Evidence for Precipitation on Mars from Dendritic Valleys in the Valles Marineris Area

Nicolas Mangold,1* Cathy Quantin,2 Véronique Ansan,1 Christophe Delacourt,2 Pascal Allemand2

Dendritic valleys on the plateau and canyons of the Valles Marineris region were identified from Thermal Emission Imaging System (THEMIS) images taken by Mars Odyssey. The geomorphic characteristics of these valleys, especially their high degree of branching, favor formation by atmospheric precipitation. The presence of inner channels and the maturity of the branched networks indicate sustained fluid flows over geologically long periods of time. These fluvial landforms occur within the Late Hesperian units (about 2.9 to 3.4 billion years old), when Mars was thought to have been cold. Our results suggest a period of warmer conditions conducive to hydrological activity.

The formation of valley networks on Mars has been the subject of considerable scientific debate (1–4). Valleys were attributed to fluvial erosion implying a warm and wet climate on early Mars (5), possibly conducive to biological activity (6). Several recent observations argue in favor of such conditions on early Mars (7, 8), but valley networks could also have formed by water-lubricated debris flows (4), hydrothermal activity (9, 10), or groundwater sapping (11–13) due to geothermal activity (14), and these hypotheses do not require conditions warmer than the current cold climate.

Here, we describe terrestrial-like dendritic valleys identified using THEMIS images (15) of the Mars Odyssey mission. These valleys are located in the Valles Marineris region (Fig. 1) on the plateau west of Echus Chasma (Fig. 2) and on the inner plateau west of Melas Chasma (Fig. 3). These landforms occur within Late Hesperian units (16), about 2.9 to 3.4 billion years old (17); they are thus unexpectedly younger than the Noachian (16) period, which is considered to be the potential primitive warm period (4).

The plateau west of Echus Chasma (0°N, 81°W) is covered by densely branched valleys that are frequently sinuous and extend over tens of kilometers (Fig. 2). Infrared (IR) images taken at night by THEMIS (Fig. 2A) show mainly intrinsic thermal properties of the ground (15). Valleys buried under loose material are outlined by variations of the thermal signal and resemble terrestrial deserts where sand covers the floor of dry valleys (Fig. S1). On drainage basin G, the main valley is larger upstream than downstream close to the mouth, implying a thicker mantling at this location. With the exception of this place, most valleys have widths increasing from their sources to their mouth, as seen in terrestrial valleys. An IR image taken during the day by THEMIS shows that these dendritic valleys have their heads scattered at random points on the plateau (Fig. 2C).

References
8 March 2004; accepted 25 May 2004

1Laboratoire IDES, UMR CNRS and Université Paris-Sud, Orsay Campus, 91405 Orsay, France. 2Laboratoire des Sciences de la Terre, UMR CNRS UCB Lyon 1 and ENS Lyon, La Doua Campus, 69622 Villeurbanne, France.

*To whom correspondence should be addressed. E-mail: mangold@geol.u-psud.fr

2 JULY 2004 VOL 305 SCIENCE www.sciencemag.org 78
are also gullied by small valleys with heads at the crestline of the hill (Fig. 2D). These characteristics are similar to terrestrial features of surface runoff due to atmospheric precipitation.

These characteristics are inconsistent with subsurface seepage induced by hydrothermal activity because water would not seep at the crest of hills. Moreover, no valleys with theater-shaped heads are observed, as would be the case if sapping had occurred (11, 12). Sapping has been invoked to explain the development of tributary canyons in the Valles Marineris region (18), such as the narrow tributaries of Echus Chasma, 1 to 3 km deep, that dissect the plateau borders. The main valleys of basins E, G, and I connect to the heads of tributaries, implying that these valleys were active during the formation of tributaries, as observed on Earth (fig. S1B). This contemporaneous activity suggests that the backward recession of tributary canyons by sapping was connected to the hydrological processes existing over the plateau.

Two drainage basins with dendritic valleys are also observed on THEMIS images (Fig. 3) of the inner plateau of west Melas Chasma (77.5°W, 10°S). Several valley heads located at the foot of the southern wall slopes would suggest subsurface seepage. However, most valley heads are located on the opposite perched interior plateau and along the divide separating both drainage basins, thus suggesting another source of water than seepage from canyon walls (19). THEMIS visible-light images also show the presence of meandering valleys (Fig. 3C) and inner channels (Fig. 3D) on the floor of some of these valleys, indicating surface conditions with stable liquid water and sustained fluvial activity (20, 21).

