Morphology of drainage basins as an indicator of climate on early Mars

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Received 13 April 2005; revised 21 August 2005; accepted 12 September 2005; published 2 December 2005.

[1] We show that drainage basin morphology correlates with climate. Computational analysis of the 46 basins extracted from the western slopes of the Andes reveals the existence of four different basin morphologic classes. This purely geomorphic partition correlates with division of the same basins on the grounds of climate types. Basins are compared using circularity functions as their formal representations. Self-organizing maps and dendrograms are employed to provide basin classification. One class of basin morphologies corresponds to sites in the arid Atacama Desert, and the other class corresponds to sites in the Atacama exhibiting groundwater sapping landforms. Using the same technique, we study a larger sample of 94 basins that, in addition to the Andean basins, includes other terrestrial basins and 26 basins from Martian sites that show prominent valley networks. The classification of this larger set shows that morphologies of Martian and terrestrial basins bifurcate at the root of the dendrogram, forming two separate domains of basin morphologies. The similarity map reveals that, of all the terrestrial basins, the Atacama Desert basins are morphologically closest to the Martian basins. Extrapolating the terrestrial morphology-climate linkage to Mars points to formation of valley networks in a hyperarid climatic environment. We submit that the Atacama Desert provides the best possible terrestrial morphologic analog to valley network sites on Mars. We discuss climatic and hydrologic particularities of the Atacama Desert and hypothesize that a similar environment existed on early Mars.


1. Introduction

[2] There is now substantial geomorphic evidence (e.g., a review by Baker [2001] and the paper by Craddock and Howard [2002]) that precipitable water was present on the surface of Mars throughout its history, with the peak activity occurring during the Noachian epoch. Thus the water-on-Mars debate shifts from its groundwater versus precipitation focus to the issue of specifying the particularities of Noachian climate that admits precipitation but also accounts for the presence [Pieri, 1980] of apparent groundwater sapping landforms.

[3] Valley networks are perhaps the most widely studied Martian landforms because they provide visually compelling evidence for past fluvial activity. In order to infer the character of such an activity, both a global morphology and a local morphometry of valley networks have been studied and compared to the analogous properties of terrestrial river networks. In particular, the drainage density of valley networks is often used as a determinant of runoff erosion process, and thus as a probe of the past precipitation [see, e.g., Hynek and Phillips, 2003; Mangold et al., 2004]. A drainage density has the virtue of being a quantitative morphometric attribute of valley networks that is relatively easy to calculate from images, but its value for inferring past climate is questionable. First, the observable networks are only remnants of original, possibly more extensive systems. Second, although a relation between drainage density and climate is observed in terrestrial context [Abrahams, 1984], extending it to Mars is not straightforward [Irwin et al., 2004]. Another approach is to use statistical properties of valley networks extracted from digital topography [Stepinski et al., 2002; Caldarelli et al., 2004]. It is based on an observation that terrestrial rivers are fractal structures exhibiting scale-invariant features characterized by exponents that are the same for rivers around the world, thus constituting a telltale of runoff erosion process. Comparing such exponents to those calculated for valley networks diagnoses a possible runoff history of Martian landscape. In practice, exponents of any oriented, hierarchical networks, regardless of their physical origin, are similar, making a reliable diagnosis difficult.
Braking with studying the valleys themselves, Stepinski and Coradetti [2004] submitted that a quantitative, comparative study of drainage basin morphologies provides a better method for inferring the past climate. A drainage basin on Mars is a unit of land that underlies a valley network. It is computationally delineated as a watershed of imagined present-day drainage of a site containing this network [Stepinski and Collier, 2004]. A basin is a more robust geomorphic feature than a valley network, it contains more information, and its large scale morphology is more tolerant of contamination by cratering. In addition, basins can be extracted from sites showing no evidence for valley networks, further increasing our ability to infer past climate. The present-day morphology of a Martian basin reflects morphology of the site’s primary landscape and its erosional degradation. Stepinski and Coradetti [2004] have shown that these two factors can be deconvolved, and basin morphologies can be used to compare effects of erosion, and thus to compare climates.

