the flow on image is about 500 m. Channels are about 10 m large. The main alcove is about 100 m large. Elevation is 2400 m at the gully head. A main thrust fault crosses these terrains with a tilt of 20° to the east (right).

Comparison to Mars: These examples in the Alps document some characteristics of debris flows that also exist on Mars:

1. Association with layers. It has been argued that gullies all head at the same layer [1]. The examples of Nirgal Vallis and Dao Vallis have especially been documented [1]. The head of debris flows is mainly controlled by the angle of the slope and the availability of debris. Navier-Coulomb law gives: $\tau=C+(\sigma-P)\tan\phi$; where τ is the critical shear stress at failure, C the cohesion, σ the normal stress, P the pore fluid pressure and ϕ the coefficient of internal friction. As the fluid pressure increases, the critical shear stress decreases and failure may occur. This process is very efficient if debris lay over steep slopes because the dry material is already near the critical shear stress before the incorporation of water. This property explains why debris flows usually start at the most elevated point of debris aprons. The observation that Martian debris flows start at the same level underneath scarps may therefore be explained by such criteria. The debris flows of Izoard region are controlled by the thick debris accumulation at the foot of the summit cliff (Fig. 1). No springs are observed at this place and layers are tilted to the NE at about 20° impeding any subsurface seepage in the direction of the hillslope where debris flows formed. The head of gullies takes place here due to the large accumulation of debris in their steepest position. This geometry is similar to gullies observed on the central peak of Hale crater where the layering is also tilted. On the other hand, many MOC images on Mars shows that gullies can head at different levels. In this case, this is due to the existence of more than one strong layer under which debris accumulate.

2. Regional cluster: MOC observations show that gullies occur in regional clusters poleward of 28° of latitude. These clusters could be evidence for regional subsurface aquifers [8]. However, terrestrial debris flows are also not homogeneously distributed. This distribution depends on many parameters involving climate (meteorology, local winds, global change), topography (slope, total elevation, insulation), pedology (presence of soil or vegetation) and geology (rock composition, fracturation, tectonic patterns). Debris flows are more frequent in the southern Alps because the climate is drier than in northern Alps [9]. When the climate is wet, erosion is dominated by runoff erosion in rills and rivers. When the climate is dry, quick snow melting or summer storms can produce floods and associated debris flows if the proportion of water does not reach about 40-50% of the rock-water mixture.

The cluster of debris flows in the massif of the Izoard (Fig. 1) is especially developed. The explanation is especially the large accumulation of rocky debris on the hillslope, known by the name "Casse déserte" which is one of the largest debris accumulation in this mountain massif. These debris are accumulated just over a main thrust fault which had strongly fractured the rocky limestones visible on the cliff (Fig. 1). The large amount of debris is thus a consequence of the strong fracturation of the rocks. On Mars, as debris are usually covered by dust, it is difficult to estimate the amount of debris available. Dust itself is likely also involved in the flow. Nevertheless, some examples exist where wrinkle ridges crosscut craters [10]. At this place, gullies are especially developed (Fig. 2). Rocky layers are likely strongly fractured due to both impact and faulting, explaining the large alcove above the gullies. Thus, these Martian gullies could be due to these local effects of debris formation due to fracturation while others could be due to many other effects such as local topography, freshness of the cliffs, etc. More detailed studies of MOC images should be done to document these relationships.

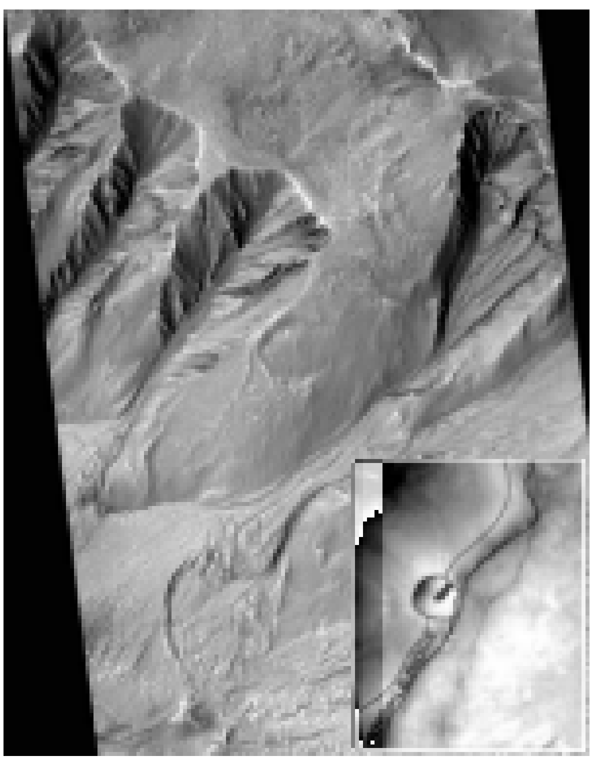

Fig. 2: MOC image of deeply incised gullies (about 200-300 m large alcoves). The context image shows the coexistence of a wrinkle ridge and a crater.