The drainage densities (i.e., the total length of valleys divided by the area of each basin) vary from 0.6 to 1.0 km−1 for the nine basins of Echus Plateau measured using IR images at 100 m/pixel (table S1). The drainage densities in Melas Chasma are 1.1 km−1 and 1.5 km−1, as measured using visible-light images at 18 m/pixel. By comparison, drainage densities of terrestrial valley networks are usually from 2 to 100 km−1. However, such high densities are obtained with maximum-resolution mapping, whereas the same terrestrial networks mapped at the scale of Viking image mosaics (22) have densities of only 0.1 to 0.2 km−1. Thus, densities measured at THEMIS resolution, a scale slightly better than Viking mosaics, are equivalent to terrestrial fluvial valleys mapped at the same scale. Additionally, morphometric parameters such as valley order, bifurcation ratio, and valley length ratio (23, 24) give values similar to terrestrial river networks for the drainages of both regions (table S1 and fig. S2).

Precise depths of valleys are not measurable at the resolution of the Mars Observer Laser Altimeter (MOLA), but they can be estimated roughly from THEMIS images to a few tens of meters for widths of several hundreds of meters. These valleys, like rivers, are always oriented in the direction of the local slope (fig. S3). Moreover, the variations in the geometry of valleys are consistent with the variations of the slope, with dendritic valleys on nearly flat areas and subparallel valleys on slopes >1.3° (fig. S3). This relationship is observed in experimental streams and terrestrial rivers formed by surface runoff due to precipitation by rainfall or snowmelt subsequent to snow deposition (25).

Snowmelt under a cold climate was proposed to explain some valley networks (26, 27). However, alluvial valleys with inner channels (Fig. 3D) require stable liquid water, favoring subaerial flows under a warmer climate. Moreover, snow accumulation would create glaciers (27), but subglacial valleys are discontinuous with large undissected areas and abrupt inception and termination of valleys [e.g., (28)], unlike such dendritic valleys. The maturity of the valley networks is also inconsistent with short episodes of glacial outburst with large and braided channels. For example, terrestrial networks become mature (i.e., with fully branching patterns) only after several tens of
thousands of years of activity (24). The formation of dendritic valleys thus likely involves a relatively warm climate with liquid water stable at the surface.

If atmospheric processes are invoked, similar valleys should be observed elsewhere than in the Echus and Melas areas. Nonetheless, dust deposition could completely fill in valleys that are only a few tens of meters deep. Other valleys may be hidden beneath this mantle. No valleys exist west of the Echus plateau valleys except for some relics present in inverted topography (29) (Fig. 2D), demonstrating the role of wind erosion in the removal of the uppermost deposits. Differences in the strength of eroded rocks may play a role in the development or preservation of fluvial landforms. Meso-scale variations of the climate could also affect their distribution.

Echus Chasma plateau valleys formed over a Late Hesperian volcanic unit (30), and they are buried at the north by Early Amazonian lava flows, thus restricting their formation to that interval of time. The connections of the main valleys and the heads of tributary canyons (Fig. 2C) also imply an age contemporaneous with or slightly younger than the Echus canyon, which formed during the Late Hesperian. Melas Chasma valleys are younger than the development of Valles Marineris, as they developed on inner plateaus dated to the Late Hesperian epoch (18). Thus, they may have formed at the same period as Echus Chasma plateau valleys. The transition from a possible warm early Mars to a colder climate is usually dated to the Late Noachian–Early Hesperian boundary (4), about 3.6 billion years ago (17). The apparent age of the valleys suggests that significant fluvial activity occurred until the Late Hesperian.

Surface runoff in the Late Hesperian epoch could correspond either to a progressive transitional climate after the warmer Noachian epoch (7) or to episodic warmer periods, such as those that could be related to the increase in atmospheric water vapor due to the outburst of outflow channels (31). Stable liquid water at the surface in the Hesperian epoch was previously suggested to explain potential lake deposits inside Candor Chasma (18) or in highland craters [e.g., (32)], and other Hesperian valley networks were noticed on highlands (7, 10) and volcanoes (7, 9). Such conditions could also solve the paradox of the ocean in the northern lowlands (33), which is dated to the Late Hesperian. Finally, longer term hydrological activity until the Late Hesperian would lead to interesting exobiological consequences, because life—if it ever existed on Mars—would have benefited from a longer period of warmer conditions.

