Hypsometric analysis of Margaritifer Sinus and origin of valley networks

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[1] The formation of Martian valley networks has been debated since their discovery. The relative roles of groundwater sapping and fluvial runoff processes have different implications on Martian paleoclimate. This paper uses a hypsometric analysis technique that has been tested on terrestrial landforms to analyze the hypsometric attributes of watershed basins in the Margaritifer Sinus region on Mars using Mars Orbiter Laser Altimeter (MOLA) gridded topographic data. On the basis of quantitative characteristics of their hypsometric attributes, the majority of the basins (covering ~3/5 of the study area) look more like terrestrial basins of sapping origin, and a significant number of basins (covering ~1/5 of the study area) are more fluvial like. The classification of the rest of the basin is less certain at the presently available resolution of the digital elevation model (DEM). Overlay with Viking photomosaic indicates that the classification is generally consistent with the morphology shown in Viking images. Although this analysis alone cannot make a sure determination of valley network origin, combined with other morphometric analysis, the results from this study are consistent with a valley network formation by precipitation-recharged groundwater sapping, suggesting a warm and wet climate for early Mars. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 1824 Hydrology: Geomorphology (1625); 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5455 Planetology: Solid Surface Planets: Origin and evolution; *KEYWORDS:* Hypsometric analysis, groundwater sapping, Margaritifer Sinus, Mars, valley networks, landform

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1. Introduction

[2] The origin of Martian valley networks has been debated since their discovery and the debates have been focused on the processes responsible for their formation and the climatic conditions required [e.g., *Sharp and Malin*, 1975; *Pieri*, 1976, 1980; *Carr*, 1981, 1999; *Baker*, 1982, 1990; *Higgins*, 1982; *Mars Channel Working Group*, 1983; *Laity and Malin*, 1985; *Gulick and Baker*, 1989; *Haberle*, 1998; *Malin and Carr*, 1999; *Grant*, 2000; *Malin and Edgett*, 2000; *Goldspiel and Squyres*, 2000]. The fact that most valley networks cut into Noachian terrain in the older southern highlands [e.g., *Carr and Clow*, 1981; *Mars Channel Working Group*, 1983] and the fact that liquid water is unstable everywhere on the surface under current climatic condition [*Leighton et al.*, 1965; *Farmer and Doms*, 1979] have led to the suggestion that early Mars may have had a warmer and wetter climate and have changed to present condition soon after the heavy bombardment (~3.9 Gyr) as the atmosphere lost most of its CO_2 to formation of carbonates [e.g., *Fanale*, 1976; *Pollack*, 1979; *Pollack et al.*, 1987; *Fanale et al.*, 1992]. While some geomorphic characteristics of valley networks (such as integrated dendritic form) suggest terrestrial-like surface fluvial activity [e.g., *Milton*, 1973; *Sagan et al.*, 1973; *Baker et al.*, 1992], many attributes (such as U-shaped cross-section, amphitheater termination, and low drainage density) also point to an alternative process: groundwater sapping, an erosional process by emerging groundwater that weakens basal support and leads to sidewall collapse and headward extension [e.g., *Pieri*, 1976; *Sharp and Malin*, 1975; *Howard et al.*, 1988; *Baker and Kochel*, 1979; *Baker*, 1990; *Malin and Edgett*, 2000; *Gulick*, 2001]. Although in either case, water appears to be the primary candidate erosion agent, whether the valley networks are formed predominantly by groundwater sapping or by surface runoff has important and different implications on Martian paleoclimate [e.g., *Squyres and Kasting*, 1994; *Carr*, 1995].

[3] If surface runoff is the dominant erosion style, an early warmer and wetter climate is required [e.g., *Masursky*, 1973; *Carr*, 1995]. However, this simple model also met challenges on several grounds. For example, the solar constant would be significantly lower for early Mars [*Kasting*, 1991]; there is little spectroscopy evidence for surface carbonates; and some valley networks are formed after Noachian [*Carr*, 1995]. If groundwater sapping is the dominant erosion style, then the valley networks could be formed under current climate conditions [e.g., *Pieri*, 1980; *Squyres and Kasting*, 1994], perhaps under thick ice cover [e.g., *Wallace and Sagan*, 1979; *Carr*, 1996]. However, this mechanism alone cannot explain all the valley network

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features observed. In addition, estimates of water passing through the valley networks and outflow channels range from several hundred meters to kilometers [e.g., *Baker and Kochel*, 1979; *Carr*, 1986, 1996] much larger than the inventory inferred from atmosphere composition and geochemical evidence in SNC meteorites [e.g., *Fanale*, 1976; *Fanale et al.*, 1992; *Carr and Waenke*, 1992; *Dreibus and Waenke*, 1987; *Donahue*, 1995; *Jakosky and Phillips*, 2001]. Thus, some recycling mechanism to bring the water that flowed to the northern lowlands back to the highland to recharge the groundwater system is required. Alternative hypotheses proposed for recharging groundwater include hydrothermal convection [e.g., *Brakenridge et al.*, 1985; *Gulick and Baker*, 1989], basal melting at the pole and transport from pole to equator through a global, interconnected megaregolith [*Clifford*, 1987, 1993], and episodic temporary warm climate conditions throughout Martian history under which short-term hydrologic cycle would occur [*Baker et al.*, 1991].

