How Ground Water Sapping Processes Carved Terrestrial and Martian Valleys

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December 13, 2017

Abstract:

Multiple studies on Earth and Mars support that groundwater sapping is the dominant erosion process that forms valleys. Many people argue that groundwater sapping processes cannot occur on Mars, since liquid water is unstable on Mars. Goldspiel and Squyres (2000) attacked this controversial question by using a numerical approach and using different climatic and hydrological conditions. They concluded that although liquid water is unstable on Mars today, groundwater sapping could have been the dominant erosional process if and when the conditions were right. Laity and Malin (1985) and Nash (1995) all conducted experiments and field observations on Earth to try to summarize how groundwater sapping processes occur and why. Grant (2001) conducted a study on Margaritifier Sinus, Mars and concluded that the valley he was focusing on was not formed by groundwater processes, but possibly by a runoff dominated process. This opens the question to what other processes could occur on Mars that also occur on Earth?

Introduction:

Based on geomorphological studies on Earth, we know that groundwater sapping is an important erosional process that occurs in valleys that are dominated by permeable, quartz-rich sandstones and in climates where precipitation rates are low over a long period of time. But is groundwater sapping possible on Mars? Nash (1995) conducted studies focused on the Hackness Hills in North Yorkshire, England. Laity and Malin (1985) concentrated on the geomorphological processes and discharge rates of the tributaries of the Lower Escalante River in Utah. Goldspiel and Squyres (2000) conducted equation-based studies on Mars to study how different climatic and hydrologic conditions effect groundwater sapping processes. Grant

(2001) also performed studies on Margaritifer Sinus, Mars focused on the geomorphology of the valleys. Groundwater sapping processes tend to occur in specific settings and leave evidence through characteristic erosion patterns.

Case Studies:

Many geomorphological studies of groundwater sapping have been conducted on Earth, specifically at the Hackness Hills Plateau in North Yorkshire, England *(fig 1)*, and the Glen Canyon region of the Colorado Plateau in the United States *(fig 2)*, while the main area of study is focused on Martian valleys on Mars *(fig 3)*, particularly on Margaritifer Sinus *(fig 4).*

Hackness Hills, England: The Hackness Hills Plateau in North Yorkshire, England is located on the eastern edge of the North York Moors National Park, about 10 km northwest of Scarborough. The Hackness Hills are very well known to British geologists as “one of the first large-scale geological mapping surveys in Britain by William Smith (the ‘Father of English Geology’) in 1829” (Nash, 1995). The Hackness Hills are approximately 220 meters above sea level and receive a mean annual rainfall of 893 mm; November and December being the wettest months, while July is the driest month. Summers are typically warm, while the winters are considered to be relatively mild. This area of study is lithologically composed of permeable Middle and Upper Jurassic rocks below the impermeable Upper Oxford Clay. These rocks are considered to be structural outliers to the rest of the British Isles because these lithologies are typically unfolded and dip gently, approximately 1 to 4 degrees to the South. The valleys found in this plateau are highly vegetated with trees, shrubs, and grasses; resulting from a wetter, temperate climate. Bedrock samples from above, within and below zones of seepage were collected in seven valleys of the Hackness Hills and analyzed by X-ray diffraction to determine the mineralogy differences among the different zones. Morphological surveys were also composed and logged in ten major tributary valleys.

Results: Using x-ray diffraction analysis in the Hackness Hills, Nash (1995) states that "samples HD-1 and HD-2 were taken from 1.0 meters and 0.5 meter, respectively, above the seepage lines, sample HD-3 was collected at the seepage line, whilst samples HD-4 and HD-5 were from 0.5 meters and 1.0 meter, respectively, below the line of seepage" (Nash, 1995). The x-ray diffraction analysis (*table 1)* shows that quartz is the most dominant mineral present in these lithologies, followed by feldspars, micas, and calcite. While the occurrence of clay minerals is very low, they increase with depth in the Lower Calcareous Grit. The upper section of the Lower Calcareous Grit is composed of coarser sand, cemented together by silica with some calcite, making this lithologic section more permeable to groundwater. The lower section of the Lower Calcareous Grit is composed of more fine-grained material with an increase in calcite and clay minerals, making this lithologic section, along with the Upper Oxford Clay Formation, less permeable. The lack of clay minerals in the analysis, and the difference in grain-sizes throughout the Lower Calcareous Grit suggest that the groundwater emergence zone occurs primarily in the upper section of the Lower Calcareous Grit Formation.