References and Notes
The Normal Function of a Speciation Gene, Odysseus, and Its Hybrid Sterility Effect

Shi Sun,1* Chau-Ti Ting,2 Chung-I Wu1†

To understand how postmating isolation is connected to the normal process of species divergence and why hybrid male sterility is often the first sign of speciation, we analyzed the Odysseus (OdsH) gene of hybrid male sterility in Drosophila. We carried out expression analysis, transgenic study, and gene knockout. The combined evidence suggests that the sterility phenotype represents a novel manifestation of the gene function rather than the reduction or loss of the normal one. The gene knockout experiment identified the normal function of OdsH as a modest enhancement of sperm production in young males. The implication of a weak effect of OdsH on the normal phenotype but a strong influence on hybrid male sterility is discussed in light of Haldane's rule of reproductive isolation and (ii) what is the connection between the normal function in the pure species and the incompatibility effect in the hybrids?

We address these questions by studying the hybrid male sterility gene, OdsH (Odysseus), in Drosophila. OdsH is a fast-evolving homeobox gene that causes male sterility in the D. simulans background when co-introgressed with closely linked factors from D. mauritiana (2, 3). Divergence in OdsH among closely related species has been observed for both DNA sequences and expression patterns. OdsH has been evolving away from the ancestral embryonic function toward a predominantly spematogenic expression (4). We used three approaches, gene expression assay, gene transformation, and gene knockout, to link the hybrid sterility effect of OdsH to its normal function in reproduction. The expression analysis was carried out with RNA in situ hybridization in the testes of fertile and sterile hybrids (Fig. 1). The fertile and sterile lines we used differ by only 3 kb, which spans the exons 3 and 4 of OdsH (fig. S1) (2), but are otherwise genetically identical. Figure 1A shows the expression of OdsH in the sterile introgression line. The striking observation is the strong accumulation of the OdsH transcript near the apical tip of the testis. This distinct pattern is not observed in the fertile line (Fig. 1B), nor in any of the pure species assayed, including D. simulans and D. mauritiana (4). The apical region of the testis contains primarily premeiotic cells that have not yet entered the rapid growth phase when transcription becomes highly active (5). Apparently, the testicular expression of OdsH is misregulated in the sterile introgression line. We reproduced this expression pattern for a comparison with the expression of unc-4, the duplicate homolog of OdsH (fig. S2). The expression of unc-4 shows no transcript accumulation at the apical end and is comparable between the sterile (fig. S2C) and the fertile (fig. S2D) lines.

In addition to the misexpression of OdsH, we tested the sterility effect from OdsH coding sequence using transgenic analysis. OdsH full-length cDNA was driven by the testis-specific β2-tubulin promoter (6, 7). We used OdsH alleles from D. simulans (OdsHsim) and D. mauritiana (OdsHmau). The P-element constructs, P[w+], β2-tubulin::OdsHsim and P[w+], β2-tubulin::OdsHmau, were each injected into D. simulans, and the expression of each transgene was confirmed by reverse transcription polymerase chain reaction. We observed no sterility effect with the transgenes (heterozygous or homozygous) in the pure D. simulans background. This observa-

1Department of Ecology and Evolution, University of Chicago, Chicago, IL 60637, USA. 2Department of Life Science, National Tsing Hua University, Hsinchu, Taiwan 300, ROC. 3Present address: Department of Molecular and Cell Biology, University of California, Berkeley, 16 Barker Hall, MC 3204, Berkeley, CA 94720, USA. 4To whom correspondence should be addressed. E-mail: ciwu@uchicago.edu

12. Sapping is a consequence of the infiltration of water from rainfall or snowmelt that induces groundwater flow and seepage, forming valleys with theater-shaped heads.
15. P. R. Christensen et al., Science 302, 2061 (2003); published online 5 June 2003 (10.1126/science.1080885).
16. The geology of Mars is divided into three main periods, Noachian, Hesperian, and Amazonian. The Noachian period (~3.6 billion years ago) (17) is a period of heavy bombardment and potential warmer climate. The Hesperian age (3.6 to 2.9 billion years ago) is usually considered to be cold with a thick permafrost (4).
21. A portion of channel was observed in Nanedi valleys, northeast of the Valles Marineris region, and was interpreted as evidence for sustained liquid flow.
29. Inversion of relief occurs by denudation in cases where a material at the floor of a channel is more resistant to erosion than is the surrounding material. Similar inverted channels may exist on West Juven-tae Chasma plateau [reference 13 in (8)].
Supporting Online Materials