[4] The purpose of this paper is to evaluate the relative role of groundwater sapping versus surface runoff in formation Martian valley networks using a hypsometric analysis technique [*Luo*, 1998, 2000], which could provide an additional piece of evidence in understanding the climatic history of Mars. This technique takes advantage of digital elevation models (DEMs), which are important data sets that can be used to evaluate the geomorphic characteristics resulting from different processes and thus can provide additional constraints on the processes that lead to the landform. However, due to the poor vertical resolution of previous topographic data, geomorphic studies prior to the Mars Global Surveyor (MGS) mission were primarily based on qualitative interpretation of Viking images and planform geometry of networks. With recent availability of higher resolution topographic data (both MGS data and stereographic Viking data), it is now possible to conduct more detailed quantitative morphometric analysis of Martian valley networks. This work is complementary to those that use more traditional morphometric analysis techniques [e.g., *Grant*, 2000; *Gulick*, 2001; *Cabrol and Grin*, 2001; *Williams and Phillips*, 2001; *Hynek and Phillips*, 2001].

[5] An area encompassing Margaritifer Sinus region (0°–40°W, 20°N–30°S), located near the eastern end of Valles Marineris, is selected as the study area because it has well-developed valley network systems [e.g., *Boothroyd and Grant*, 1985, 1986; *Baker*, 1982; *Carr*, 1995]. *Grant* [2000] conducted a basin wide geomorphic analysis of this area based on detailed stereographic and geologic mapping. He concluded that its valley characteristics (drainage density, relief ratio, ruggedness number, estimates of sediment sink, and channel excavation) are consistent with formation by precipitation-recharged groundwater sapping within a layered, permeable substrate.

2. Hypsometric Analysis Methodology

[6] Recent studies have demonstrated that hypsometry is very valuable in geomorphic analysis because it is sensitive to processes responsible for the landform (e.g., the relative importance of hillslope diffusive transport and channel fluvial transport) [*Willgoose and Hancock*, 1998; *Hurtrez et al.*, 1999]. Thus, quantitatively describing the shape of the curve becomes important in hypsometry analyses. Hypsometric integral (the area under the curve) is the most often used quantitative measure. While this is a useful parameter, it has its limitation, i.e., different hypsometric curves may have very similar integral. *Harlin* [1978] developed a technique that is able to describe the subtle changes of the shape of the curve quantitatively with statistical skewness and kurtosis by treating the hypsometric curve as a cumulative probability distribution (see *Harlin* [1978] and *Luo* [2000] for details). In this technique, the hypsometric curve is represented by a continuous polynomial function and the statistical skewness and kurtosis of this cumulative probability function (the hypsometric curve) and its density function (first derivative of the curve) can be derived in terms of the polynomial coefficients [*Harlin*, 1978]. The integral of the hypsometric curve, the skewness and kurtosis of the hypsometric curve and the skewness and kurtosis of its density function are collectively called hypsometric attributes or parameters in this paper. These parameters portray different characteristics of a basin that are suggestive of processes (Table 1). For example, density skewness indicates the rate of change in slope and a positive value is usually associated with typical fluvial landform and a negative one with sapping landform [*Luo*, 2000]. Results from terrestrial application based on 30 m/pixel resolution United States Geologic Survey (USGS) 7.5 minute DEM data indicate that these hypsometric attributes can reasonably well separate typical terrestrial sapping and fluvial landforms and that density skewness, integral and skewness are most effective in separating the two landforms [*Luo*, 2000]. In addition, discriminant functions that can separate typical terrestrial sapping and fluvial landforms have been established [*Luo*, 2000]. They are listed below for easy reference:

Table 1. Physical Meaning of Hypsometric Attributes[a]

Parameter	Meaning
Integral (INT)	Mass left after erosion
Skewness (SK)	Amount of headward erosion in upper reach of basin
Density Skewness (DSK)	Rate of slope change
Kurtosis (KUR)	Erosion on both upper and lower reaches of basin
Density Kurtosis (DKUR)	Midbasin slope

[a] Compiled from *Harlin* [1978].

$$F = -157.3274 + 98.9434 \times DSK + 536.7120 \times INT + 164.4041 \times SK \tag{1}$$

$$S = -161.9439 + 93.3136 \times DSK + 551.2865 \times INT + 154.4376 \times SK \tag{2}$$

where F = linear discriminant function for fluvial landform
S = linear discriminant function for sapping landform
DSK = skewness of hypsometric density function
INT = hypsometric interval
SK = skewness of the hypsometric curve

[7] A basin's possible origin can be determined by simply plugging its hypsometric attributes into the above discriminant equations. It is possibly of sapping origin if S-F>0; it is possibly of fluvial origin if S-F<0.

[8] The terrestrially derived disciminant functions provide a basis for applying this technique to Mars. However,