In this paper we apply the methods of Stepinski and Coradetti [2004] to demonstrate the correlation between basin morphology and climate. A climate is only one of the factors influencing landscape evolution and morphology; it governs the amount of water received at the surface. Other factors, such as lithography, vegetation, soil type, and existing topography, govern the subsequent distribution of the water, and also contribute to landscape morphology. Despite this mix of various factors, we show that, using our analytic tools, a correlation between basin morphology and climate can be established. In order to demonstrate such a correlation we study basins located on the western slopes of the Andes. The Andes provides the best place on Earth (see section 2 and Montgomery et al. [2001]) to perform such a study. We define three broad types of climate: wet, moderate, and arid, and show (section 4.1) that basins within each of these climates have a characteristic morphology. That means that given an unknown Andean basin (in the form of a digital elevation map), we can predict its climate. Extrapolating the terrestrial morphology-climate correlation to Martian terrain with prominent valley networks, we argue that Martian basins developed in a hyperarid climate. The only terrestrial basins that are roughly similar to Martian basins are all located in the Atacama Desert, which may be the best morphologic terrestrial analog to valley network sites on Mars. Atacama basins, like Martian basins, exhibit a mixture of runoff and some groundwater sapping landforms. The Atacama climate is arid with intermittent precipitation, but the high Andes located above the desert presents a unique “laboratory” for such an investigation because the influences of climate and tectonics on the morphology of the Andes can be deconvolved. The Andes are a hemisphere-scale mountain range that uplifted ~2.5 × 10^7 years ago [Allmendinger et al., 1997]. Because of its north-south extent, the Andean range experiences large climate variations. The annual precipitation rate (APR) in the western slopes of Andes is >2000 mm/yr in the 10°N to 3°S zone, <200 mm/yr in the 3°S to 15°S zone, almost no precipitation in the 15°S to 33°S zone, and >2000 mm/yr south of 33°S. Crucially, these climatic latitudinal gradients are robust features of the zonal atmospheric circulation in the Southern hemisphere (Hadley cell) and are expected to be stable over the lifetime of the range. This expectation is, at least partially, confirmed by the sedimentological record.
from the Central Andes indicating that an arid climate has prevailed along the western slopes of central Andes from their formation in the late Oligocene to present day [Hartley, 2003]. Thus climatic conditions constitute a dominant control on the morphologies of Andean drainage basins, and a clear morphology-climate correlation is expected for those basins. The DEMs in the second sample were degraded to 180-meter resolution. This resolution represents a compromise between compatibility with Martian DEMs and the need to resolve relatively small basins. Basins delineated from the DEMs in the second sample have areas of 1.2 \times 10^3 to 1.3 \times 10^4 km^2 and reliefs of 705 to 6200 m. The mean of these reliefs is 4282(1302) m, and the mean of the slopes is 0.047(0.016). The basins are labeled 52 to 94, and their locations are shown in Figure 1d.

3. Methods of Analysis

3.1. Circularity Functions

In watershed analysis the circularity ratio, \( C \), is defined as a ratio of basin area, \( A \), to the area of a circle having a perimeter equal to the perimeter, \( P \), of the basin. Thus \( C = \frac{4 \pi}{P^2} \) approaches value of 1 as the basin becomes circular, and \( C \to 0 \) as it becomes long and thin. The circularity ratio is a scalar, a single number that characterizes the shape of the entire basin. We generalize the concept of circularity ratio to define a circularity function, \( C(z) = \frac{4 \pi}{P^2} \left( \frac{A(z)}{P(z)} \right) \), where the independent variable \( 0 \leq z \leq 1 \) is a normalized elevation.