Based on morphological field observations and surveys, Nash (1995) concluded that the differential resistance of the Lower Calcareous Grit and the Upper Oxford Clay results in slope differences above and below spring sites. Rocks above the seepage zone typically have gradients of about 7.4% to 14.8%, appear to be very dry, which results in a lack of vegetation. Rocks below the seepage zone are typically very saturated resulting in more vegetation with gentler gradients of about 1.5% to 2.5%. Nash (1995) states "rock weakening occurs in the vicinity of the seepage zone, with increased jointing and fracturing along bedding planes" (Nash, 1995). Zones of seepage can be identified by more vegetation, increased fracturing or jointing and slope failures.

Colorado Plateau: The Glen Canyon region of the Colorado Plateau is located in southern Utah, in the middle of the Colorado Plateau. The Glen Canyon region is characterized by high elevations of up to 3,950 km above sea level and a semi-arid climate, resulting in limited vegetation throughout the plateau. This region typically has very hot summers and moderately cold winters. The mean annual precipitation for this region is less than 6 inches. Summer and fall months are considered to be the wettest time of year when flash flooding and 'monsoons' can occur. The Glen Canyon Jurassic lithologies in descending order consists of the permeable Navajo Sandstone, the impermeable Kayenta Formation of mudstones, siltstones, and sandstones, and the permeable Wingate Sandstone. Discharge measurements of stream base flow were measured in Bowns Canyon and Explorer Canyon, the two tributaries to Glen Canyon. Analyses of structural controls were also composed to collect data for this area of study and compare them to Martian valleys.

Results: Through observations of the morphology of the east and west tributaries to the Lower Escalante River, Laity and Malin (1985) concluded that the East and West tributaries display very different geomorphological characteristics due to groundwater sapping processes. While the western tributary displayed widths that increased downstream, meanders, and concave upward longitudinal profiles; the eastern tributary displayed constant valley widths, a less dendritic-like pattern and "steep, cuspate valley-headwall terminations associated with a stepped discontinuity in the longitudinal profile" (Laity and Malin 1985). After a series of discharge measurements conducted by Laity and Malin (1985) in the Glen Canyon region of the Colorado Plateau, they concluded that "groundwater discharge is greatest at the valley head and decreases distally from it" (Laity and Malin, 1985). Measurements and observations at Explorer Canyon concluded that discharge increases 180 liters per minute for every kilometer traveled downstream. The head spring of Explorer Canyon contributes 35% of stream flow, while lateral seepage contributes to 55%, and two sidewall springs provides 10% of the stream flow. Measurements taken at Bowns Canyon determine that Bowns Canyon has the same discharge value as Explorer Canyon at 150-190 liters per minute. Stream flow from the double theater head is responsible for 20% of the total discharge calculated in this canyon, "seepage from twelve sideway springs accounts for 30%. The main tributary accounts for 7%, flowing at about 50 liters per minute. The remainder of flow (43%) is derived from lateral inflow to the channel" (Laity and Malin, 1985).

Based on close examination of aerial photographs of valleys in the Glen Canyon Region, Laity and Malin (1985) determined that joint sets in the Navajo Sandstones coincide with canyon and plateau runoff channels. After many studies focusing on the structural control of canyon development and growth, they also concluded that surface-runoff processes are the main source of drainage development in lithologically homogenous materials with moderate permeability and no structures, while groundwater sapping tends to dominate in moderately fine-grained, permeable materials with fractures and joints; such as the Navajo Sandstone. Environmental factors can also influence the domination of either runoff or sapping drainage patterns. Laity and Malin state that "high rates [of rain] over short durations favor runoff, whereas low rates over longer periods favor sapping".