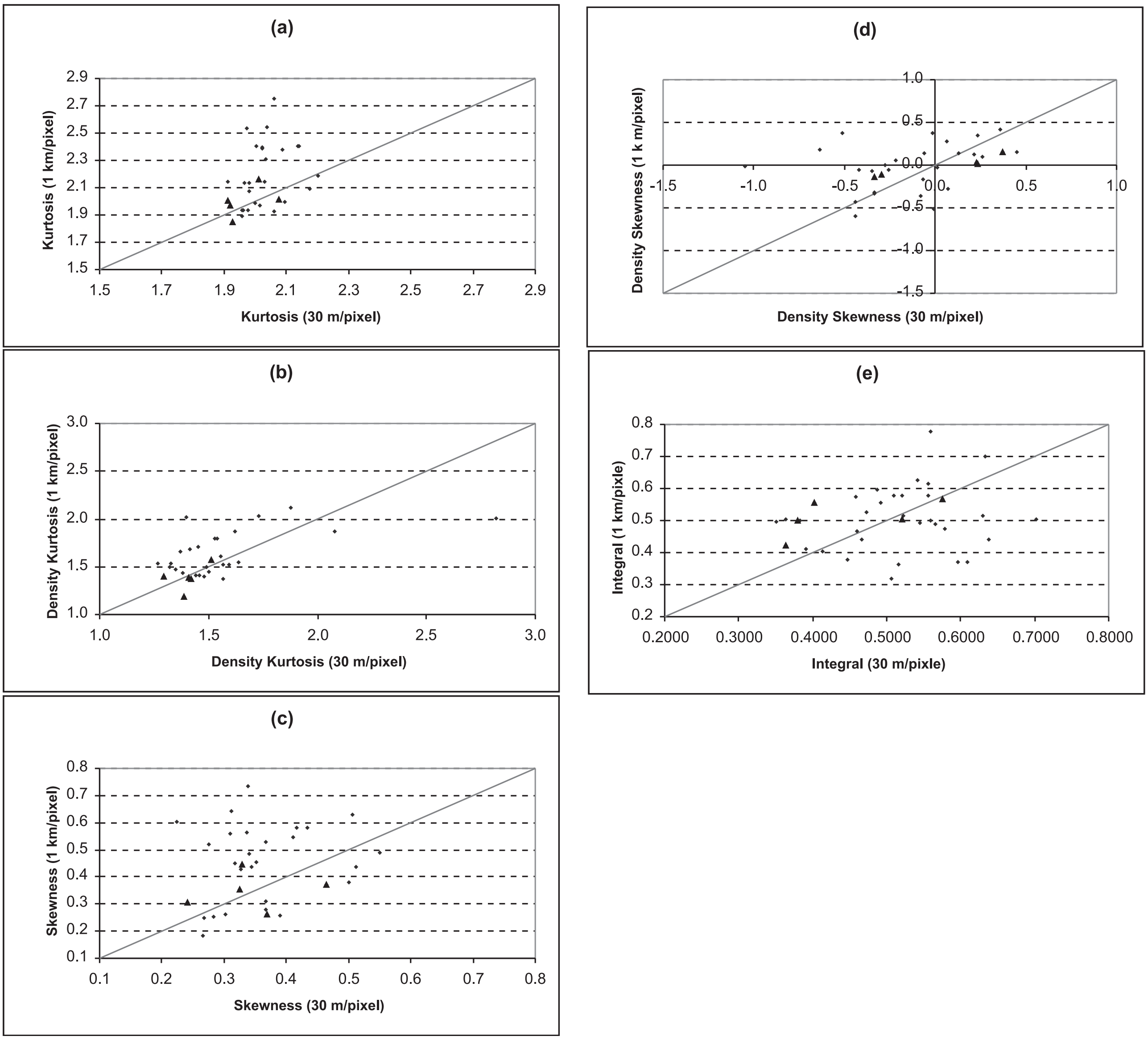

Figure 1. Scatterplots of hypsometric attributes based on 1 km/pixel DEMs vs. those based on 30 m/pixel DEMs. The solid line is the 1:1 line. If the hypsometric attributes are truly resolution independent, the data points should fall on the 1:1 line. Despite the scattering, the general trend of the points follow the 1:1 line. This is especially true for the five basins with area greater than 100 km^2 (shown as triangles).

this technique is not meant to replace existing traditional morphometry analyses [e.g., *Baker and Partridge*, 1986; *Grant*, 2000; *Craddock and Cook*, 2000; *Gulick*, 2001; *Cabrol and Grin*, 2001; *Williams and Phillips*, 2001], but to provide additional, complementary quantitative information that could be suggestive of underlying processes.

3. Effects of DEM Resolution

[9] Although MOLA data has very high vertical and downtrack resolution [*Zuber et al.*, 1992], the finest spatial resolution of gridded topographic data currently available for Mars is the 1/32 degree/pixel or 1.864 km/pixel MOLA Experiment Gridded Data Record (EGDR) (http://wufs.wustl.edu/missions/mgs/mola/egdr.html), far coarser than the terrestrial 30 m/pixel resolution USGS 7.5 minute DEM. To evaluate the effects of the DEM resolution on hypsometric analysis technique, this technique was applied to two terrestrial data sets of different resolutions: the ~1 km/pixel resolution global 30 arc seconds DEMs (GTOP30) and the 30 m/pixel resolution 7.5 minute DEMs. The two data sets were projected to the same map projection and the 5 hypsometric attributes for the same watersheds studied by *Luo* [2000] were calculated from each data set. The results are compared in Figure 1 in scatterplots. If the attributes were truly resolution independent, the points should plot along the 1:1 line. While there is scattering of the points, the trend of the points generally follows the 1:1 line. This is especially true for those basins with an area greater than 100 km^2 (shown as triangles in Figure 1). This is consistent with previous findings that the qualitative shape of the hypsometry curve and the hypsometric integral are generally inde-