The basin is “sliced” by a large number of horizontal planes located at progressively higher elevations starting with an outlet (\( z = 0 \)) and ending at the summit (\( z = 1 \)). A given plane (\( z = z_0 \)) bisects the basin into above-the-plane and below-the-plane sections. Denoting the below-the-plane section’s area and perimeter by \( A(z_0) \) and \( P(z_0) \), respectively, we define its circularity ratio as \( C(z_0) = \frac{4 \pi}{P^2} \left( \frac{A(z_0)}{P(z_0)} \right) \). Aggregating the values \( C(z_i) \) from all different bisecting planes, we construct the circularity function \( C(z) \).

By construction, \( C(z) \) is similar to a hypsometric curve (specifically, to an inverse of commonly defined hypsometric curve), \( H(z) = A(z)/A(z = 1) \), that measures the changes of a basin’s accumulated area with elevation. Although the two functions are constructed in a similar fashion, they encapsulate different aspects of basin morphology. The hypsometric curve gives a distribution of basin areas at different elevations. A typical, mature terres-

Figure 1. Location of all 94 basins used in the study. (a) Locations of Martian basins. (b and c) Location of terrestrial basins in the first sample. (d) Location of Andean basins. For Andean basins the APR in mm/yr is indicated.
trial basin has a bowl-like shape with most of its area located at low elevations. It yields a characteristic hypsometric curve. The bowl shape is a result of landscape evolution driven by the runoff erosion. In the absence of such an evolution, the basin would have a markedly different shape and would be represented by a non-characteristic hypsometric curve. Thus \( H(z) \) should be able, in principle, to discriminate between different styles of fluvial erosion. Indeed, Luo [2000] applied a hypsometric analysis to a number of fluvial and sapping terrestrial landforms. He used several statistical attributes of the hypsometric curve (integral, skewness, kurtosis, density skewness, density kurtosis) to derive a discriminant function measuring the relative role of groundwater sapping versus surface runoff in forming a basin. Subsequently [Luo, 2002], this discriminant function was used to classify basins in the Margaritifer Sinus region on Mars. A surprising result was the spatial intermingling of differently assigned classes of basins, suggesting a difficult to understand mix of fluvial and sapping processes on Mars. However, Fortezzo and Grant [2004] pointed out that Martian basins, unlike their terrestrial counterparts, have a natural tendency to be bowl-shaped without any fluvial evolution because of the role of impact cratering in forming the Martian landscape, thus putting in doubt the ability of hypsometric analysis to indicate the style of erosion on Mars.

[12] On the other hand, the circularity function measures the changes of basin’s elongation with elevation. Starting from an outlet, elongations of progressively larger segments of the basin are measured. For a typical terrestrial basin, an erosion rate increases by orders of magnitude toward the lower portions of the basin due to accumulating (fractal) geometry of the discharge. This intensification of runoff erosion causes the lower parts of the basin to elongate along the flow directions yielding a characteristic form of circularity function. This specific form is a direct result of the nature of runoff erosion and cannot be systematically mimicked by other factors. Thus the circularity function is a better discriminant of the style of erosion than the hypsometric curve.  

[13] Figure 2 compares a terrestrial basin (Green River basin in Utah, # 36 in Figure 1) with a Martian basin (Warrego Valles, # 25 in Figure 1). These two basins have similar areas (\( \approx 12000 \text{ versus} \approx 18000 \text{ km}^2 \)) and similar slopes (0.03 versus 0.034). The upper row shows a visual rendering of elevation fields for the two sites. Channels are visible in both renderings, but the landscapes are markedly different. This difference can be readily described but is difficult to quantify without any additional processing. The middle row shows topographic maps of the two basins. For each basin its elevation range is divided into 10 equispaced zones indicated by different colors. Extracted drainage networks are also shown for reference. Again, the differences in topography are clearly visible, but further processing is needed in order to quantify them. Construction of circularity functions provides the processing necessary for quantitative analysis. The bottom row shows circularity functions for the two basins. The different shapes of the functions capture, in an abbreviated but clear and quantitative fashion, the different morphologies of the basins. The circularity function for Green River basin has a typical shape associated with runoff erosion. This shape represents a basin morphology that could be succinctly described as “conformance of topography with drainage,” a telltale of runoff. On the other hand, the circularity function for Warrego Valles shows no clear trend. It fluctuates, but stays approximately constant for the entire range of \( z \). This reflects well the character of topography seen on both the topographic map and the shaded relief of this site. The morphology of Warrego Valles basin could be succinctly described as “non-conformance of topography with drainage.”