Mars: Present-day Mars is considered to be a "cold desert, devoid of liquid water where atmospheric pressures average a mere 0.6% that of on Earth, and where temperatures average $220°C$" (Gulick, 2001). Mars is divided into the southern highlands and the northern lowland plains. The southern highlands consist of megaregoliths covered by extensive lava flows, aeolian, or fluvial deposited material. The northern lowland plains topographically are 3 km lower than the southern highlands, and are composed of younger, less cratered lava flows and sediments. Specifically, "Margaritifer Sinus is located near the eastern end of Valles Marineris and straddles the Chryse Trough (*fig 5)*" (Grant, 2001). In Goldspiel and Squyres (2000) study, multiple experiments used a combination of a one-dimensional heat conduction-advection model and a two-dimensional model of an evolving aquifer to record how groundwater sapping effectiveness varies due to different hydrologic and climatic conditions. Gulick's (2001) study focuses on the formation of the Martian valley networks from a hydrological perspective using morphology, volumes, and spatial relationships of multiple valleys found on Mars. In Grant's (2001) study, Margaritifer Sinus's geomorphology is being evaluated using stereographic and geologic mapping.

Results: After multiple studies using a combination of a one-dimensional heat conduction-advection model and a two-dimensional model of an evolving unconfined aquifer, using a numerical approach, Goldspiel and Squyres (2000) concluded that "simulations under a variety of environmental and hydrogeologic conditions show that wind friction velocity, aquifer temperature, and hydraulic conductivity are important parameters with respect to sustainable erosion by sapping" (Goldspiel and Squyres, 2000). Using Mars' current climatic conditions, a friction velocity of $1.0\ m\ s^{-1}$, an aquifer temperature of 275 K, a hydraulic conductivity of $2\ x\ 10^{-5}\ m\ s^{-1}$, and an equatorial latitude, Goldspiel and Squyres (2001) constructed a table (*table 2)* summarizing nominal values and alternate values. Goldspiel and Squyres's (2001) calculations and observations conclude that groundwater sapping could be sustainable on Mars today, if the regolith is highly permeable and if water temperatures were high enough due to volcanic activity.

Using geologic maps at 1: 2,000,000 and 1: 500,000 scales, Grant (2001) studied the trends of valley distributions and valley morphology found on Margaritifer Sinus, Mars. Grant (2001) ultimately discovered characteristics in these valleys based on runoff and ground-water sapping. Grant (2001) discovered that the valleys found on Mars, such as the Samara and Parana-Loire basins, have relatively uniform widths and have low drainage densities compared to terrestrial drainage densities that are 14 times higher than the Samara and Parana-Loire basins, using 80 m/pixel Landsat data. Calculations using Earth-based radar topography data also show that these valleys on Mars have relatively low ruggedness numbers compared to terrestrial valleys at values of 0.001-0.13 and 0.005-0.086; "implying limited runoff from substrates capable of storing considerable water" (Grant, 2001).

Discussion:

Nash (1995), Laity and Malin (1985) did multiple studies focused on the geomorphological processes that form theater-headed valleys on Earth. After studies using x-ray diffraction analysis in the Hackness Hills in North Yorkshire, England; Nash (1995) concluded that quartz is the most dominant mineral found in ground-water erosion dominated valleys, while clay minerals were virtually non-existent. This supports the evidence to why groundwater sapping would occur in these channels because quartz-rich sandstones are more permeable, while clay minerals are much less permeable to groundwater. After morphological field observations and surveys, Nash (1995) also concluded that the seepage zone is steeper than rocks below the seepage zone. These observations make it much easier to identify that groundwater sapping is the dominant erosion process occurring in a certain channel.

Laity and Malin (1985) conducted field projects in the Glen Canyon region of the Colorado Plateau and observed that groundwater sapping leaves very distinct characteristics such as a steep, cuspate valley head wall. Laity and Malin (1985) also performed discharge measurements in groundwater sapped valleys in the Glen Canyon and concluded that groundwater discharge is highest at the valley head, and decreases as you move away from the source; resulting in a decrease of slope and/or valley width.

Laity and Malin (1985) also studied the relationship between structural processes and groundwater sapped valleys, and concluded that groundwater sapping tends to occur prominently in highly permeable sandstones, such as the Navajo Sandstone, and where jointing or fracturing has already occurred. Groundwater sapping processes are typically more favorable in areas where precipitation rates are low over a long period of time, such as the semi-arid climate of Utah and the Navajo Sandstones.

Goldspiel and Squyres (2000) conducted multiple studies focused on the geomorphology of valleys on Mars using a combination of a one-dimensional heat conduction-advection model and a two-dimensional model of an evolving unconfined aquifer and concluded that there are many factors that favor groundwater sapping processes such as friction velocity, aquifer temperature, and hydraulic conductivity. Ultimately, if the conditions were right, groundwater sapping could be sustainable and could have caused the valleys we see on Mars today.