3. Temporal evolution: Gullies are young features on Mars but are not uniformly young [11,8]. MOC images show gullies blanketed by dust or even few ones with small fresh craters. MOC images show also gullies of different aspects at same place documenting an evolution with time at the same location. This is also observed on Earth because gullies are depending on climate variability and availability of debris. Return periods in Europe can vary from several years to several hundreds of years [9]. For example, the formation of a new debris flow can clean the hillslope of its debris. Subsequent debris flows can therefore not form until debris are progressively deposed again on the slope. On the contrary, a new debris flows can also create an instability in the slope which increases the number of subsequent debris flows until a new equilibrium is reached again. This aspect of debris flows research is not well understood on Earth [9]. On Mars, we miss any timescale to estimate return periods of debris flows but they should depend on both debris availability and climate effects like on Earth [9]. On the other hand, no new gullies have been observed during last two years of MOC mapping [8] in agreement with processes involving formation at higher obliquity several hundreds of thousand years [4].

4. Occurrence of levees: Levees on each sides of the channels are typical of a particular kind of flows with a yield strength [12]. The yield strength corresponds to the minimal shear strength the material needs to reach before to flow. They are typically associated to flows containing 50 to 90% of solid particles (silt to pebble size) [12]. In Izoard, levees are 2 m high for a 10 m large channel, a size comparable to gullies observed on several MOC images. The existence of levees implies the incorporation of meltwater in the debris over a significant thickness of material. This is possible only if thawing of the ground occurs over a significant thickness (several tens of cm), on the contrary to the model of snowmelt proposed by Christensen [5] under present conditions. The ratio of water to sediment of 10:1 proposed by Christensen (so 10% of rock) is also not in the range of debris flows with levees which are characterized by a proportion of more than 50% of rock [12]. Nevertheless, if existing during high obliquity periods, the presence of snowpacks would favor the process of debris flows because snowmelt can efficiently fill the porosity of debris as observed in cold regions in Greenland [4] or North Canada [7].

5. Lack of terminal deposits for dune gullies: It has been argued that the absence of terminal deposits is against the process of gullies formation by debris flows [8]. Gullies without terminal deposits are especially visible on the flank of dunes in Russell craters (Fig. 4) [13]. Nevertheless, mountains above Allos lake (Fig. 2) shows gullies without terminal deposits. These gullies were formed by debris flows with only terminal levees but no strict terminal deposits. Such case seems relatively common for narrow debris flows which depose material inside levees progressively. Dune gullies are similar to this case of debris flows and thus can be include in the understandings of Martian gullies. These dune gullies present sinuosities and connections with a geometry that allows the calculation of flow properties like the viscosity [13]. The range of magnitude found for viscosity is of 10 to 10,000 Pa s which is consistent with value of debris flows on Earth [13]. This is more than 1000 times more viscous than pure liquid water. Thus, surface runoff and erosion of pure liquid water can not explain the properties of the flows observed.

Conclusion: The association of gullies with layers, the regional clustering and the variability of ages of the Martian gullies are consistent with observations of terrestrial debris flows which have the same characteristics. These variations are controlled by both external, surface and internal processes which can create a complex distribution. This spatial distribution over Mars should be better studied taking terrestrial examples in account. On the other hand, snow melt is possible during periods of high obliquity but the properties of gullies, especially the existence of levees, strictly focus the formation of gullies by quick flows of rock-water mixture with high rock proportion inconsistent with the slow erosional process described by Christensen [5]. An external process due to episodic melting remains the most likely process to explain recent gullies [4].

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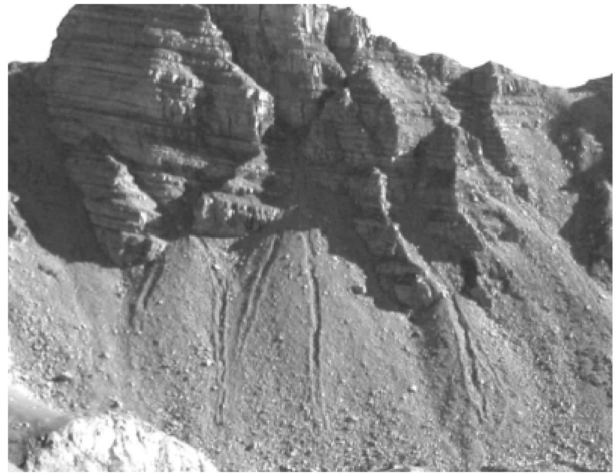

Fig. 3: Debris flows in Allos Lake, Mercantour, South Alps. No deposits are observed at the termination of gullies. Channels are about 5 meters large. Elevation is approximately 2500 m.

Fig. 4: MOC image in a dunes field of Russell crater.