### 3.2. Similarity Maps

[14] The purpose of representing a basin by a mathematically simpler object, like the circularity function, is to facilitate a quantitative comparison between different basins. Using circularity functions in lieu of actual basins we can define a metric, \( d(b_1, b_2) \), that measures a “distance,” or level of similarity, between the two basins, \( b_1 \) and \( b_2 \). We use the Euclidean metric on circularity functions as a measure of similarity between basins.  

[15] The circularity function \( C(z) \) is represented by an \( N \)-dimensional vector \( C = (C(z_1), \ldots, C(z_j), \ldots, C(z_N)) \), where \( z_i = (i - 1)/(N - 1) \) is the set of equispaced relative elevation values. In our calculations we use \( N = 100 \) obtaining a rather detailed sampling of \( C(z) \). To obtain a measure of similarity between the two basins we calculate

\[
d_C(C_1(z), C_2(z)) = d_E(C_1, C_2),
\]

where \( d_E \) is defined as

\[
d_E(C_1, C_2) = \sqrt{(C_2^1 - C_1^1)^2 + \ldots + (C_2^N - C_1^N)^2}.
\]

In order for \( d_E \) to reflect basin similarity in a fashion that is relevant to our purposes, the original circularity functions are first normalized. The end value of a circularity function reflects the elongation of the entire basin. The two basins having similar internal morphology, and thus having similar forms of circularity function, may, nevertheless, be measured as “distant” if they have different overall elongations. This is because the value of the overall basin elongation sets the magnitude of the circularity function. Normalizing a circularity function using the whole basin circularity, \( C_0(z) = C(z)/C(1) \), frees the function from an influence of overall basin shape. Two basins having similar internal morphologies but different external shapes are represented by normalized circularity functions that are similar in form and magnitude, assuring that the basins are measured as similar by our metric. Note that, unlike the values of \( C_0(z) \), the values of \( C_0(z_0) \) do not pertain to the values of circularity ratio for sections of the basin located at \( z \leq z_0 \).  

[16] We construct a similarity map in order to visualize similarity relations between all the basins in a comprehensive yet simple fashion. The self-organizing map (SOM) concept [Kohonen, 1995] is used to construct a similarity map. The SOM is a neural network technique that maps similar vectors (in our case \( C \) vectors representing basins) into points on a 2-D grid composed of nodes. Through an unsupervised iterative procedure, the set of vectors (up to 94 vectors in our case) is mapped onto the grid’s nodes (225 to 900 nodes in our calculations) in such a way that similar vectors are associated with nearby nodes. Because the number of nodes is larger than the number of vectors, some nodes are not occupied. We use \( 15 \times 15 \) and \( 30 \times 30 \) grids.
30 square SOM grids with a Gaussian neighborhood for our calculations.

[17] Figures 3 and 6 are similarity maps constructed using the SOM technique. The grid of nodes fits into a square frame but it is not shown on those figures. The numbers represent basins and each is associated with a single node, but all are enlarged beyond the node size for better visibility. The numbers located close to each other on the map correspond to basins that are morphologically similar. It is important to stress that SOM is a nonlinear map, the distance between adjacent nodes is not constant. In particular, some nodes have larger than average distance to their adjacent nodes. The collection of these nodes corresponds to gaps between different parts of the SOM and provides a natural division of all basins into separate morphologic classes. We identify these classes using the Ward hierarchical clustering algorithm [Ward, 1963]. The separations between different classes are marked by dashed lines in Figures 3 and 6.

