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Hydrogeologic Evolution of Gale Crater and Its Relevance to the Exobiological Exploration of Mars

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The presence of an Amazonian impact crater lake in the Noachian crater Gale (located in the Aeolis northwest subquadrangle of Mars) is indicated by evidence from young floor deposits, streamlined terraces, layers, and channels observed on the central sedimentary deposit. Evidence for the filling of this lake by two processes is described: (a) the drainage of the aquifer in the Aeolis Mensae region, supported by extended mass-wasting and rim sliding in the crater at the contact with the mensae and (b) the overspilling of the northern rim by an Amazonian south transgression of the Elysium Basin. This last hypothesis is supported by hydrologic features such as channels and channel-like depressions north of the crater and by the crescent-like shape of the central sedimentary deposit. The presence of an impact melt sheet and uplifted central peak may have also generated hydrothermal activity, including an early crater lake, shortly after the formation of the crater in the Noachian period. With time, decreasing heat flux, and changing climates Gale may have experienced transitions in aqueous environments from warm and wet to cold and ice-covered water that could have provided suitable oases for various communities of microorganisms. Preservation of the biological and climatic record may have been favored in this paleolacustrine environment, which probably occured episodically over two billion years. © 1999 Academic Press

Key Words: **Mars; Mars surface; exobiology; impact processes.**

INTRODUCTION

This study of Gale crater shows that a late lacustrine episode occured in the 170-km diameter crater during the Amazonian. We propose a bathymetric model based on topographic data deduced from paleolacustrine morphologies. Results suggest that the lake formation is related to (a) the sapping of the surrounding aquifer in the Aeolis Mensae region, (b) the rose of the water level of the Elysium Basin, and (c) the potential geothermal energy from the central peak region. A lake within Gale crater during the Amazonian provides another piece of evidence that water was present in significant quantity at the surface of Mars in a relatively recent past.

Amazonian fluvial features are observed all across the planet. They are not as numerous as during the Noachian/Hesperian boundary period, but their size is often much larger. In addition, most of them have a common characteristic: their source of water can be related to ground-ice/heat flux interaction. For instance, we will refer to a nonexhaustive list of typical examples: the sources of Ma'adim Vallis are related to volcanic and faults regions (Landheim 1995, Cabrol *et al.* 1996, 1997, 1998a, 1998b, Kuzmin *et al.* 1998, Landheim *et al.* 1998), and so are the sources of Mangala Valles. There is a plausible relationship, because of the contemporary chronology and a large common boundary, between the formation of the Elysium Basin and the Elysium Mons activity. The sources of Granicus Valles are located on the flanks of Elysium Mons, and the young bed deposits of Dao Vallis in the southern hemisphere of Mars are located on the flanks of the Hadriaca Patera. As a final example, there is a strong chronological correlation between the last outflow generation and the last activity on Olympus Mons. These are only a few examples of the numerous large-scale fluvial features of the

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Amazonian. They strongly suggest a thermally and hydrologically very dynamic Mars during this period, where stored water could still circulate at depth and at the surface, though probably protected by ice covers at the surface because of the climatic conditions.

The evidence of massive water bodies, such as the 850,000 km^3 Elysium Basin (Scott and Chapman 1995) 500 million years ago or less, and the existence of smaller Amazonian basins like the Gusev crater contradict the Mars drying out picture in the recent geological past, and experiencing only isolated water outbursts in the Chryse Planitia region. During the Amazonian, Mars was able to generate a water body equivalent to the Mediterranean Sea (2,000,000 km^2). Moreover, part of the water contained in the aquifer was still able to circulate to generate lakes in deep craters like Gale and Gusev. In addition, the depth of young fluvial valley system headwaters are often located a few hundred meters below the surface, even in the intertropical band of Mars, suggesting that the water table was not necessarily far from the surface everywhere in recent geologic times. If we list these recent water bodies, we see a distribution over a large area. For instance: (1) the lake in Gusev was generated by the Amazonian activity of Ma'adim Vallis (Cabrol *et al.* 1996, Grin and Cabrol 1997, Cabrol *et al.* 1998a, 1998b, Kuzmin *et al.* 1998, Landheim *et al.* 1998), (2) Gale, as we propose in the next sections, was generated by aquifer drainage, water infiltration, geothermal activity, and surface drainage in recent geologic times, (3) possible sources for the Amazonian Elysium Basin range from northern source areas (Tanaka and Scott 1986), volcano–ground-ice interaction (Mouginis-Mark 1985, Squyres *et al.* 1987), and large channels originating from the cratered uplands (Scott and Chapman 1989, Cabrol *et al.* 1986, Grin and Cabrol 1997, Cabrol *et al.* 1998a, 1998b).

The 170-km diameter Gale crater is located $5°S/222.5°W$, in the northwest part of the Aeolis subquadrangle of Mars, at the boundary of the cratered uplands and the lowlands. The crater is characterized by the presence of a massive streamlined terraced and channeled sedimentary structure in its center that may suggest (a) the reshaping of the ancient sedimentary deposit by ice-push from an ice-covered lake, the variation of the level of the frozen water body being illustrated by the layering of the central sedimentary structure, and/or (b) a possible accumulation of lacustrine deposits. Gale crater is bordered by the Elysium Basin to the north and by the Aeolis Mensae to the east (Fig. 1). The interpretation of the crater sedimentary material was previously proposed in a broader context of regional and global geological mapping. For instance, the crater floor material has been interpreted as lava flows and aeolian deposits by Scott *et al.* (1978), Greeley and Guest (1987) proposed the presence of volcanic, aeolian, or fluvial sediment, and Scott and Chapman (1995) suggested aeolian, lava, pyroclastic, fluvial, and mass-wasted deposits. The present study shows that Gale crater experienced a late lacustrine formation during the Amazonian. We propose a bathymetric model based on topographic data deduced from paleolacustrine morphologies. Results suggest that the lake formation is related to (a) the sapping of the surrounding aquifer in the Aeolis Mensae region and (b) the rise of the water level of the Elysium Basin.

