MODES OF GULLY FORMATION AROUND NORTH EAST OF ARGYRE BASIN AND THE ROLE OF VOLATILE DISCHARGE DUE TO MICROCLIMATIC SHIFTS. Rishitosh K. Sinha, Vijayan S. and S.V.S. Murty, PLANEX, Physical Research Laboratory, Ahmedabad 380009, India (rishitosh@prl.res.in).

Introduction: Discovery and analysis of recent gullies has improved our understanding of the climate that favored top-down flow of liquid water during the 0.4-2.1 Ma history of Mars [1, 2]. Despite their dominant poleward formation trend at lower elevations in mid-latitudes [3], it remains to be tested whether the different volatile sources at the cliff wall drained in similar pattern to carve gullies in response to the episodic microclimatic shifts. We present our high-resolution investigation of the geomorphic signals within a geological suite around north-east of Argyre basin (Fig. 1) to address this issue.

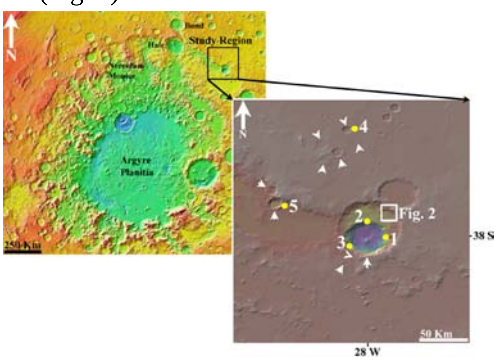

Fig. 1. Contextual map showing the location of study region. Arrows in the expanded view indicate location of investigated craters and yellow circles mark the location of five different modes of gully formation.

Observation: Inspection of crater floor morphology from the study region revealed multiple parallel flow features extending away from floor of poleward face (Fig. 2). This initial downward flow of ice-rich materials was facilitated by significant amount of ice/snow, whose base was later modified during moderate phase of accumulation by raised concave depressions, called arcuate ridges [4, 5]. The flow of these ice-rich features eroded and left several depressions at the surface of pole-facing wall. The subsequent aeolian processes widened these depressions, transforming them to alcoves, where ice/snow trapped during the geologically recent period of minor accumulation. The top-down flow of meltwater from these alcoves entrained debris that carved linear-sinuous gullies, producing depositional aprons at the base. The overall process and the array of geomorphic features observed here helped us to demonstrate wanning of glaciation and formation of gullies on Mars. However, our extensive survey of the region led us to infer that the geological mechanisms, characterized by different volatile sources and pattern of discharge, capable of forming gully, could be divided into five different modes, of which some are still active today.

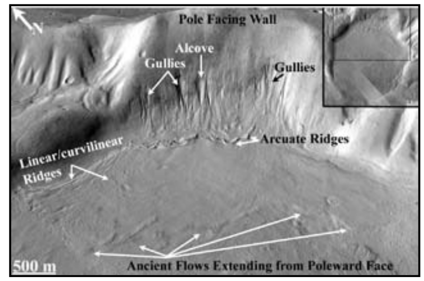

Fig. 2. Wanning of glaciation on Mars. Ancient flows extending from poleward face followed by arcuate ridges at base of wall, and gully formation at top.

Modes of Formation: (1) *Gullies on topographically isolated alcoves*. The gullies identified in Fig. 3 (Mode 1) indicate that formation of gullies within the mid-latitude (30˚–45˚ S) was related to past snow and ice accumulation in topographically isolated alcoves and melting due to climatic processes [6]. These gullies show a dominant poleward trend, well developed, more carved, with longer narrowed channels, and tend to deposit larger fans at the base of downslope.

(2) *Gullies on large alcoves that originally bear ancient flows*. The ancient (>10 Ma) flow of accumulated ice from these alcoves had left small amount of ice trapped in the etched/blocky ends at the top (Fig. 3, Mode 2). Exposure of this trapped ice to the elevated temperature during summer afternoons caused it to melt and entrain debris [7]. These gullies tend to deeply incise the surface and support that the major accumulation phase had played a key role in forming gullies. However, the overall gully length will be relatively small because it involved less ice-melt.

(3) *Gullies on extremely young erosional/depositional systems*. Gullies observed here demonstrate importance of top-down melting of recent ice rich deposits and the cold preservance of ground ice beneath sedimentary facets in the formation of gullies (Fig. 3, Mode 3). The gully channels appear to originate from the top of alcoves than their base, similar to the prediction of groundwater model [8]. We suggest that these gullies mark as youthful features on Mars on the basis of their depositional fans overlying the TARs at the base and lack of superimposed impact craters on the channels and fans.

(4) *Gully deposits that represent gully activity but not necessarily gully formation*. The gully deposits observed in Fig. 3 (Mode 4) lack presence of typically

carved gully-like channels, which hints that the overall mechanism differs from typical gully formation. The older gullies underlying these deposits are very narrow, shallow, and pristine, which suggest the host walls to be the most recent sites of gully activity.