4. Results

4.1. Andean Basins

[18] We study the sample of 46 Andean basins searching for a correlation between basin morphology and climate (as expressed by the APR). This sample contains the three

Figure 2. Comparison of (left) Green River basin to (right) Warrego Valles basin. The top row shows visual renderings of elevation fields. Black lines show the basins’ boundaries. The middle row shows topographic maps of the basins. Colors from red to purple indicate increasing elevations. Blue lines represent drainage networks. The bottom row shows circularity functions.
sapping-dominated basins (# 49 to # 51) included in the first terrestrial sample and the entire second terrestrial sample (see section 2). The normalized circularity functions have been calculated for all basins in this sample and the similarity map (SM1) has been constructed using the SOM with a 15 × 15 grid of nodes. The APR values for Andean basins are calculated as averages over an area of each basin using precipitation data [Legates and Willmott, 1990] with spatial resolution of 2 pixels/degree. We have divided climatic conditions in the Andes into three groups, dry (APR < 100 mm/yr), moderate (100 < APR < 400 mm/yr), and wet (APR > 400 mm/yr). Dashed lines indicate separation between morphologic classes denoted by the letters A to D.

[19] Figure 3 shows the SM1, the basins are indicated by their numbers; basins' locations and the values of their APRs can be found using Figure 1. The morphologically similar basins are located close to each other on the map. The distance gaps divide the sample into four morphologic classes indicated by the letters A to D. The climate of a basin is indicated by a designated symbol. It is clear from Figure 3 that basin morphology correlates with the climate. All 13 basins in morphologic classes A and C are from sites in the Atacama Desert that have a very dry climate. Class A contains the two basins identified as sapping landforms. Of the 13 basins in the morphologic class B, 11 are from sites characterized by the wet climate. These sites are geographically split between the north and the south reaches of the Andean range, further supporting the conclusion that it is the climate and not the geographical location that correlates with the morphology. Finally, of the 20 basins in the morphologic class D, 13 are from the sites having a moderate climate. The mean of the reliefs of the basins in classes A + C, D, and B is 4414(1074), 4770(1053), and 3630(1504) m, respectively. The mean of the slopes in classes A + C, D, and B is 0.04(0.019), 0.05(0.015), and 0.04(0.017), respectively. The reliefs and slopes are similar in all morphologic classes leaving the APR as the only plausible variable that correlates with basin morphology.

[20] Another, more detailed but less convenient, way to visualize similarity relations between different basins is to construct a dendrogram. A dendrogram is a binary tree similar to a phylogenetic tree often used to study historical or genetic relation between groups of biological species. The basins form the leaves of the tree, and the two most similar basins are linked through a hypothetical “common ancestor basin,” which forms an internal node in the tree. The length of the branch between the basins and their “ancestor” is calculated using the $d_E$ metric and indicates the degree of similarity between the two basins. Figure 4 shows a dendrogram of the 46 Andean basins constructed using the same clustering algorithm as applied for classification of the SOM. The four major branches on the dendrogram correspond to the four classes identified on the SM1. Unlike the SOM, the dendrogram gives the specific value of similarity between different basins and shows hierarchical description of similarity relations between all the basins. For example, the dendrogram shows that the class A (the two sapping-dominated basins) are quite dissimilar from the other Atacama basins grouped in class C, further supporting their different origin.

[21] Selected basins from four different morphologic classes (four major branches on the dendrogram) are com-

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**Figure 3.** Similarity map for the 46 Andean basins (SM1). The basin climate is coded by the shape and the shade of the symbol enclosing the basin number, light gray hexagons indicate APR < 100 mm/yr, white squares indicate 100 < APR < 400 mm/yr, and dark gray pentagons indicate APR > 400 mm/yr. Dashed lines indicate separation between morphologic classes denoted by the letters A to D.