1. CRATER MORPHOLOGY AND SEDIMENT DISTRIBUTION

Gale experienced multiple erosional processes. The north rim is partly destroyed (Fig. 2.1). Extended mass-wasting occurs in the north and east inner ramparts at the contact with the Aeolis Mensae fractured formation (Fig. 2.2). Mass-wasted units are characterized by portions of rims embayed in smooth deposits that slide toward the bottom of the crater. Locally, some of the rim debris observed on the crater floor indicate a downward movement of lubricated material over tens of kilometers (Fig. 2.2). The rim is partly destroyed in the north, and remnant pits and blocks are embayed in smooth material.

1.1. Evidence of Water Action

Derived from the topographic data (M 2M I-2121, 1991), the central sedimentary structure in Gale crater is 2500 m high from the crater bottom located at -4500 m according to the MGS MOLA topographic profile No. 03 published by Smith *et al.* (1998) to the central summit at -2000 m elevation (Figs. 3 and 4). We estimate that the central structure corresponds to about 2.5×10^3 km^3 volume of material. This structure is crescent-like in its northern portion. It is strongly asymmetrical, dividing the deposit into two almost equal halves: (a) the northern sector is the most prominent and diverse in erosional features, (b) the southern sector is almost featureless and covered by an extended smooth deposit observed on the crater floor. At the margin of the two sectors, a prominent peak rises above the deposit. Because of its central position, it is likely that it corresponds to the remains of the crater central peak. Streamlined terraces and layers are spectacular in the northern sector and are distinctly organized: seven terraces make the junction between the crater floor and a more round-shaped formation on the summit. On the top of the structure, the deposit displays a succession of 13 horizontal to subhorizontal layers (Fig. 5). The terraces surround the northern sector almost entirely. They are not observed on the southern part of the crescent-like deposit. They are continuous elsewhere, regularly spaced, and locally eroded by perpendicular drainage systems that cut the different levels. Because of their stratigraphic position, we conclude that these drainage systems are the youngest features of the deposit. At the margin with the southern sector, the terraces are streamlined and parallel to each other. They are also intensely perpendicularly eroded, forming elongated remnants that may suggest later wind action resulting in yardang-like formations. Other streamlined remnants are observed on the floor of larger channel features on the deposit. We estimate the thickness of the terraces and layers using shadow-length measurements. The survey was made using pixel count on Viking images 631A05, A07, and A08 (100 to 250-m/pxl mean resolution). Both terraces and layers vary from

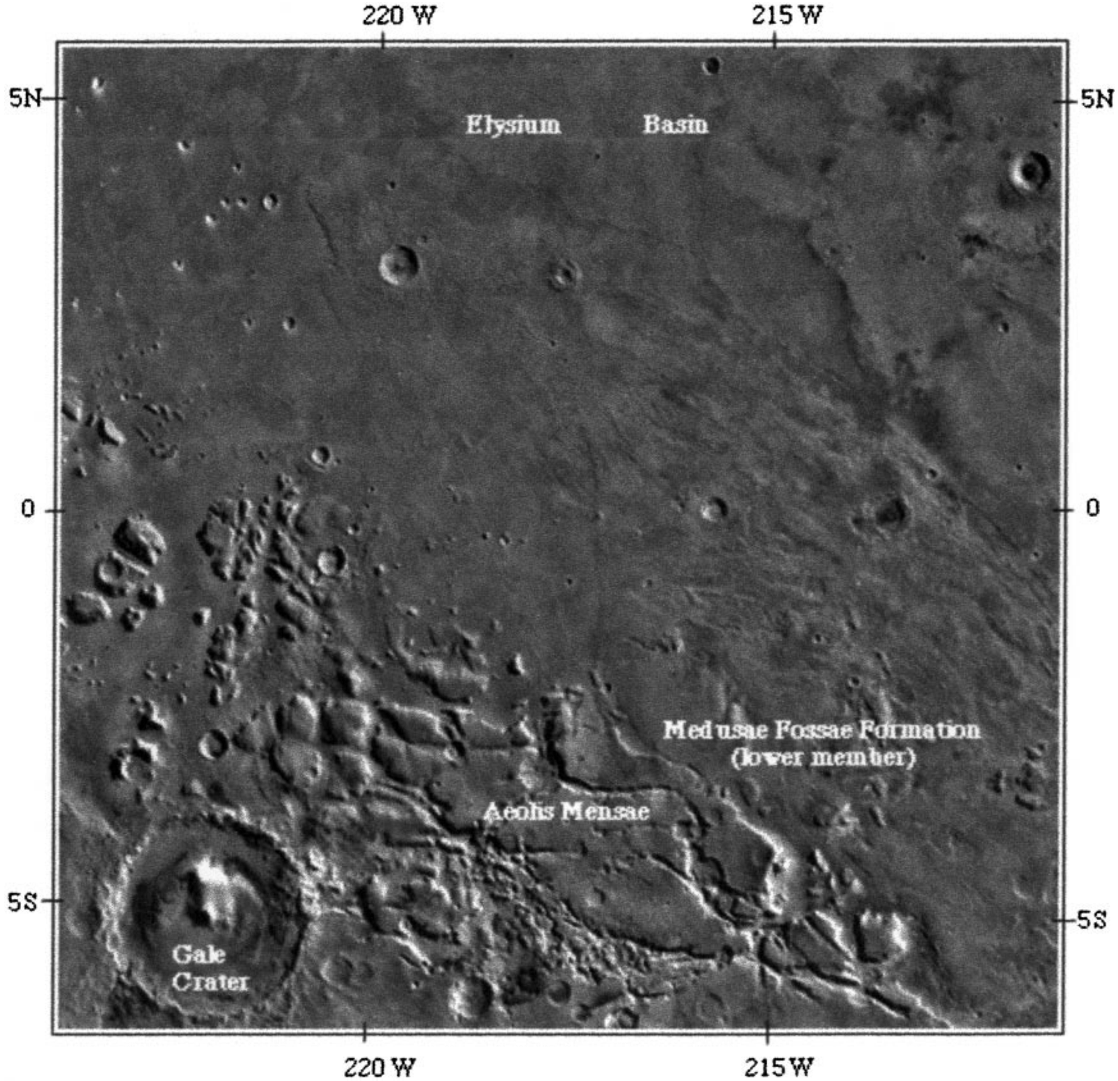

FIG. 1. Regional view of Gale crater in the Aeolis Mensae region at the plateau/plain boundary. The drainage system of Aeolis Mensae adjacent to the northern rim of Gale ends in a smooth plain. In the debouchment area, the morphology characterized by channels, channel-like depressions, and embayed craters suggests an erosional agent coming from both the east and north.