(5) *Gullies that form over eastward/westward oriented crater walls.* This mode is an unsolved problem. The gullies observed here (Fig. 3, Mode 5) are not different in their overall appearance, though, they have strong bearing on the pattern of ice/snow accumulation and their formation age. The close association of investigated crater with the glaciated Argyre basin point toward the possibility of redistribution of ice from this basin into the proximal craters. This had presumably led to deposit ice over the east/west ward faces of crater and contributed in the formation of gullies at those places during the past 5 Ma.

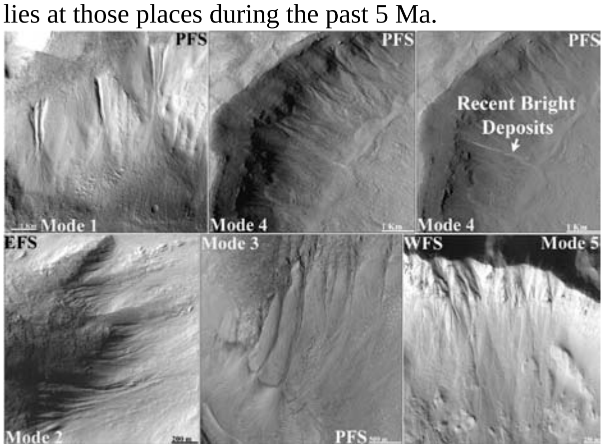

Fig. 3. *Different modes of gully formation at the pole/equator/west ward facing slopes. Mode 4 represents recent gully activity between 2009 and 2011.*

Results and Discussion: It has been often envisaged that the gully formation may have occurred in multiple episodes within a small time frame of 5 Ma [9]. Additionally, the ancient flows emerging from pole-facing wall of craters have been often expected to be associated with gullies from alcoves at the wall top [8]. From our morphologic observations we validate and present both these hypothesis, and report that Martian gullies developed at 5 different stages during the past ~5 Ma driven by the obliquity parameters, insolation conditions, and episodic microclimatic shifts of recent past. The distinct phases of gully formation/activity can be broadly constituted as (1) an older phase for downslope flow on equatorward faces; (2) a moderate phase for top-down melting on eastward/westward slopes; and (3) a younger phase exclusively on pole-facing slopes. Our morphologic observations mainly document two patterns of volatile discharge for formation of these five stages of gully; (1) top-down melting of ice/snow trapped within wall alcoves [7] and (2) release of volatiles under pressure from space between rock contact faces [8].

We have found that the extent and patterns of ice/snow accumulation played a key role in the formation of gullies and indicates a major transition in the late Amazonian climate of Mars. Similar to the crater in Phlegra Montes, exhibiting characteristics of concentric glacial-like flows on its floor and interpreted to reveal evidence for kilometer-scale ice accumulation [10], we document evidence for nutshell accumulation of ice. This small, localized accumulation in the alcoves at cliff wall has played key role in forming gullies in our study region (Fig. 1). Such a format of alcove-gully-fan system was comparatively smaller than those observed elsewhere on Mars.

The Argyre basin (1700 Km; early Noachian age) located in the southern hemisphere of Mars (51˚S, 317˚ E) has been already demonstrated to undergo extensive glaciation [11]. Despite the fact that at higher latitudes (>45˚), snow/ice accum ulated irrespective of the slope orientation, gullies are found predominantly on equator ward facing slopes between 44˚-58˚ S [12]. It would be interesting to understand the reason for this preferred orientation of gullies between 44 - 58˚ S. Floor of Argyre basin has preserved evidence for small-large crisp polygons that point towards possible sublimation of ice from its floor during the time of polygon formation. We propose a possible redeposition of sublimated ice from this basin (centered at 51˚ S) onto the east/west ward wall of craters facing towards the basin and lying within the nearby latitudes, i.e. atleast 7-8 degrees apart, which is up to 44˚-58˚ S. The onset of such an ice redistribution process would have triggered during the stage of polygon formation on Mars (past 5-10 Ma), which has later produced meltwater during the recent glacial epoch (0.4-2.1 Ma) to form gullies. Taken together, in all the modes we found role of microclimatic shifts to be significant, which has at certain favorable times and at certain locations accumulated the volatiles (ice and snow) and facilitated formation of gully-like features.

References: [1] Malin M.C. and Edgett K.S. (2000) *Science, 288*, 2330-2335. [2] Head J.W. et al. (2008) *PNAS, 105*, 13258-63. [3] Dickson J.L. et al. (2007) *Icarus, 188*, 315-323. [4] Sinha R.K. and Murty S.V.S. (2013) *PSS, 86*, 10-32. [5] Berman D.C. et al. (2005) *Icarus, 178*, 465-486. [6] Schon S.C. and Head J.W. (2011) *Icarus, 213*, 428-432. [7] Costard F. et al. (2002) *Science, 295*, 110-113. [8] Hartmann W.K. et al. (2003) *Icarus, 162*, 259-277. [9] Morgan G.A. et al. (2010) *Icarus, 208*, 658-666. [10] Dickson J.L. et al. (2010) *Earth Planet. Sci. Lett., 294*, 332-342. [11] Kargel J.S. and Strom R.G. (1992) *Geology, 20*, 3-7. [12] Dickson J.L. et al. (2012) *Icarus, 219*, 723-732.