**Figure 4.** Dendrogram of 46 Andean basins. The leaves of the dendrogram are annotated by the basins’ numbers and their climate symbols. See caption to Figure 3 for description of climate symbols. The four major branches are denoted by letters A to D.
pared in Figure 5. This comparison helps to explain the relationship between the shape of the circularity function and the visual appearance of a basin. The bottom row in Figure 5 shows normalized circularity functions for the four basins. A division of Andean basins into the four classes is based on the similarity of circularity function. Therefore all basins in a given class have circularity functions similar to the representative function for this class shown in Figure 5. The representative function for class B has the smooth shape, characteristic for typical terrestrial basins outside of the Andean. This shape corresponds to a basin morphology (top and middle rows in Figure 5) that is characterized by well developed valleys along the major branches of a drainage network. These valleys reach deep into the basin. This describes a mature fluvial landscape with topography conforming to the drainage (like in the Green River basin discussed in section 3.1). This maturity is understandable in the light of the fact that the basins in this class are located in wet climates. On the other hand, the representative function for class C has a less smooth, more broken character. The upper part of this function has a linear character indicating that above a certain elevation the landscape morphology is a valley-free, simple inclined plane. The lower part of this function has some resemblance to circularity functions for class B basins. This function describes an immature fluvial landscape; there is some erosion in the lower part of the basin, but the upper part remains poorly eroded. Class C basins correlate with dry climates, which explains their immature character.

The representative function of the most abundant class D has a distinct character, quite different from characters of circularity functions of classes B and C basins. For most of the elevation range the function stays approximately constant at the level that is significantly higher than the value of circularity for the lower segments of the basins in class B. It rapidly grows at the end of the elevation range. The constancy of the circularity function indicates that a basin maintains its shape with increasing value of $z$. This maintained shape is quite elongated, but less elongated than typical valleys. This feature is well illustrated by the topographic map of basin # 64 in Figure 5. This type of basin morphology correlates with moderate precipitation, although a few wet basins are also in this group. Finally, circularity functions of class A basins are irregular and non-monotonic. This corresponds to basin morphology lacking developed valleys with watershed boundaries controlled by processes other than fluvial erosion. The basins in this class are located in dry climate, but, in addition, they have been identified as sapping landforms.

4.2. Comparison of Martian and Terrestrial Basins

We have made a similarity map (SM2) for all 94 basins in our data set to look for systematic morphologic differences between Martian and terrestrial basins and to
extrapolate the basin morphology-climate correlation, established for the Andean basins, to Mars. The normalized circularity functions have been calculated for all basins and the similarity map has been constructed using the SOM with $30 \times 30$ grid of nodes. We have also calculated a dendrogram for all 94 basins. This dendrogram, which is too large to be shown here, forks off the root into two major branches that happens to coincide with the division between Martian and terrestrial basins.

[24] The SM2 is shown in Figure 6; the basins are indicated by their numbers and basins' types are denoted by designated symbols. Black circles specify Martian basins, white squares specify terrestrial basins, and light gray hexagons indicate terrestrial basins in the Atacama Desert. The long-dashed curve indicates the separation between the two major morphologic domains, and the short-dashed curves indicate separations between different classes, mA to mD, within the Martian domain.

Figure 6. Similarity map for all 94 basins in the data set (SM2). The basin type is coded by the shape and the shade of the symbol enclosing the basin number, black circles indicate Martian basins, white squares indicate terrestrial basins, and light gray hexagons indicate terrestrial basins in the Atacama Desert. The long-dashed curve indicates the separation between the two major morphologic domains, and the short-dashed curves indicate separations between different classes, mA to mD, within the Martian domain.

of the left-central zone of the SM2. The amount of intermixing between the wet and moderate climate basins on the SM2 is the same as on the SM1. The locations of additional terrestrial basins, for which the values of the APR are unknown but are expected to be in the wet or moderate climate categories, coincide with the locations of the Andean wet and moderate climate basins. Finally, the dry climate Andean basins are located in the central zone of the SM2. Note that the additional terrestrial basins have slopes that are comparable with the slopes of the Martian basins and are much smaller than the slopes of the Andean basins. Nevertheless, their locations on the SM2 intermix with the Andean basins and not with the Martian basins. This provides an additional support for our claim that basin morphology derived from its circularity function correlates with climate and not with quantities like slope or relief.