about 100 to 200 m thick and are parallel and regular. South of the central peak, the crater floor shows a featureless smooth deposit, locally displaying slight variations in albedo, higher-albedo material being observed at the transition with the terraced deposit. The topographic survey shows that this smooth deposit lies about 300 m above the floor of the northern sector of the crater. The main hydrologic feature observed on its surface is the 250-km long drainage system that successively cuts Gale's rim and the floor of the southern deposit, and debouches in the southern sector at −4500 m elevation. The stratigraphic position of this channel demonstrates an activity at least as recent as the floor deposit.

1.2. Stratigraphic Age of Gale and Relative Age of Sediment

The time of emplacement of Gale is a critical parameter in the discussion of the formation of the lake, as we will show in the next section. Considering its size and erosional stage, Gale crater appears ancient, though its stratigraphic position compared to the surrounding geologic units does not allow a positive conclusion. Scott and Chapman (1995) proposed that the crater is buried under Amazonian and Upper Hesperian units. Greeley and Guest (1987) proposed that Gale was superimposed on a Noachian plain unit (Npl 2). Considering these observations, our suggestion is that the most likely stratigraphic position of Gale would be Late Noachian to Early Hesperian. By contrast, the sedimentary structure observed on its floor appears relatively young. We established a crater survey of the floor to estimate a probable age of the last geological event that took place in the crater. The surveyed surface area (A) is about 15,400 km^2. Our results show a recent resurfacing for the entire area (central sedimentary structure and floor). Only seven craters are observed: three of them are under the statistic limit ($\geq$2 km in diameter),

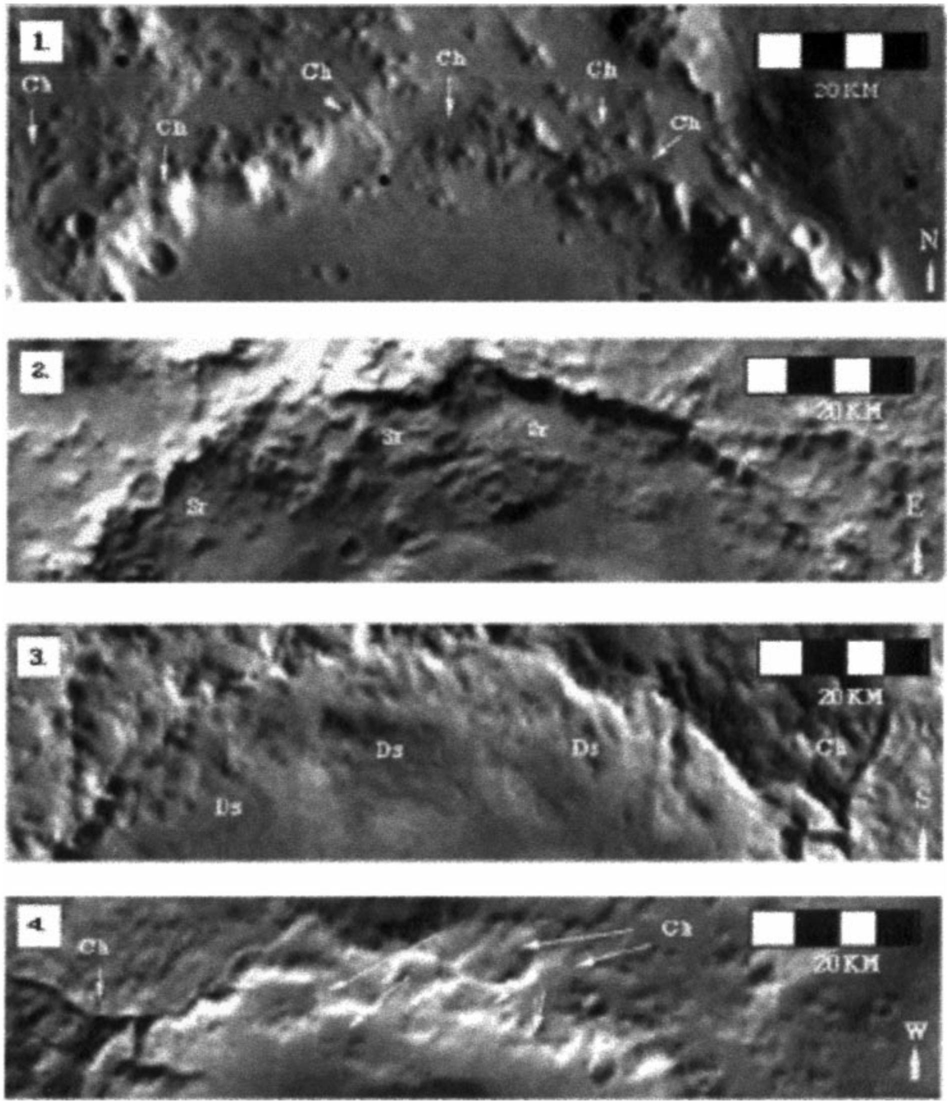

FIG. 2. Diverse morphology of the rim of Gale crater. (2.1) View of the north rim showing small sinuous channels (Ch), which suggest a gentle overspilling of the rim. (2.2) View of the east rim characterized by long sliding faces (Sr), which have transported rim remnants over tens of kilometers down the slope. This morphology is likely explained by the undermining of the rim material by sapping processes. (2.3) View of the south rim corresponding to the less degraded portion of Gale. Debris slopes (Ds) covers the bottom of Gale, with possibly some posterosion by water and/or wind of some of the material accumulation, which are longitudinally shaped. The longest channel debouching in Gale is entering by the south rim and is labeled (Ch). (2.4) West rim of Gale with streamlined erosion that could indicate influx of water coming both from north and west of the crater.

