PROLONGED LATE-STAGE VALLEY NETWORK FORMATION: LANDFORM SIMULATIONS OF PARANA BASIN, MARS. C. J. Barnhart[1], A. D. Howard[2] and J. M. Moore[3]. [1]Dept. of Earth and Planetary Sciences, University of California, Santa Cruz, CA (barnhart@pmc.ucsc.edu), [2]Dept. of Environmental Sciences, University of Virginia, Charlottesville, VA, [3]Space Sciences Division, NASA Ames, Moffett Field, CA.

Overview: Using a Landform Evolution Model, we test how a suite of climatic and geologic parameters effect the formation and evolution of late-stage valley networks present in the Parana Valles drainage basin catchment (PDC) (Figure 1). In particular, we explore the geomorphic effects of climate on the martian surface and show that valley networks were necessarily formed over prolonged periods. Their formation involved multiple floods with intermin quiescent dry-spells that allowed for evaporation and ground water infiltration. We use morphometric analyses to create an approximate pre-incision version of the PDC and then use landform evolution simulations to qualitatively and statistically explore climatic and geological controls on valley network formation. We find that simulations involving short deluge-style climate optima lasting on the order of 10^3 to 10^4 years can easily carve the valley networks, but these extreme climates fill, overflow, and breach all impact craters producing ubiquitous exit breaches a landform rarely seen on the surface of Mars.

Background: Researchers have advanced two end-member hypotheses to explain the evolution from widespread fluvial activity across much of Mars during Noachian time to the limited yet focused fluvial erosion during the Noachian-Hesperian transition (so called late-stage activity) [1-8]. In one hypothesis, the long-term decline was gradual and resulted from a reduction of atmospheric temperature and pressure caused by waning geothermal and volcanic activity, and by loss of atmospheric components both to space and to weathering reactions [9]. In the second hypothesis, episodic and catastrophic events including orbital cycles, outflow floods, volcanism, and impact-induced climate optima generated or contributed significantly to short-lived greenhouses and brief dramatic fluvial episodes [10,11]. These two mechanisms are not exclusive and could have been operating in conjunction, such that short-lived events punctuated a trend of gradual decline. They should, however, produce different diagnostic erosional and depositional features, and different regional signatures. Presumably, large, sustained discharges create thoroughly integrated networks that breach crater walls and connect large drainage basins. Moderate discharges and associated periods of quiescence, on the other hand, would concentrate valley network development to areas with large catchments and regional slopes.

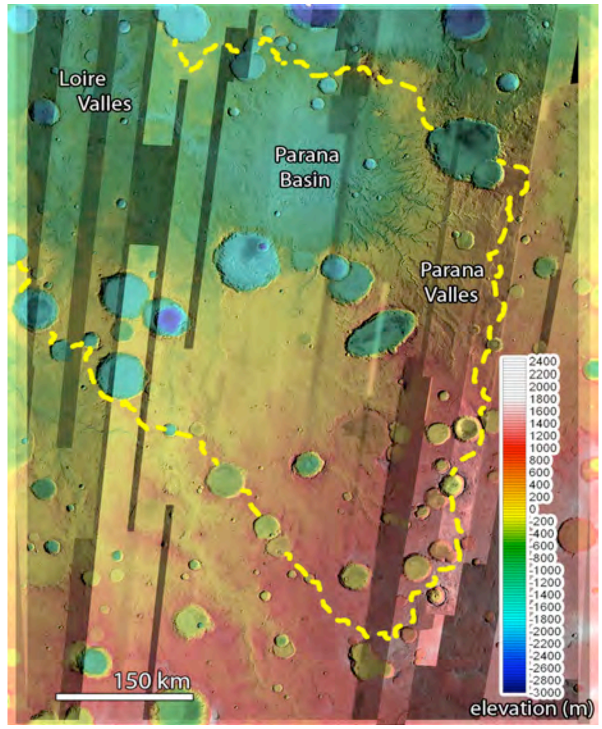

Figure 1: The Parana Drainage Catchment (PDC), 25.5° S, 12.25° W, is defined by drainage divides (dashed yellow line) derived from MOLA elevation. The southeastern portion of the PDC is characterized by a strong regional slope to the NW, and is deeply incised by the Parana Valles system. In general the depth and density of fluvial incision correlates with regional gradients. A row of craters became erosionally breached, permitting headward erosion of the stubby canyon just south of the basin. Other craters throughout the PDC possess whole, intact crater rims without any evidence of breaching.