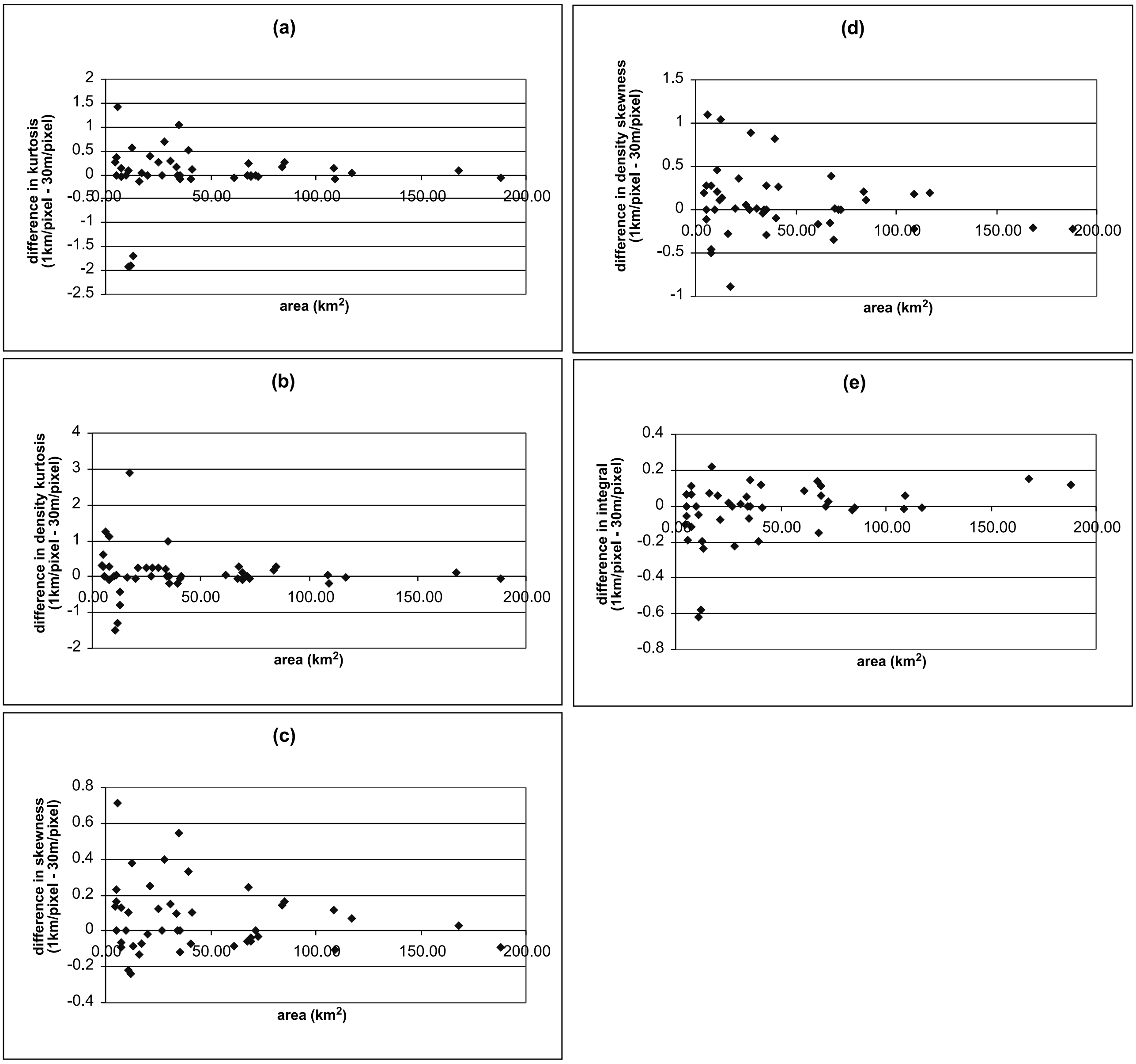

Figure 2. Difference of hypsometric attributes obtained from coarse and fine resolution DEM as a function of basin size. The differences are generally minimized if the basin size is greater than 100 km^2.

pendent of DEM spatial resolution based on data from central Nepal with varying spatial resolution ranging from 20, 40, 100, 200, 400, to 800 m [*Hurtrez et al.*, 1999]. Furthermore, a closer look at the discrepancies of the parameters between the two different resolution data sets as a function of the basin size (Figure 2) indicates that, in general, the larger the basin size, the smaller the difference. This result suggests that the differences between using a coarser resolution DEM (such as MOLA EGDR) and a finer resolution DEM (such as 7.5 minute DEM) may be minimized if this technique is applied to large sized basins (>100 km^2).

[10] In order to further examine the effects of scattering in hypsometric attributes obtained from different DEM resolutions on the discriminant analysis result, data from terrestrial study [*Luo*, 2000] were re-analyzed. First, the range of differences in hypsometric attributes between the two resolutions were obtained from basins that are larger than 100 km^2 (see Table 2). Next, random "perturbations" of the obtained ranges were added to each basin's hypsometric attributes and the "perturbed" hypsometric attributes were plugged into the same discriminant functions (equations (1) and (2)). The results of 1000 random simulations indicate that changes of these ranges to the hypsometric attributes did change the classification of the landform origin for some basins. However, for those basins that the difference between the sapping and fluvial discriminant function is greater than a threshold of about 2 (i.e., $|S\text{-}F| > 2$), the

Table 2. Range of Differences in Hypsometric Attributes Between 1 km and 30 m Resolution DEM for Basins Greater Than 100 km^2