and the larger is about 5 km in diameter. We obtain a normalized population of 259 ± 112.4 craters for 10^6 km^2. The deduced relative age thus ranges from Early to Middle Amazonian for the crater population lesser or equal to 2 km in diameter and defined as N(2), and Early Amazonian for N(5). However, the survey for N(5) relies on a unique crater. For superimposed craters only, the normalized results give 194 ± 112 for N(2), and 64.9 ± 64.9 for N(5). The estimate of relative ages are the same as for the first population. Error margins (E) are calculated as

$$E = \frac{\sqrt{N}}{A} \cdot 10^6.$$

These results imply that the last significant geological event in Gale was Amazonian and involved the entire crater floor.

2. ORIGIN AND EXTENT OF THE PUTATIVE LAKE

Evidence of water activity is given in the central deposit itself by the presence of streamlined and parallel terraces and by drainage systems. Moreover, the amplitude of the morphologic record cannot be understood without the presence of a massive water-body inside Gale crater during the Amazonian period. The northern crescent-like deep hollow and the eroded remnants of the northern crest suggest two processes of formation of the crater lake. For both processes, the origin of water

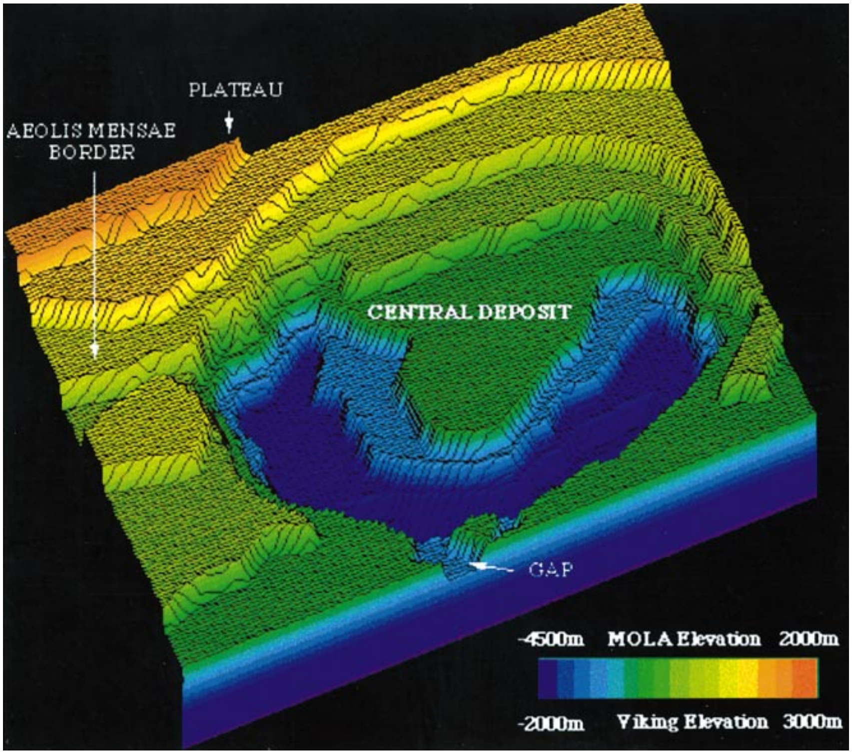

FIG. 3. Topographic model of Gale crater based on the Viking 2M topographic Map I-2121 (MC-23NW, 1991), and in the scale-bars, revised altimetry from MGS MOLA data (Smith *et al.* 1998). The connection between the flooded region and Gale crater has been possible because of the presence of a deep gap entering the crater. One of the most spectacular features of Gale is the crescent-like −2500 m deep depression, which is probably close to the melt layer of the initial crater.

is related to the putative existence of the Elysium Basin paleo-lake during the Amazonian, which is inferred by shorelines, terraces on the lower member of the Medusae Fossae formation, and/or the existence of active channels in the Aeolis Mensae formation, described as a potential source area for the Elysium Basin by Scott and Chapman (1995). The hydrogeologic relationships between the Elysium Basin system and Gale crater are (a) the Aeolis Mensae source area that borders the Gale crater rim perimeter over 300 km, (b) the crater bottom that is about 2500 m below the Elysium shoreline level, and (c) the elevation of the observed gap in the north rim, which is located at about −1000 m elevation.

We consider two processes: (a) the first process is the sapping of the rampart of the proximal source area saturated zone in

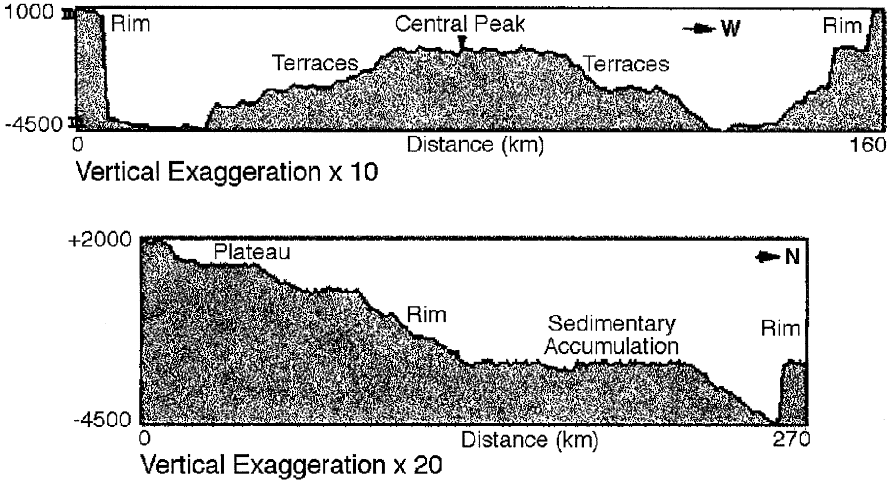

FIG. 4. Topographic profiles of Gale and the surrounding region, extracted from the Viking 2M topographic Map I-2121 (MC-23NW, 1991), and revised altimetry after MGS MOLA data (Smith *et al.* 1998).