Using mapping techniques to observe valleys on Margaritifier Sinus Mars, Grant (2001) concluded that the valleys on Mars have uniform widths, low drainage densities, and a low ruggedness number compared to studies conducted on Earth, summarizing that groundwater sapping may not have occurred here; instead runoff dominated processes due to impermeable lithologies could have occurred to form these valleys based on the characteristics of the valleys found on Mars.

Conclusions:

Based on these studies on Earth from Nash (1995), Laity and Malin (1985); and studies from Grant (2001) and Goldspiel and Squyres (2001); we can assume that valleys on Mars formed by groundwater sapping. Nash (1995), Laity and Malin (1985) observed and identified ways on how to identify a groundwater sapped valley, and why that process occurred based on mineralogy, geomorphological observations, and mapping. Grant (2001), Goldspiel and Squyres (2000) focused in on the studies of Martian valleys on Mars using geologic mapping techniques and equation-based models. They supported the hypothesis that terrestrial groundwater sapping processes can occur on Mars today, if the factors and conditions were just right. Grant's (2001) study offers an opportunity to question if other geomorphological processes, such as run-off dominated systems, could occur on Mars. After these findings, we can conclude that groundwater sapping is a dominant erosion process of terrestrial and Martian valleys.

References:

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Laity, Julie E., Malin, Michael C. 1985. Sapping processes and the development of theater-headed valley networks on the Colorado Plateau, *GSA Bulletin,* v. 96, p. 203-217.

Nash, David J. 1995. Groundwater Sapping and Valley Development in the Hackness Hills, North Yorkshire, England, *Earth Surface Processes and Landforms,* v. 21, p. 781-795.

Appendix:

Figure 1. North York Moors National Park, North Yorkshire, England. The Hackness Hills are 10 km Northwest of Scarborough.

Figure 2. Glen Canyon region of the Colorado Plateau in southern Utah in the middle of the Colorado Plateau, circled in red.

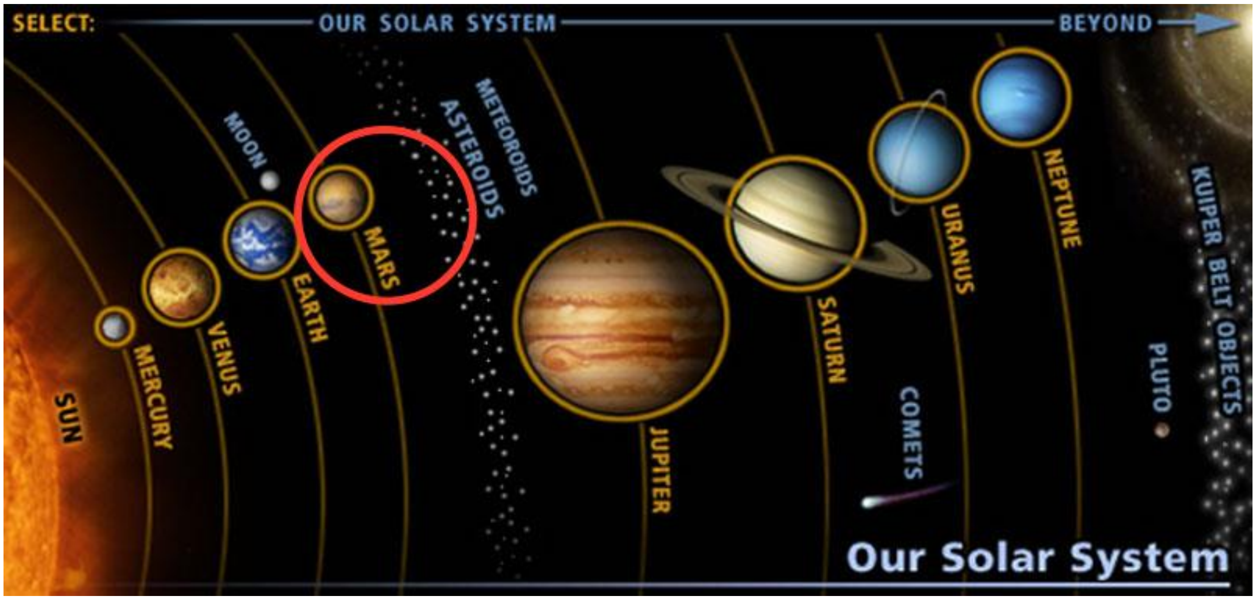

Figure 3. Picture of the solar system, Mars circled in red.