	INT	SK	KUR	DSK	DKUR
Max	0.15168	0.10254	0.10724	0.26999	0.10074
Min	−0.01016	−0.10664	−0.08045	−0.22756	−0.19929

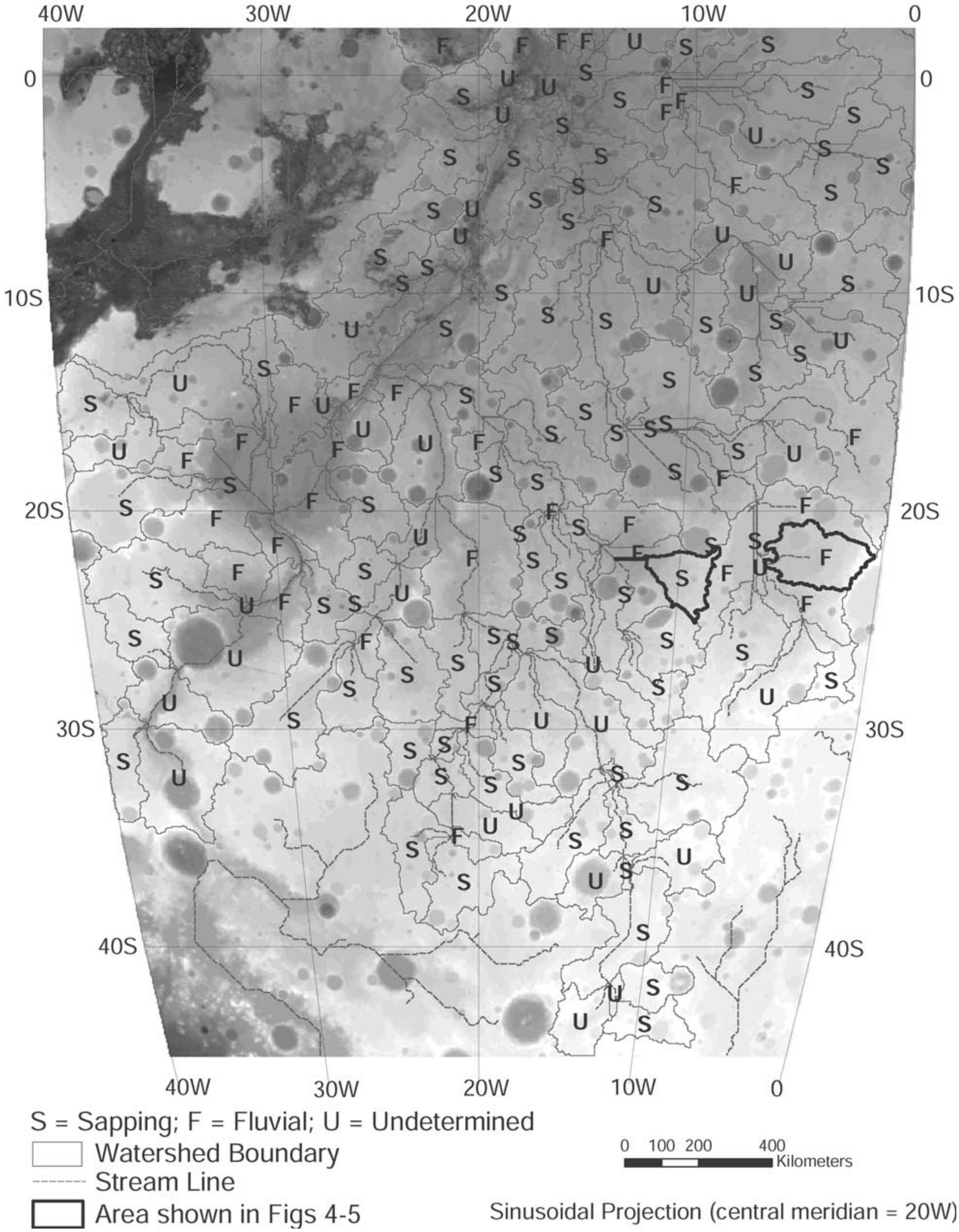

Figure 3. Drainage basins of Margaritifer Sinus and drainage networks derived from 1/32 degree/pixel MOLA EDGR data and their classification based on hypsometric attributes. *F* indicates the basin is more fluvial like; S indicates the basin is more sapping like; N indicates its origin cannot be determined with current spatial resolution. The discriminant function was established based on typical terrestrial sapping and fluvial basins [*Luo*, 2000]. Although the study area covers 0°–40°W, 20°N–45°S, only area south of equator is shown here to be more consistent with the extent of Margaritifer Sinus Quadrangle.