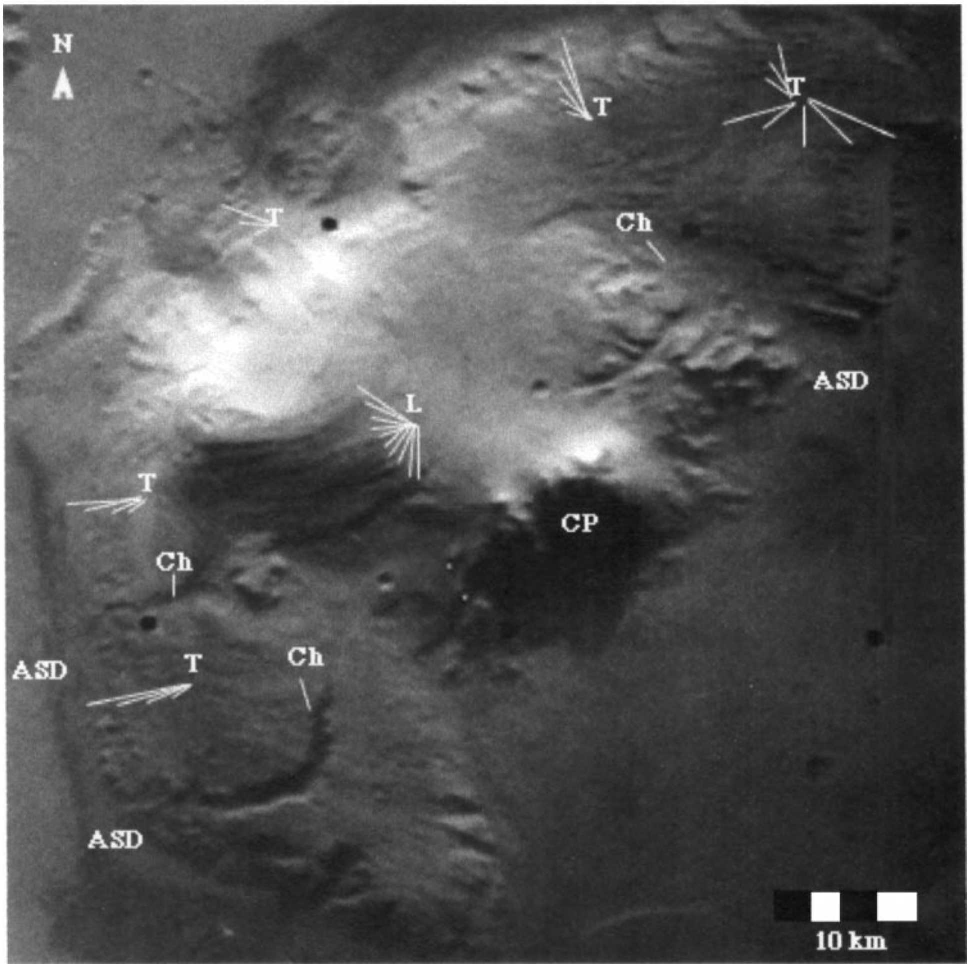

FIG. 5. Close-up view of the central sedimentary structure. The peak located in the center of the impact crater, labeled CP, is probably the remnant of the crater central peak. Usually eroded in ancient craters like Gale, this peak may have been preserved by an early sedimentary cover. The sediments could have different origins: aeolian, pyroclastic, and fluvio-lacustrine. They are spectacularly exposed both in terraces (T) and layers (L). Several channels (Ch) deposited aqueous sedimentary deposits (ASD) at the bottom of Gale. Their stratigraphic position show that they are one of the youngest features in the crater, and indicate the presence of water in Gale during the Amazonian.

Aeolis Mensae and (b) is the supply of water by surface overspilling, which might be obtained in three cases: (i) the overspilling of the northern rim (labeled G in Fig. 1) by the release of Aeolis Mensae channels that border the plateau/plain boundary, (ii) by a channel that drained the plateau south of Gale (labeled C in Fig. 1), and (iii) by the rising of the Elysium Basin water level.

The presence of a water-rich aquifer is suggested by fluvial valley systems in the plateau in the vicinity of Gale and by the presence of smooth deposits on the floor of the Aeolis Mensae formation that were interpreted as Amazonian river-bed material and channel sediment by Scott and Chapman (1995). Three observations suggest the possibility of a crater drainage by gravity: (a) the recent map of the Elysium Basin by Scott and Chapman (1995) suggests a source area for the Elysium Basin between 0 and 1000 m elevation in the Aeolis Mensae region, which displays extended morphological evidence of drainage and flooding that supports the hypothesis of a past water-rich aquifer, (b) according to MOLA (Smith *et al.* 1998), the elevation of the crater bottom shows a depth of 5500 m relative to the surrounding cratered uplands, and, (c) the undermining of the eastern rim associated with rim sliding processes occurs at the contact with the Aeolis Mensae formation. Thus, we assume that the 5500-m difference in elevation between a potential water table of the source area and the bottom of the crater might be sufficient to generate drainage by gravity. To describe this process, we assume that a water body contained in the crater could have been formed by gravity drainage of the Aeolis Mensae proximal aquifer (0 m elevation). To estimate the water volume, we approximate the crater-bowl volume from existing topographic data (Smith *et al.* 1998) by the volume of successive frustrum cones between the crater bottom (−4500 m elevation) up to a conservative level below the northen gap (−1000 m elevation). Taking into account the volume of the central peak, this calculation gives 20,500 km^3