Valley Networks and past climates: The study focuses on valley networks because they provide evidence of mass transport over significant distances, and therefore imply sustained or repeated surface flow. Furthermore, valley network integration is evidence of substantial modification of the land surface by erosion. Fluvial processes, such as valley network incision, are strongly sensitive to their climatic environment; incision and deposition often alternate in response to climatic and geologic factors. Finally, valley networks are a landform class that is readily amenable to quantitative analysis through the use of digital elevation models (DEMs) [12,13].

Our study consists of two parts. First, we used the Mars Simulation Landform Model (MSLM) [14,15] to simulate various scenarios for the erosional processes responsible for valley incision and evolution in the PDC. Then, we compared model surfaces to the actual surface both qualitatively and statistically.

Climate Parameters: We explore various discharge-scaling relations with respect to contributing area as a proxy for different precipitation climates and substrate hydrologic properties (fig. 2).

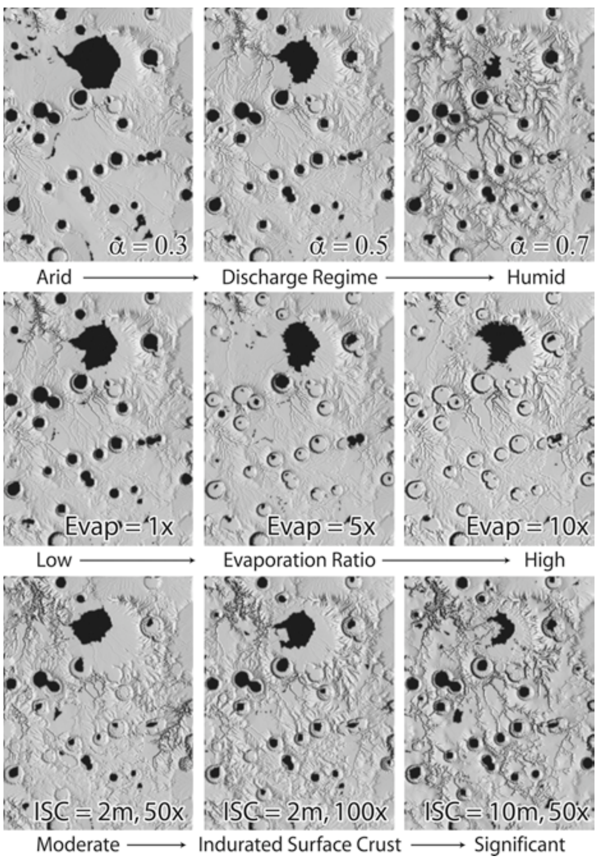

Figure 2: Model Output DEMs of nine runs that cover study parameter space. Each row demonstrates the affect of a particular parameter: α, evaporation ratio, and indurated surface crust (ISC). For each row all other parameters are held fixed. Many simulations here fail to match the pattern of late-stage valley incision and occur at the extreme range of simulation parameter values. They either fail by forming premature valley networks or by over-incising the surface and downcutting crater rims.