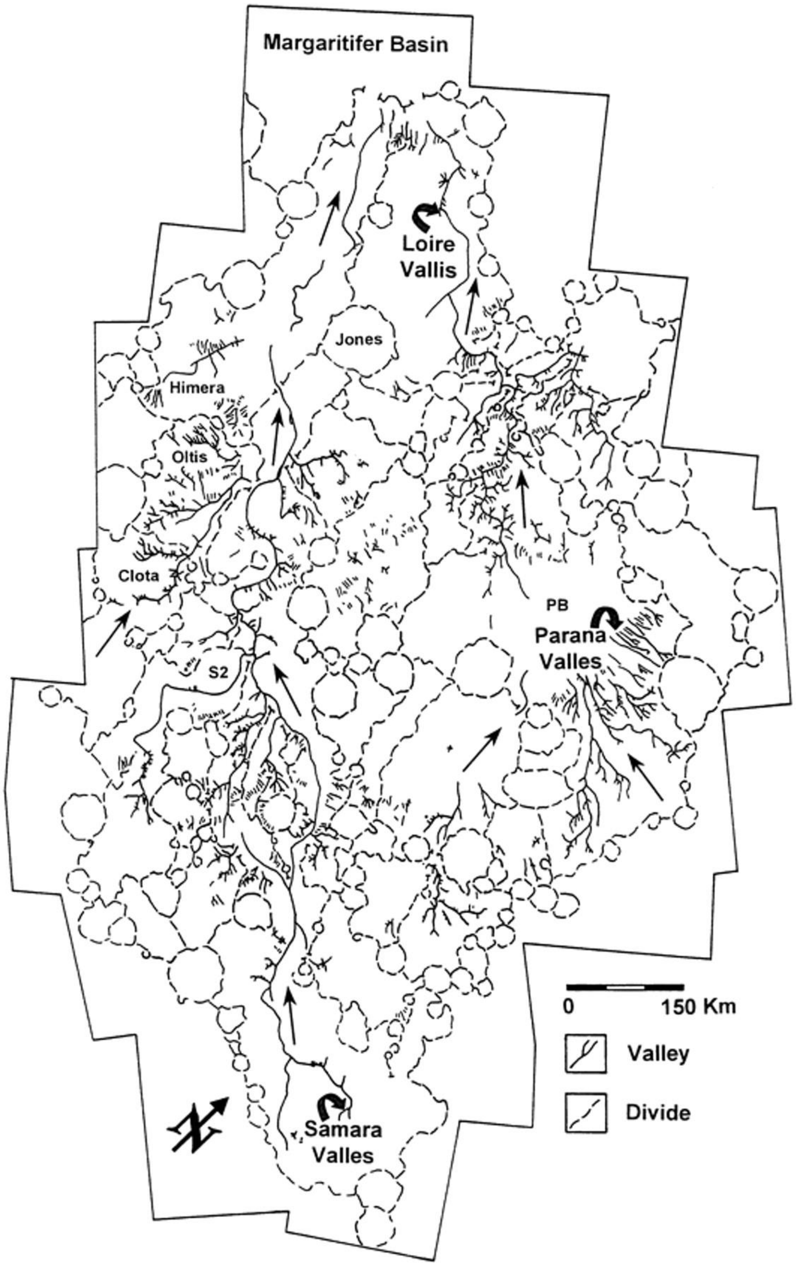

Figure 4. Map of the valley features on Margaritifer Sinus, Mars.