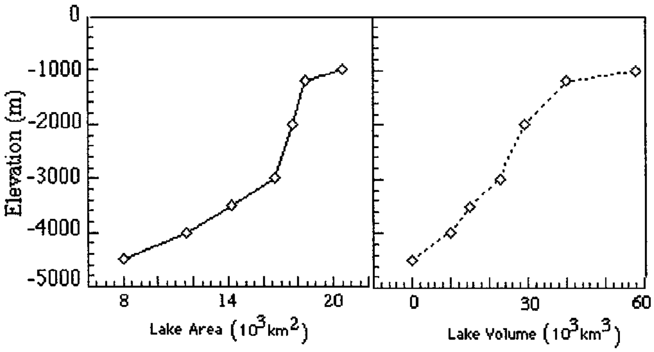

FIG. 6. Bathymetric model of Gale crater constructed from the imagery and the topographic data. The solid line is the graphic representation of the function between the volume, the area, and the elevation of the lake. The dotted line shows the relationship between the lake water level and the volume. The decrease of the water-table level (see initial and final water table) shows the limit of the sapping process. The overspilling episode may have filled the remnant volume in the crater.

(Fig. 6). The volume of available underground water is defined by the areal extent of the drainage and by the thickness of the saturated zone of the unconfined aquifer. This thickness is the distance between the water table (0 m) and the emergence level. The emergence level is located at the base of the crater inner wall at −4500 m elevation. The area where the putative water level is localized in our model is characterized by relics of large mesas that could be the remnants of subsidence surface formed by the underground drainage (Grin and Cabrol 1997). We consider that the expelled water causes the decline of the water table. The void created by the loss of water generates a compaction of the aquifer skeleton that is transferred to the surface, where land subsidence occurs. To estimate the possible volume of expelled water, and the extent of the drained aquifer, we introduce the concept of specific storage coefficient as the compressibility of the aquifer media. Thus, we define the storage coefficient as the combination of the volume of water produced by the compaction of the aquifer skeleton and by the decrease of the water pore pressure generated by the change of the aquifer thickness (Grin and Cabrol 1997). We adopt physical parameters derived from terrestrial analog materials for the aquifer media and for the water. For the aquifer media the parameters are: the compressibility α, and the porosity n, and for the water: the compressibility β, and the density ρ.

For an aquifer thickness unit $b = 1000$ m, the storativity coefficient is dimensionless

$$S = \rho g(\alpha + n\beta) \times b,$$

where g is the martian gravity acceleration. For $g = 3.7\ \mathrm{m/s^{-2}}$, $\rho = 1000\ \mathrm{kg/m^{-3}}$, $\alpha = 1 \times 10^{-8}\ \mathrm{m^2N^{-1}}$, $\beta = 4.8 \times 10^{-10}\ \mathrm{m^2N^{-1}}$ (Domenico and Schwartz 1990), $n = 0.30$. For an aquifer thickness $b = 4500$ m, the calculation gives

$$S = 0.6.$$

The volume of expelled water for the aquifer thickness $b = 4500$ m of an area A ($\mathrm{km^2}$) is

$$V = A \cdot S = 58 \times 10^3\ \mathrm{km^3}.$$

Then, we deduce that A is about $96 \times 10^3\ \mathrm{km^2}$. This value corresponds to an area depicted by the half-portion of a circle of 100-km radius centered in Gale (70-km radius). The drained aquifer is then an area surrounding Gale's rims over 15 km. This radius includes the region of the Aeolis Mensae, which displays extended morphological evidence of drainage and floods that support the model of a water-rich aquifer.

The survey of the northern rim shows a 4-km wide gap at −1000 elevation (see Fig. 3), these elevations being comparable to the Elysium paleolake shoreline level (Scott and Chapman 1995). We now consider the contribution of each of the previous processes listed above. The Aeolis Mensae region is characterized by a 750-km long drainage network, which headwaters are located on a Noachian unit on the plateau. The bed floor of the channel is approximately at the same elevation (−1000 m) as the gap in Gale's northern rim. This observation suggests that the water may have percolated through the rampart and also overtopped the lowest portions of the crest. In addition, the drainage networks may have generated, and sustained, an underground aquifer north of Gale. South of Gale, the 250-km long fluvial valley network originates in the cratered uplands in a Noachian crater material plain (Nc) and crosses northward Hesperian and Amazonian plain material (AHc) (Scott and Chapman 1995). Considering the dimensions of this fluvial system, it cannot have accounted for the total volume of sediment deposited in the crater.

The other contribution by overspilling is related to the rising of the Elysium Basin water level. We assume that the rising level of Elysium paleolake might have overtopped the gap. This gap is extended by several 200-km long channel-like depressions, where water may have traveled from the lake into the crater. The topographic survey gives additional evidence of water release from the north. The crescent shape of the sedimentary deposit shows the summit of the arch-like feature oriented north, consistent with a north-entering erosional agent. This shape is also observed in the contour lines at −3000 and −4000 m. Considering all the above observations, we propose two comprehensive models of a lake inside Gale crater that could predict the topography and the morphology of the central deposit.

3. DISCUSSION

The considered processes are related to the existence of the Aeolis Mensae drainage networks and the Elysium Basin rising level. The downstream part of the Aeolis Mensae region is located at the same −1000-m elevation as Gale's rim gap (Fig. 3). The morphology of this region resembles a flood plain, which could have been partly drained by small channels through the rim of Gale (Fig. 2.1). The elevation of the flood plain north of Gale is at the same elevation as the Elysium Paleolake proposed shoreline (Scott and Chapman 1995). The source area in the Aeolis Mensae region is both at the same elevation as Elysium Paleolake and connects to the paleolake at 3.1°S/202.1°W. From this location to Gale crater, the plateau/plain boundary is characterized by smooth deposits and eroded mesas often displaying channels and/or channel-like depressions on their top suggesting important water erosion. Thus, we propose that instead of a distinct source area, Aeolis Mensae may have been the southern limit of an Amazonian transgression of the Elysium Basin. This explanation will be consistent with the terracing observed on the eastern and western borders of the lower member of the Medusae Fossae unit, and it is in agreement with the regular terracing of Gale's central sedimentary deposit. The morphology of the inner northern rampart suggests an undermining process resulting from the aquifer drainage. The consequence of such drainage would have been the generation of a former lake within Gale prior to the overspilling of the northern rim. The regional morphology supports the idea of a gentle and progressive transgression rather than a catastrophic outflow episode. Because of the wide area of Elysium Paleolake (2,000,000 km^2), the variation of the water level may have been most likely very slow. This scenario supports observational evidence such as the lack of a large erosional inflow system cut in the northern rim that would be expected if the crater was empty at the time of the overspilling. Moreover, we can assume, according to the size of the few small channels cutting this north rim (Fig. 2.1), that the level of the former lake in Gale was already about −1500 m, or very close to the elevation of the overspilling water outside the crater.