Discharge, Q (m^3 s^{-1}), is the flow going through a stream and is assumed to be proportional to the contributing area:

$$Q = kA^{\alpha} \qquad (1)$$

where A is the upstream contributing area (m^2) and α scales the dependence of discharge on contributing area. In terrestrial settings, discharges of magnitude approximating the mean annual flood perform the majority of annual geomorphic work (e.g., [16]). The assumed default value of constant, k, scales discharge to the mean annual flood for terrestrially semi-arid conditions. An α of 1 means that the mean annual flood is directly proportional to the contributing area. Lower values of 0.5 or 0.3 mean that discharge does not increase as rapidly downstream. For drainage networks on Earth, an α of 0.7 would be typical of a humid environment; whereas lower values are characteristic of semi-arid to arid environments [16]. This study tests alphas of 0.3, 0.5, and 0.7. The discharge constant, k, is adjusted so that the discharge, Q, generated by a moderate contributing area of 7.5 km^2 is the same for all simulation runs and scaled to terrestrial semi-arid conditions. Discharge is further limited by evaporative losses within depressions, mostly craters. For Mars we do not know within wide limits the actual values of precipitation and evaporation, but the degree to which basins overflow is determined by our second parameter, the ratio of net evaporation in lake basins to runoff depth on uplands. Finally, we tested the effect of an indurated surface crust (ICS). An ICS channelizes flow, which limits drainage denisties and carves deeper valleys. These three parameters dramatically effect the evolution of the model DEM.

Statistical Analysis: The principal statistical tool we used in this study was an elevation-difference histogram. As a simulation proceeds, the DEM continues to evolve by diffusive and fluvial transport processes. Material erodes from higher elevations, and valleys become incised, so that material is deposited at lower elevations and in local minima. Elevation-difference DEMs are produced by subtracting the 'initial,' pre-incision DEM node-by-node, from DEMs generated by the simulation. We employ a Chi-Square ($\chi 2$) distribution to quantify differences between the baseline histogram (generated by subtracting the initial conditions DEM from the actual surface) and histograms generated from model runs. This has two purposes, (1) to statistically compare elevation-difference histograms between model simulations, and (2) to compare multiple elevation-difference histograms from a particular simulation in order to determine when that run came to its closest statistical match to the inferred pattern of late-stage incision. Because the ICS is an estimation of the pre-incised surface, an exact $\chi 2$ match (equaling zero) would not be expected. Thus, relatively low $\chi 2$ values indicate a close statistical fit between the range of incision depths in the simulation and the inferred range of actual incision depths based on modern topography and on our initial pre-incision topographic reconstruction. We find that simulation runs that model a low (0.3 to 0.5) drainage discharge exponent, α, provide the best qualitiative and statistical match to the actual surface (Figure 3).

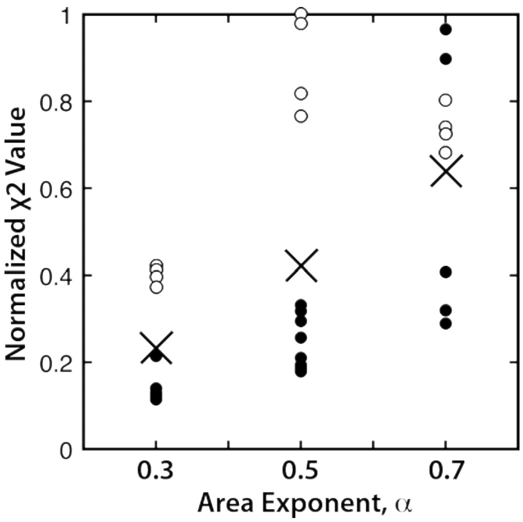

Figure 3: Discharge scaling exponent α vs normalized χ2 value. Minimum χ2 values strongly correlate with the Area exponent, α. Closed circles represent runs with an indurated surface crust. Column averages are marked by an X. Output DEMs from model runs with lower α values are a proxy for arid climates and produce a superior statistical match to the actual surface.