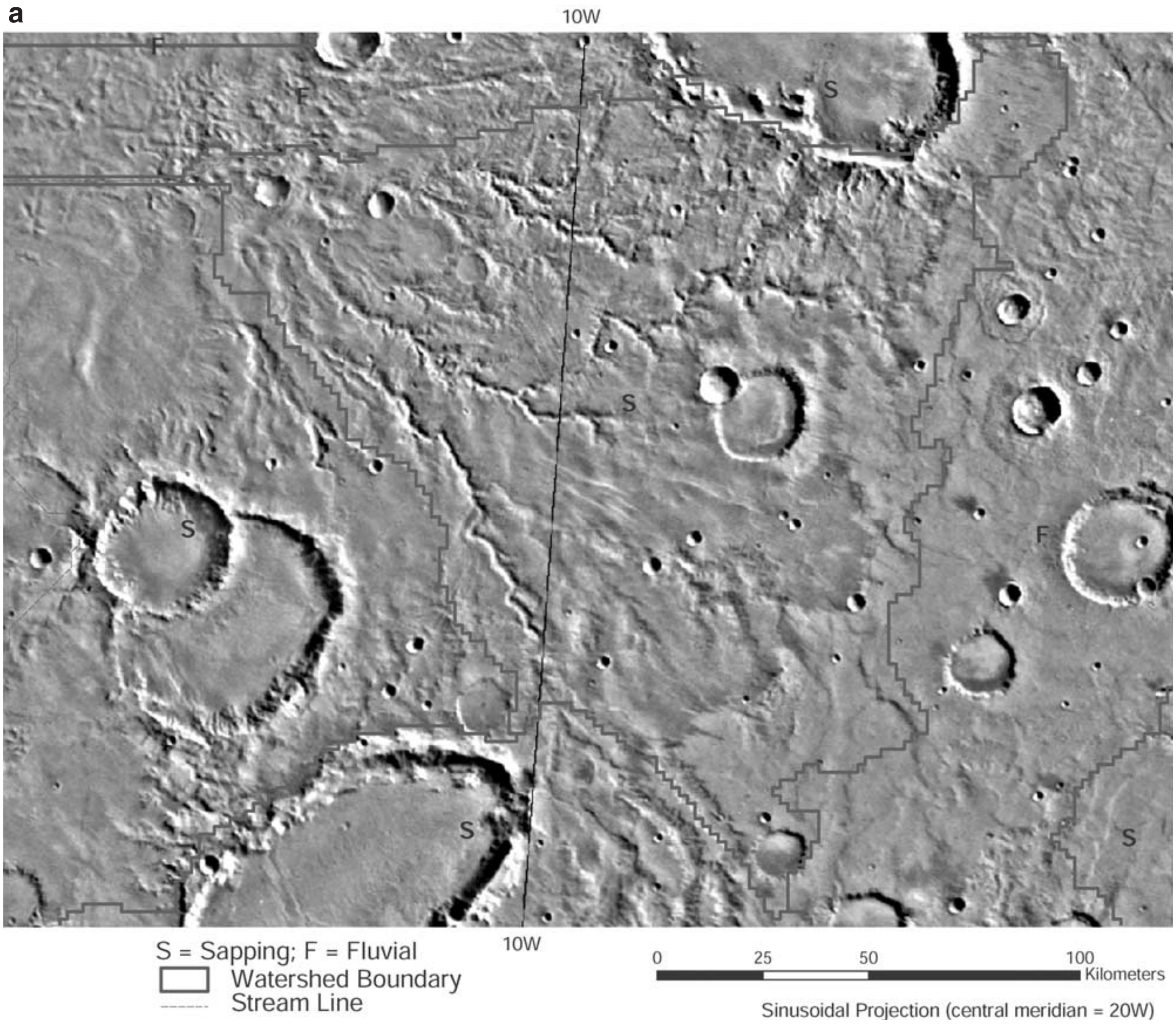

Figure 4. (a) Overlay of a sapping like watershed basin and Viking image. Although there is drainage network, their morphology is consistent with sapping erosion, possibly initiated as fluvial channels. (b) The hypsometric curve and attributes of this basin. Hypsometric curve characteristics clearly look like a sapping basin. INT represents hypsometric integral; SK, skewness of the hypsometric curve; KUR, kurtosis of hypsometric curve; DSK, skewness of hypsometric density function; DKUR, kurtosis of hypsometric density function; *F* and S discriminant functions for sapping and fluvial basins respectively, see equations (1) and (2).

possible origin classification did not change between pre- and post-perturbation. In other words, the current DEM resolution does not bias the possible origin classification if (1) the basin size is greater than 100 km^2 and (2) the discriminant difference is greater than 2 ($|S-F| > 2$). Thus, in this study, care is taken to make sure that these two conditions are met when identifying possible origin of Martian landform. Basins with a discrimant difference small than 2 (i.e., $|S-F| < 2$) were classified as undetermined.

4. Application and Discussion

[11] The 1/32 degree/pixel resolution EDGR data were imported into Arc/Info Geographic Information System (GIS) commercial software and projected in sinusoidal projection, an equal area projection necessary for accurately computing basin areas needed for constructing hypsometric curves (as the study area spans over a latitude range of the 65°, non-equal area projection would cause distortions in basin area). The GRID functions of Arc/Info [*Environmental Research Systems Institute*, 1992; *Jenson and Domingue*, 1988; *Tarboton et al.*, 1991] were then used to delineate watershed boundaries of the Margaritifer Sinus region (Figure 3). The flow direction was first determined from the DEM by finding the direction of steepest descent, or maximum drop, from each cell. Local depressions (sinks) were filled to ensure better flow direction determination, as the flow directions for sinks are undefined. Then flow accumulation at each cell was computed based on the flow direction, i.e., for each cell, determining how many upstream

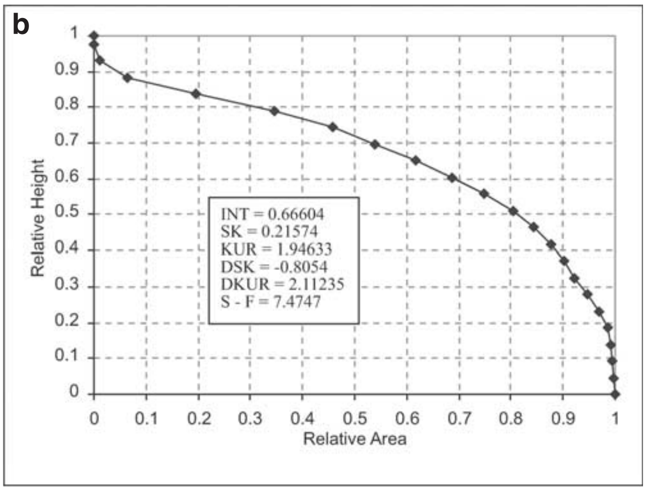

Figure 4. (continued)