The lifetime of the crater lake depends of the duration of the water supply in the Elysium Basin system, where evidence of water are found for the Hesperian and Amazonian periods. During this period, Gale's lake may have been sustained by two ways: in the first one, the lake could have been sustained is by assuming drainage by gravity. For instance, we take terrestrial values of discharge adapted to Mars of 0.01 m^3 per day (3 m^3 per year) per square meter of seepage face. For a seepage face averaging 100 m in height, developed over the 210-km long inner perimeter of the crater walls, the time necessary to fill 20,000 km^3 of the lower volume of the crater lake is 3.0×10^5 years. We suppose that the northern rim of the crater was surrounded by an active unconfined and unfrozen aquifer permanently sustained by the Aeolis Mensae network water. The drainage by gravity could have been favored by a hydraulic conductivity of the aquifer media and a permeability between 1000 and 3000 Darcies (Carr 1979, Moore 1995) to allow the water to travel approximately 20 km.

The second way to fill the remaining volume of Gale crater is by overspilling. We assume a conservative shallow water rising at of 0.02 m/yr, and a flow velocity of 0.5 m/s^1 in the channel, the corresponding discharge rate in this channel would then equal 40 m^3/s^{-1}. The time required to fill the upper volume of a 500-km^3 lake by overtopping is about 5×10^3 years. The time required to fill the lake entirely by sapping and overspilling is then 8×10^5 years. We suggest, according to climate models, that the Elysium Paleolake was covered by a thick ice-sheet. In addition, the activity of Elysium Mons at the same period (Middle to Upper Amazonian, Scott and Chapman 1995) may have provided a cover of ash flows, which mixed with ice, and could have prevented rapid sublimation of the ice-sheet cover.

4. HYDROTHERMAL SYSTEMS IN GALE CRATERS

The formation of Gale crater was probably associated with the formation of hydrothermal systems heated by impact melt and by geothermal energy from the uplifted basement. Because of the large deep size of Gale, the basin was probably flooded by groundwater immediately after formation of the crater. The flooding of the crater may have been accompanied by some of the erosion and slumping observed in the rim of the crater, due to sapping or slope instability from the hydraulic pressure. These events represented a stage in the interaction of water with Gale that occurred shortly after formation of the crater, but prior to the resurfacing and erosion events reflected in the current morphology of the crater and sedimentary deposits. The evidence of these early events is not obvious because of the apparent long duration of fluvial and aqueous processes occurring in Gale. However, constraints can be placed on the possible magnitude of the heat sources, the possible evolution of the hydrothermal environments, and the possible locations of hydrothermal spring deposits.

The two major heat sources present after the formation of Gale crater are impact melt and geothermal energy from the uplifted basement. The amount of impact melt can be estimated from the diameter of the crater, using 140 km as an estimate of the original rim diameter prior to the extensive erosion of the rim deposits. From this diameter, and data compiled by Clifford (1993), a melt volume of approximately 3,900 km^3 can be estimated. Assuming this melt was spread over a crater floor with a diameter of 130 km, a melt thickness of approximately 670 m is obtained. While very uncertain, this thickness represents a reasonable order of magnitude estimate for considering possible hydrothermal effects. The cooling of large impact melt sheets has been considered by Onorato *et al.* (1978), using both numerical and analytical techniques. The postulated Gale melt sheet is approximately three times thicker than the 200-m thick melt sheet studied by Onorato *et al.* (1978). The work of Jaeger (1968) showed that the cooling times are proportional to the square of the length scale, therefore, the solidification and cooling time of the Gale melt sheet will be about 10 times that of the 200-m melt sheet. The influence of a melt sheet and other heat sources on the cooling of a martian impact crater lake was studied by Newsom *et al.* (1996). Extrapolating from these results, a liquid lake with an ice cover could be maintained under current climatic conditions for as long as 100,000 years. This assumes that ground water or surface runoff can replace the water lost by ablation from the surface of the ice cover. Another important assumption is that the cooling would be mostly conductive. Conductive cooling is likely considering the rapid development of a thick crystallized melt rind protecting the molten interior of the melt sheet (Newsom 1990). In addition, convective cooling will be limited due to the burial of the impact melt under material slumped from the walls of the crater, and the common occurrence of self-sealing of hydrothermal systems in terrestrial hot spring and mid-ocean ridge systems. Even if the cooling is partly convective, the lifetime of a liquid lake could be quite long.

An additional heat source for the lake could come from geothermal heat derived from the uplift of the basement due to the formation of the crater. This process has been connected with the deposition of hydrothermal minerals in the Manson crater (McCarville *et al.* 1996). In the case of Gale crater, a central uplift approximately 8 km in diameter is present, and the size of Gale suggests that a peak ring might also be present (Pike 1985). Peak rings often have diameters approximately half the crater diameter, which would fall beneath the annular central deposit on the floor of the crater. If the sediments are partially draped on remnants of such a peak ring, the estimated volume of sediments may be an upper limit. The depth of excavation represented by the materials of the central peak in Gale could be important for obtaining deep samples of the crust. Based on Croft (1985) the depth of excavation is about 0.1 times the transient cavity diameter, or about 8.5 km for Gale. This depth is still in the crust, because geophysical models suggest that the crust is probably 100 to 250 km in thickness (Sohl and Spohn 1997).