<table>
<thead>
<tr>
<th>Basin name</th>
<th>Density (km⁻¹)</th>
<th>Bifurcation ratio</th>
<th>Stream length ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echus A</td>
<td>0.6</td>
<td>3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Echus B</td>
<td>0.9</td>
<td>4.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Echus C</td>
<td>0.8</td>
<td>3.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Echus D</td>
<td>0.7</td>
<td>3.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Echus E</td>
<td>1.0</td>
<td>3.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Echus F</td>
<td>0.8</td>
<td>4.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Echus G</td>
<td>0.9</td>
<td>4.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Echus H</td>
<td>0.9</td>
<td>2.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Echus I</td>
<td>1.0</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Average Echus</strong></td>
<td><strong>0.8</strong></td>
<td><strong>3.6</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basin name</th>
<th>Density (km⁻¹)</th>
<th>Bifurcation ratio</th>
<th>Stream length ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melas East</td>
<td>1.5</td>
<td>4.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Melas West</td>
<td>1.1</td>
<td>4.9</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Average Melas</strong></td>
<td><strong>1.3</strong></td>
<td><strong>4.5</strong></td>
<td><strong>1.8</strong></td>
</tr>
</tbody>
</table>

STable 1: Morphometric characteristics of the valley networks of West Echus Chasma plateau and Melas Chasma interior deposits. The drainage density is the ratio between total length of valleys and the area of each basin. The larger values of Melas network can be due to the resolution because drainage densities vary according to the scale at which they are measured (S1). On Mars, valley networks in the highlands mapped with Viking mosaics (S1) have densities of about 0.01 km⁻¹ whereas the valleys located on the flanks of the volcano Alba Patera (S2), mapped with high resolution Viking images, have the largest density of Mars with 2.3 km⁻¹. Valleys can also be ordered by taking the smallest fingertip tributary as first-order valley of order n=1 and successive n+1, valleys are found at each intersection of two streams of order n. The bifurcation ratio corresponds to the ratio of the number of valleys of order n and n+1 and the stream length ratio as the ratio between average length of valleys of successive orders (S3,S4). On Earth, these two parameters are typically of 3 to 5 for the bifurcation ratio, and 1.5 to 3.5 for the valley length ratio in layers for which surface runoff dominates over infiltration in the underground. For the nine networks of West Echus Chasma plateau the bifurcation ratio range from 2.7 to 4.4, and valley lengths ratio range from 2.7 to 3.5. In Melas Chasma, the bifurcation ratios range from 4.2 to 4.9 and the stream length ratio from 1.7 to 1.9 for the two basins. All these values fit with values of terrestrial river systems. It is not clear whether these relationships have any value for determining what processes are responsible for network formation (S1), but their similarity with terrestrial networks suggests similar fluvial processes.
Fig. 1: (a) Aerial photograph of dendritic valleys of a dry drainage basin in Mauritania, Sahara. Sand fills valley floors outlining the dendritic geometry like on figure 2a except that sand is bright in visible image. Width: about 10 km. (b) Canyons of the Green River on the Colorado Plateau in Canyonland, Utah. Small valleys on the plateau connect to theatre shaped heads of canyons formed by sapping like on West Echus Chasma plateau on figure 2c (photos N. Mangold).
SFig. 2: Graphs of bifurcation ratio (a) and stream length ratio (b) for all drainage basins considered. Data A to I correspond to drainage basins of West Echus Chasma plateau. See caption of STable1 for further explanations.
SFig. 3: (a) MOLA DEM (50 m elevation curves) of valley networks of West Echus Chasma plateau Valley are always in the direction of the slope (b) Slopes derived from MOLA data for the same valleys. North is to the bottom for (a) and (b) as on figure 2. The geometry of streams formed by precipitation is constrained by the average value of the slope. Indeed, experimental runs and terrestrial examples show that valleys are dendritic with orthogonal junctions at slopes lower than 1.3° whereas valleys are subparallel with small junction angles at slopes steeper than 1.3° (S5). Networks A and B (Fig. 2) of West Echus consist of subparallel valleys connecting with angles of less than 60° which occur on an average slope of 1.5°, thus above the critical value. Valleys networks C to I display mainly orthogonal junctions and they occur on average slopes of 0.8° to 1.1°. (c) MOLA DEM (50 m elevation curves) of valley networks of inner plateau Melas Chasma (d) Slopes derived from MOLA DEM for the Melas Chasma inner plateau valleys. The same relationship between slopes and geometry exists in Melas area, where dendritic valleys become subparallel on slopes greater than about 1.3°. The consistency between geometry of valleys and basin slopes favors a formation by precipitation.

S3 e.g Horton, R. E., Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology, Geol. Soc. Am Bull., 82, 1355-1376, 1945.
S4 e.g. Leopold, L. B., M. G. Wolman and J. P. Miller, Fluvial processes in geomorphology, Dover pub, 1992, 520 pp.