cells would flow into it. Group of cells with high values of flow accumulation represent stream. A cutoff threshold values is used to define the stream network. The smaller the cutoff threshold, the more detail the stream networks and thus the smaller the resultant watersheds. As discussed in previous section, to minimize the adverse effect of applying the hypsometric technique to coarse spatial resolution DEMs, a contributing threshold area of 5,000 cells was used to define the drainage network and delineate the watersheds, which resulted in delineated watersheds of areas range from about 300 km^2 to 200,000 km^2. The GIS automation procedure of the hypsometric analysis technique [*Luo*, 1998] was then applied to each watershed of this region and their hypsometric attributes obtained. If we assume that groundwater sapping or surface fluvial processes similar to the terrestrial ones had dominated on Mars in the past, we would expect to observe respective resultant landforms on Mars similar to what we see on Earth. Under this assumption, the hypsometric attributes obtained from Mars topographic data were plugged into the established discriminant functions obtained from typical terrestrial sapping and fluvial landforms and each basin was classified as more sapping like, more fluvial like, or undetermined. Of the 194 basins in the study area (0°−40°W, 20°N−45°S), 105 of them (covering an area of about 3.0×10^6 km^2) were classified as sapping-like, 42 of them ($\sim 1.0 \times 10^6$ km^2) fluvial-like, and 47 of them ($\sim 1.4 \times 10^6$ km^2) undetermined. Thus the majority of the basins have hypsometric characteristics consistent with formation by groundwater sapping (Figure 3). However, the role of fluvial erosion cannot be ignored, as a significant number of basins look more fluvial-like (Figure 3).

[12] In order to verify the classification against remote sensing image, Viking photomosaic images were obtained from the "Map A Planet" website (http://pdsmaps.wr.usgs.gov/maps.html) and projected to the same sinusoidal map projection. Visual inspection of the overlay of Viking images and the watershed boundaries shows that the watershed delineation is generally consistent with the morphology shown in Viking imagery and that the two types of basins are generally different. Fluvial basins generally contain some visible valley networks and sapping basins generally either lack valley networks or the valley networks show characteristics of sapping origin. Figure 4 shows an example of sapping like basin along with its hypsometric curve and attributes. Although there is visible drainage network, the channels have more or less constant width from source to outlet, the tributaries are poorly developed (short and stubby looking), and there is little sign of interfluve dissection. (Lack of interfluve dissection is also observed on fine resolution MOC images [e.g., *Malin and Carr*, 1999; *Carr and Malin*, 2000].) These features are all consistent with a sapping origin basin on Earth. In addition, the visible channels are concentrated toward the outlet (lower elevation) of the basin. They may have been started as fluvial channels from basin-wide surface rainfall and runoff erosion and later modified by groundwater sapping as erosion tapped into groundwater. As water table drops when climate became progressively colder and drier, groundwater sapping was concentrated in the lower reaches of the basin. The characteristics of the hypsometric curve clearly identify this basin as one of sapping origin. Figure 5 shows an example of fluvial like basin along with its hypsometric curve and attributes. This basin has extensive valley networks extending to the upper boundary of the basin but lack visible channels in the lower reaches of the basin, indicating extensive erosion throughout the whole basin. Although its hypsometric characteristics are consistent with a fluvial origin, it is conceivable that groundwater sapping process also played a significant role in eroding the lower reaches of this basin as fluvial erosion tapped into groundwater aquifer. This basin is located at a higher elevation (average 280 m) than the one shown in Figure 4 (average 40 m). Although no statistical correlations were found between the origin classification of a basin and its mean basin elevation over the whole study area, the orographic effect related to the higher elevation of this basin could have led to higher precipitation rate, which in turn could recharge the groundwater table more to keep a higher hydraulic gradient and thus a higher groundwater discharge rate for a longer time than the basin at a lower elevation. Thus fluvial channels in the lower reaches of this basin that tapped into groundwater aquifer could be eroded away (obliterated) through basal sapping, collapse, and lateral retreat by high discharge groundwater flow. The sediments generated would then be removed by surface rainfall-runoff. As climate became drier and colder, the precipitation rate decreased, the water table dropped, and the fluvial channels are left high in the upper reaches of this basin.

[13] As both sapping- and fluvial-like basins are present in the study area, the valley networks here can be best explained by a two-step process that involve both rainfall-runoff fluvial erosion and groundwater sapping, as suggested by *Baker and Partridge* [1986] and supported by *Grant* [2000], *Hynek and Phillips* [2001], and *Williams and Phillips* [2001]. The valley networks are likely initiated as fluvial valleys through rainfall-runoff process, consistent with early warm and wet climate conditions. As fluvial erosion taped into groundwater aquifer, ground water-sapping process was initiated and modified the existing channels and basin hypsometry. The different state of modification and preservation make some basins more sapping like and some more fluvial like. Although the interpretation from hypsometric analysis is not unique, as other processes such as mass wasting [e.g., *Dunne*,