Formation Timescales: Valley network formation time is calculated from the number of mean annual flood (*maf)* magnitude flows required to perform the geomorphic work. The total number of *maf* magnitude flows that occurred in a particular simulation provides a rough estimate on the duration and frequency of channel-forming flows responsible for creating the valley networks. However, duration and frequency are necessarily coupled and, only together, estimate the temporal extent of the late-stage epoch. Sustained and frequent flows at *maf* stage would form the valley networks within the PDC much more quickly than short-lived, sparse, and infrequent flows. At minimum χ^2, runs with the best qualitative and statistical match to the actual surface require 500,000 to 700,000 *maf* size flows. Accordingly, the Parana drainage catchment subjected to an arid to semi-arid environment with terrestrial weather patterns requires ~10^5 – 10^6 years for formation. On Earth, flood stage is sustained for a week, or roughly 2% of a year. Therefore, a continuous flow at *maf*-stage sustained for ~10^3 – 10^4 years could have formed the valley networks. On the other hand, infrequent or episodic discharge spaced by long periods of quiescence would increase formation timescales; limited only by the cessation of valley development in southern highlands during the early Hesperian period. The shortest runs had a high discharge exponent. The shortest run reached a minimum χ^2 fit at 300,000 *mafs* which is equivalent to ~ 6000 years of continuous and sustained *maf*-stage discharge levels. Finally, a Martian year is ~1.88 Earth years and would, hypothetically, have longer seasons in past climate optima

Conclusions: This study focused on geomorphic controls responsible for deep valley incision associated with the concentrated and intense period of late-stage fluvial activity near the Noachian-Hesperian transition. Statistical analysis and qualitative evaluation demonstrate that simulations that model an arid to semi-arid climate over hundreds of thousands of years provide the best match to the actual surface of present day Parana Basin. Under deluge-like conditions valley formation requires a minimum of 10^3 – 10^4 years. However, observations of impact interruptions of network formation concurrent with valley incision strongly imply that valley formation occurred over a more extended period of time. Most significantly, a paucity of crater rim exit breaches in the PDC and the southern highlands in general implies that precipitation was not deluge-style and continuous but rather moderate and episodic with periods of evaporation (Figure 4b). This implies that late-stage channel erosion did not form as a consequence of giant impact-induced short-lived climate excursions alone. Therefore, if a few large impact events did perturb the climate toward periods of precipitation, these periods would have to be long-lived (~100,000's of yrs) and seasonally or semi-seasonally cyclic, with evaporation interplaying significantly with precipitation and runoff (Figure 4d).

References: [1]Grant, J. A., and T. J. Parker (2002), Drainage evolution in the Margaritifer Sinus region, Mars, *JGR*, 107, doi:5010.1029/2001JE001678. [2]Craddock, R. A., and T. A. Maxwell (1993), JGR, 98, 3453-3468. [3]Craddock, R. A., and A. D. Howard (2002), *JGR*(Planets), 107. [4]Hynek, B. M., and R. J. Phillips (2001), Geology, 29, 407-410. [5]Forsberg-Taylor, N. K., A. D. Howard, and R. A. Craddock (2004), JGR (Planets), 109. [6]Hartmann, W. K. (2005), Icarus, 174, 294-320. [7]Howard, A. D., J. M. Moore, and R. P. Irwin, III (2005), JGR (Planets), 110. [8]Irwin, R. P., III, A. D. Howard, R. A. Craddock, and J. M. Moore (2005), JGR (Planets), 110, doi:10.1029/2005JE002460. [9]Carr, M. H. (1996), Oxford University Press, New York. [10]Carr, M. H. (1989), Icarus, 79, 311-327. [11]Segura, T. L., O. B. Toon, A. Colaprete, and K. Zahnle (2002), Science, 298, 1977-1980. [12]Stepinski, T. F., and M. L. Collier (2004), JGR, 109. [13]Stepinski, T. F., and A. P. Stepinski (2005), JGR, 110. [14]Howard, A. D. (2007), Geomorphology, 91, 332-363. [15]Barnhart, C. J. (in press), JGR, doi:10.1029/2008JE003122. [16]Bull, L. J., and M. J. Kirkby (2002), 398 pp., John Wiley and Sons, Chichester.