[26] Within a terrestrial domain of the SM2, increasingly drier basins are located progressively toward the terrestrial/Martian divide culminating in the Atacama basins that are placed right along the divide. Most of the Atacama basins are on the terrestrial side of the divide, but four of them are on the Martian side, and one basin (#51) is found deep inside the Martian domain. Thus the Atacama basins have morphologies that are transitional between the morphologies of the typical basins on Earth and Mars. We interpret their borderline location in terms of the morphology-climate correlation extrapolated into the Martian domain. These basins are atypical on Earth because they have formed in locations that are uncharacteristically dry for our planet. On the other hand, the same basins would also be atypical on Mars, presumably because they have formed under conditions that are uncharacteristically "wet" for Mars. The corollary of this interpretation is that the valley networks on Mars formed in climatic conditions that were at least as dry, and perhaps significantly drier than those found at the Atacama Desert.

[27] Not all Martian basins have the same type of morphology, the Martian domain branches into four morphologic classes denoted by the symbols mA to mD and indicated by the short-dashed curves in Figure 6. This division was established using the hierarchical clustering algorithm. Class mA contains four Martian and three terrestrial basins. Their circularity functions are similar to the functions of class C in Figure 5. These are the most Atacama-like Martian basins (some of them are indeed the Atacama basins). Basins in classes mC and mD have circularity functions that lack a drainage signature. They are similar to the basins in class A in Figure 5. The overall topography of these basins is similar to the topography of the sapping dominated Atacama basin (#50) shown in Figure 5. Class mC groups the most "featureless" Martian basins, whereas basins in class mD have some, very weak indications of valley initiation. The character of basins in class mB is intermediate between classes mA, mC, and mD.

5. Discussion

[28] Drainage basins are complicated objects that require a simpler formal representation to be studied quantitatively. To our knowledge, the only previously used formal representation of a basin is the hypsometric curve [Luo, 2000, 2002]. We have investigated the feasibility of the hypso-
metric curve to represent a basin for a purpose of inferring its erosional history (and thus past climate) and came to the negative conclusion. In particular, we have constructed a similarity map of the 43 Andean basins using hypsometric curves to represent the basins. Such a map is analogous to the SM1, but it fails to reveal any (expected) correlation between basin morphology and climate. We have also constructed a similarity map of all 94 basins using the hypsometric curves in lieu of the basins. Such a map, analogous to the SM2, fails to separate terrestrial and Martian basins. Thus we claim that the hypsometric analysis of drainage basins is, in general, infeasible for inferring a basin’s erosional history. This result supports our earlier findings [Stepinski and Coradetti, 2004], as well as findings of Fortezzo and Grant [2004], and helps to explain the confusing results of Luo [2002]. However, it is at odds with the results of [Luo, 2000] who demonstrated that a hypsometric technique can be used to distinguish between runoff and groundwater sapping terrestrial landforms. It needs to be pointed out that Luo’s analysis pertained to a set of all-terrestrial, very small basins, and that no connection between basin morphology and the climate was attempted in that study.

[29] We have found that a circularity function, introduced by Stepinski and Coradetti [2004] and explained in section 3.1, constitutes a feasible basin representation for a purpose of inferring its erosional history. The viability of the circularity function can be traced to its more direct delineation of an erosional process. Using circularity functions in lieu of actual basins, we were able to divide Andean basins into separate morphologic classes and demonstrate a correlation between basin morphology and its climate (Figures 3 and 4). To our knowledge, this is the first time such a correlation has been demonstrated quantitatively. The obtained correlation is good but not perfect, underscoring the difficulties of isolating climate from the many other factors influencing basin morphology. It has to be pointed out that the Andes are an ideal place for deconvolving the climate from all of the other factors contributing to the character of basin morphology. More work is required to see whether such a correlation can be established for other regions on Earth. Nevertheless, at the minimum, we have demonstrated that basins developed under arid conditions have a characteristic morphology (class C in Figures 3, 4, and 5). Furthermore, basins developed under arid conditions with substantial contribution from groundwater sapping have a different characteristic morphology (class A in Figures 3, 4, and 5).