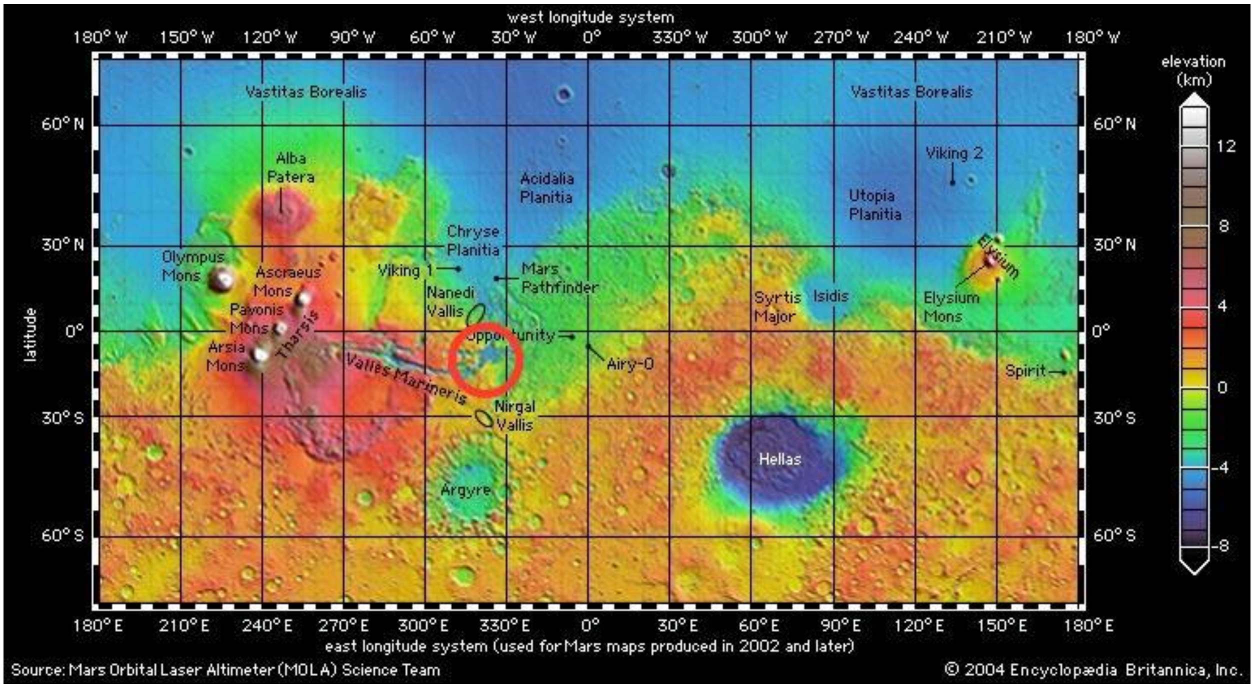

Figure 5. Margaritifer Sinus, circled in red, located near the eastern end of Valleys Marineris and straddling the Chryse Trough.

Table I. XRD analyses of siltstone samples from Hard Dale

Sample	HD-1	HD-2	HD-3	HD-4	HD-5
Sample position relative to seepage line	1·0 m above	0·5 m above	At seepage line	0·5 m below	0·5 m below
Minerals					
Quartz	*	*	*	*	*
Anorthoclase	*	*	*	*	*
Albite	*	*	*	*	*
Muscovite	*	*	*	*	*
Clinochlore	*	*	*	*	*
Illite	†	†	†	†	†
Vermiculite					
Chlorite					
Smectite					
Kaolinite					
Sepiolite					
Talc					
Glauconite					
Palygorskite					
Gibbsite					
Sericite					
Montmorillonite					
Calcite		*	*	*	*
Relative % calcite	0%	100%	61%	22%	9%

* Mineral present in sample
† See text

Table 1. X-ray diffraction analysis results (Nash, 1995). Results show that quartz and feldspars are the most abundant minerals found in the lithologies of the Hackness Hills, England; while calcite minerals are at the lowest abundance.

TABLE II
Sapping Model Variable Parameters

Symbol	Parameter	Nominal Value	Alternate Value
P_{atm}	Atmospheric pressure	0.006	1.5 bar
$\bar{\tau}_a$	Annual mean atmospheric temperature	210.0	214.0 K
T_o	Aquifer temperature	275.0	350.0 K
K_{hy_o}	Hydraulic conductivity ice-free regolith	2×10^{-5}	2×10^{-3} m s^{-1}
D_{sed}	Mean sediment size	1.0	0.1 mm
u_*	Friction velocity	1.0	0.1 m s^{-1}
	Obliquity	25.19	45.0°
	Latitude	0.0	45.0°S

Table 2. Goldspiel and Squyre (2000) conducted a table summarizing nominal values and alternate values calculated using Mars's current climatic conditions, a friction velocity of 1.0 $m\ s^{-1}$, an aquifer temperature of 275 K, a hydraulic conductivity of $2\ x\ 10^{-5}\ m\ s^{-1}$, and an equatorial latitude.