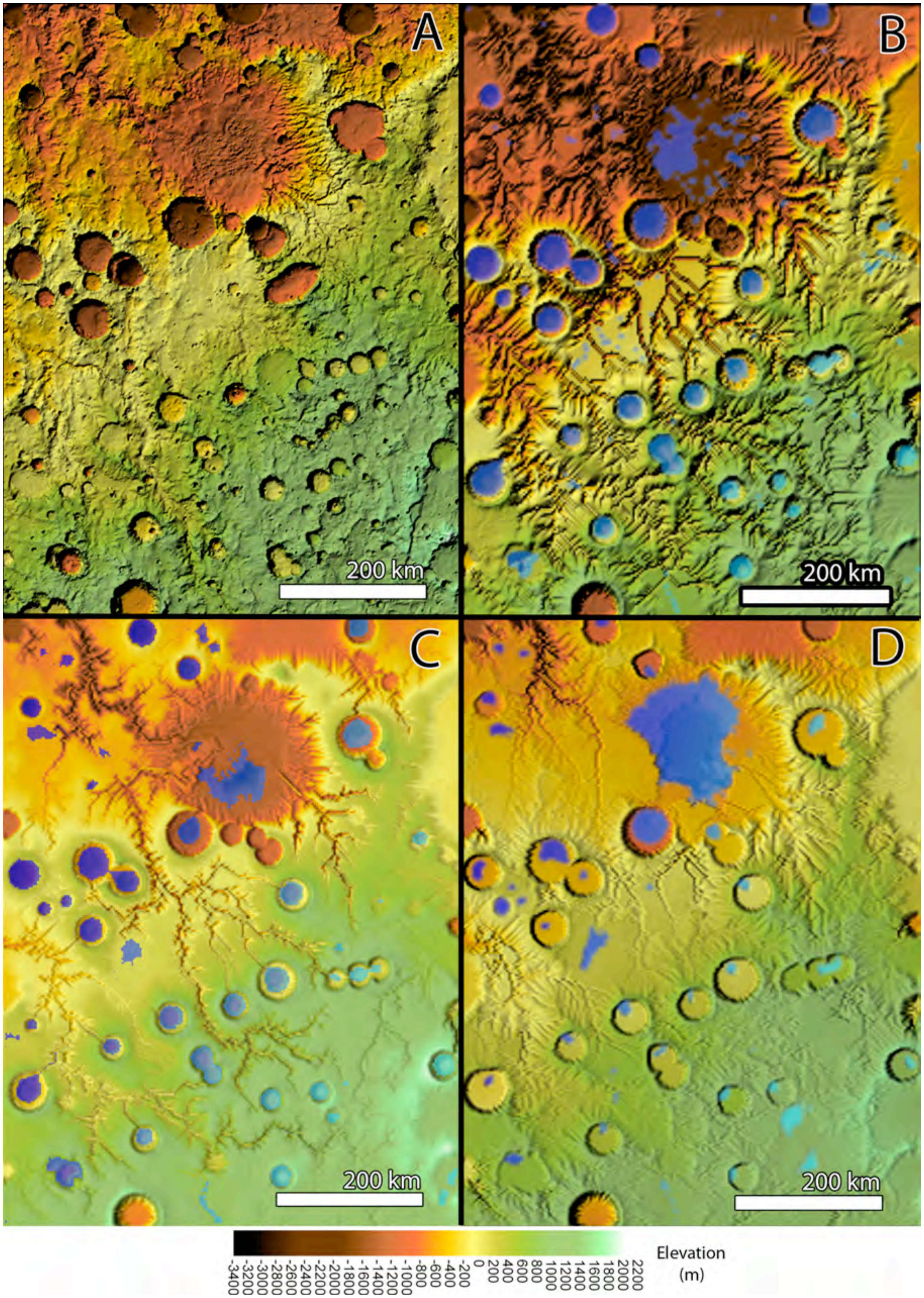

Figure 4: (A) The Actual Present Day DEM; (B) A simulated short-lived deluge-style climate produces features not seen on Maras (e.g. ubiquitous crater exit breaches); (C) A humid run with a significant surface crust still produces exit breaching; (D) A semi-arid run with a modest indurated surface crust yields the best statistical match to the actual surface.