[30] In order to infer the past climate of the 26 Noachian sites in our study, we have embedded the basins extracted from those sites into a larger sample of terrestrial basins and constructed a similarity map of the total sample (Figure 6). We have found that Martian basins are morphologically different from typical terrestrial basins, but somewhat similar to the atypical terrestrial basins located at the Atacama Desert. Extrapolating to Mars the morphology-climate correlation established for the Andean basins, we have concluded that Noachian sites had experienced past climate that was as dry or drier than the present (and past) climate of the Atacama Desert.

[31] In addition to being very low, the Atacama precipitation is also highly intermittent with most of it falling during the austral summer. In addition, the Atacama region experiences interannual climate variability (while staying arid overall as pointed out in section 2), as has been established from fossil rodent middens and wetland deposits [Betancourt et al., 2000; Rech et al., 2002]. Such changes are postulated [Vuille et al., 2000] to be caused by the Pacific sea surface temperature anomalies (El Niño/La Niña). The influence of climate variability on the basin morphology remains unknown in the context of the Atacama. Future research, including numerical simulations of landform evolution under intermittent precipitation, is needed to establish whether intermittence of precipitation is an important factor in establishing the characteristic morphology of drainage basins in this region, or whether the aridity alone is a dominant factor.

[32] Interestingly, there is also some evidence of climate intermittence on Noachian Mars. Jaumann and the HRSC Co-Investigator Team [2005] used data from the Mars Express High Resolution Stereo Camera to study an inner channel within the larger valley in the Lybia Montes. They determined the depth of the inner channel, and thus its maximum discharge rate, which happens to be comparable to discharges in large terrestrial rivers indicating high erosion activity. On the other hand, they have also found a large age difference between the valley floor and the surroundings, indicating a low average erosion rate. This discrepancy is resolved if the valley was dug by episodic floods resulting from an intermittent climate. Segura et al. [2002] suggested that intermittence of climate on early Mars may be caused by impacts that inject water into the atmosphere for a subsequent precipitation. Such a scenario envisions an arid early Mars punctuated by spells of a temporally and spatially limited wetter climate. Irwin et al. [2005] described geological evidence for a brief episode of relatively intense runoff, concentrated in higher elevations. Notwithstanding the differences in time scales, magnitudes, and causes, this scenario resembles the climatic situation in the Atacama Desert.

[33] Another hydrological peculiarity of the Atacama is the large amount of groundwater that it receives. The precipitation in the high Andes is relatively high as it is received not from nearby but dry Pacific air masses, but from moist air masses originating in the Atlantic [Zhou and Lau, 1998]. This precipitation recharges the groundwater system that flows down the Pacific slope and feeds aquifers in the Atacama. This creates potential for large scale groundwater sapping landform features, and indeed, several such features have been identified (see section 2). On Noachian Mars, under the climatic scenario described above, the impact-induced precipitation would preferentially fall at higher elevations [Colaprete et al., 2003] also creating potential for the creation of sapping landforms. Many sapping-looking landforms are indeed observed in valley networks. We found (section 4.2) some diversity in morphologies of Martian basins, with several basins showing a little bit more surface erosion than the others. However, we did not find any correlation between basin class and its geographical location, elevation, or relief. Future, more detailed work is needed to establish whether different classes of Martian basins’ morphologies can be tied to their other physical properties.
Acknowledgments. This research was conducted at the Lunar and Planetary Institute, which is operated by the Universities Space Research Association under contract CAN-NCC5-679 with the National Aeronautics and Space Administration. This is Lunar and Planetary Institute contribution 1271.

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