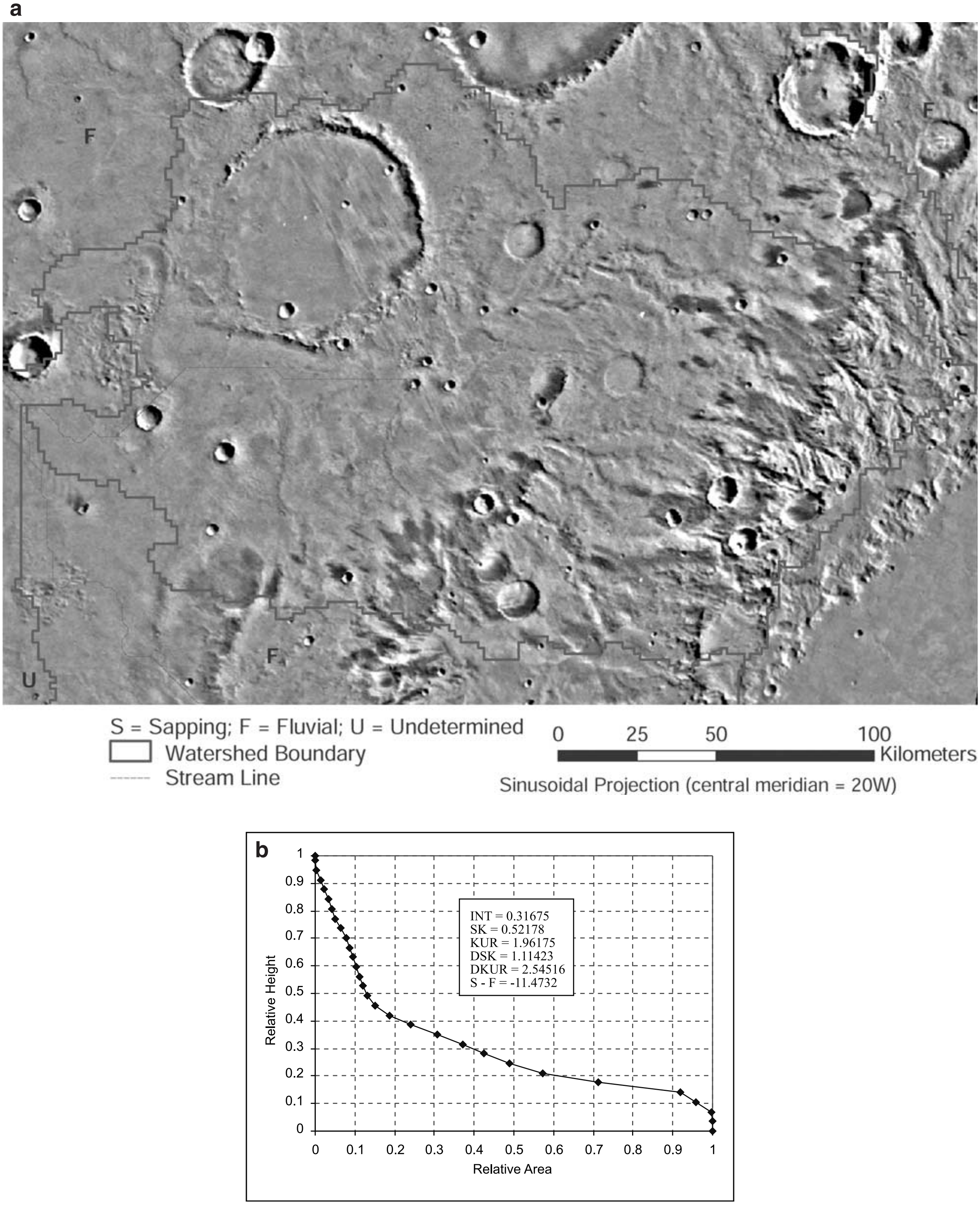

Figure 5. (a) Overlay of a fluvial like watershed basin and Viking image. Drainage channels occur at the high edge of the basin, indicating basin wide extensive erosion, consistent with precipitation runoff origin. (b) Hypsometric curve and attributes of this basin. Characteristics of hypsometric curve clearly shows it is fluvial like. Symbols are the same as those of Figure 4.

1990; *Carr*, 1995] could also make the basin more sapping like, detailed morphometry analysis of *Williams and Phillips* [2001] showed minimal modification to the original valley shape by mass wasting and eolian infill.

[14] None of the alternative groundwater recharging mechanism seems to be consistent with the findings of this study. Hydrothermal convection [e.g., *Brakenridge et al.*, 1985; *Gulick and Baker*, 1989] or polar basal melting and transport to low latitude [*Clifford*, 1987, 1993] would not have generated basins with fluvial characteristics. Episodic temporary short-term warm conditions throughout Martian history [*Baker et al.*, 1991] would have produced more basins that look like terrestrial fluvial basins. This is because fluvial erosion is much more efficient than sapping erosion. Sapping is only limited to the sites with groundwater seepage and the groundwater discharge rate has to be large enough [e.g., *Howard*, 1988], whereas rainfall-runoff fluvial erosion could happen anywhere in the basin. The fact that the majority of the basins show sapping characteristics and the fact that sapping is a less efficient process suggest that sapping process must have operated longer than fluvial process and climatic condition needed for precipitation must have stopped early in the history. Thus, precipitation still appears to be the most viable groundwater recharging mechanism. Considering results of this study and those of other more traditional morphometric analyses [e.g., *Grant*, 2000; *Williams and Philips*, 2001], a precipitation-fed groundwater sapping origin and an early warm and wet climate best explain the valley network morphology of Margaritifer Sinus.

5. Conclusions

[15] Hypsometric analysis technique has been shown to be a promising technique in quantifying landform and help infer underling processes, if it is used in conjunction with other more traditional morphometric analyses. The spatial resolution of current available MOLA DEMs can be largely compensated for by applying this technique to large sized basins. Results indicate that both fluvial and sapping characteristics are present in the hypsometric attributes of drainage basins in the Margaritifer Sinus region. Such characteristics are consistent with Viking images. Even though more basins show sapping like characteristics, the role of fluvial erosion cannot be ignored. This suggests that the valley networks in this region are probably not the work of a single process. Both sapping and fluvial processes may have been involved and sapping process may have played a more dominant role in the valley network formation and modification. Combine this work and those of *Grant* [2000], *Hynek and Phillips* [2001], and *Williams and Phillips* [2001], the hypsometric and other geomorphic characteristics of the valley network systems in Margaritifer Sinus are most consistent with precipitation-recharged groundwater sapping origin, suggesting a warm and wet climate for early Mars.

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