As discussed by Newsom *et al.* (1996), the magnitude of the heating from the uplifted basement can be substantial, but the relative importance compared to the impact melt sheet depends on the time scale on which the heat is released. Because the uplifted basement will be shattered, but not molten, the permeability will be much higher than the crystallizing melt sheet, thus convective cooling is more likely. Therefore, the channels observed on the young surface of the central deposit are unlikely to be connected with the initial hydrothermal event. Even if the hydrothermal system involving the central uplift was relatively short lived, there is a high probability that hydrothermally altered materials and spring deposits occur in the central uplift. If the exposed portions of the central uplift were above the level of groundwater supplied hydrothermal systems, there is still a possibility of deposits from an acid-sulfate hydrothermal system supplied by vapor transport from a deeper neutral chloride system.

Even if the supply of water were not sufficient to form or maintain a lake, a substantial hydrothermal system would arise in the upper part of the melt sheet and the overlying debris. If the supply of water declined even further, the hydrothermal system could have evolved into a vapor-dominated system (Newsom *et al.* 1998). This consists of a neutral-chloride hydrothermal system at the deep groundwater table, heated by the impact melt leading to vapor transport upward, where the vapor can condense to form an acid-sulfate hydrothermal system.

Another area where hydrothermal systems and the formation of associated channels may have occurred is on the rim of the crater (e.g., Brakenridge *et al.* 1985). Impact melt deposited on the rim could have supplied heat to ground water or melted ground ice to form hydrothermal alteration and hot springs. The subsequent heavy erosion of the rim and penetration by channels may have transported fragments of these hydrothermal deposits and distal impact melt deposits into the sediments within the crater.

CONCLUSION

A lake within Gale crater during the Amazonian provides further evidence that water was present at the surface of Mars in the relatively recent past. The evidence of massive water bodies, such as the 850,000-km^3 Elysium basin (Scott and Chapman 1995) 500 million years ago or less, and the existence of smaller Amazonian basins like Gusev and Gale craters are in contradiction with the old picture of Mars drying out in the recent geological past and experiencing only isolated water outbursts in the Chryse Planitia region. During the Amazonian, Mars was able to generate a water body equivalent to the Mediterranean sea (2,000,000 km^2). Moreover, part of the water contained in the aquifer was still able to circulate to generate lakes in deep craters, like Gale and Gusev. In addition, the depth of young fluvial valley system headwaters are often located a few hundred meters below the surface, even in the intertropical band of Mars, suggesting that the water table was not necessarily far from the surface everywhere in recent geologic times. If we list these recent water bodies, we see a distribution over a large area. For instance: (1) the lake in Gusev was generated by the Amazonian activity of Ma'adim Vallis, (2) Gale, as proposed in this study, was generated by aquifer drainage, water infiltration, and surface drainage in recent geological times, (3) the possible sources for the Amazonian Elysium Basin range from northern source areas (Tanaka and Scott 1986), volcano–ground-ice interaction (Mouginis-Mark 1985, Squyres *et al.* 1987), and large channels originating from the cratered upland (Scott and Chapman 1989, Cabrol *et al.* 1996, Grin and Cabrol 1997), and (4) valley systems and outflows generated by hydrothermal activity are also described during this period (Gulick and Baker 1989). The Amazonian fluvial features are observed all across the planet. They are not as numerous as during the Noachian/Hesperian boundary, but their size is often much larger. In addition, almost all of them have a common characteristic: their source of water can be related to ground-ice–heat flux interaction. For instance, we will refer to a nonexhaustive list of typical examples: the sources of Ma'adim Vallis are related to volcanic and faults regions (Landheim 1995, Cabrol *et al.* 1996, 1997, 1998a, 1998b, Kuzmin *et al.* 1998, Landheim *et al.* 1998), and so are the sources of Mangala Valles. There is a plausible relationship, because of a contemporary chronology and a large common boundary, between the formation of the Elysium Basin and the Elysium Mons activity. The sources of Granicus Valles are located on the flanks of Elysium Mons and the young bed deposits of Dao Vallis in the southern hemisphere are located on the flanks of the Hadriaca Patera. As a final example, there is a strong chronological correlation between the last outflow generation and the last activity on Olympus Mons. These are only some examples of the numerous large-scale fluvial features of the Amazonian. They strongly suggest a thermally and hydrologically very dynamic Mars during this period, where stored water could still circulate at depth and at the surface, though probably protected by an ice-covered sheet at the surface because of the climatic conditions.

Locally, the morphology and organization of the Gale sedimentary deposit provide information about the crater evolution through time and gives an open window on the surrounding hydrogeologic conditions. The regularity of the spacing between layers in the upper part of the central deposit (Fig. 5), and their comparable thickness, may suggest a major cycling event and/or a regular decrease of the water level. The major cycling event could reflect the progression and recession of the Elysium Basin through time, with transgression events that episodically flooded regions at the plateau/plain boundary. The regular decrease of the water level may also be explained by one major transgression and progressive evaporation, sublimation, and infiltration of the water within Gale.

Gale is an ancient impact crater, probably dating back from the Noachian-Hesperian boundary. Its last aqueous sedimentary episode, as shown in this study, is estimated to be Early to Middle Amazonian. Considering the fluvial activity through time in the Aeolis region, and in the Aeolis Mensae particularly, it is likely that the crater may have been filled with fluvio-lacustrine sediment for more than two billion years. The potential series of lakes during this extended period of time may have provided very diversified environments, from warm thermally driven waters to cold-ice-covered waters. In this respect, impact crater lakes are probably the most interesting places to search for life on Mars. It is unknown if any potential life on Mars existed on a continuous time scale or was terminated and restarted at multiple events, as suggested by Maher and Stevenson (1988) and Sleep *et al.* (1989). Despite this uncertainty, we expect that evolutionary trends would have allowed organisms to establish new ecological niches in response to a changing climate and environment. In the case of impact crater lakes, such as Gale and Gusev craters, we envision a series of ecological niches having been present from the time following impact until Mars lost its hydrosphere and the potential to sustain life on the surface. For some time following impact, Gale crater may have had the ability to sustain life in a thermally driven subaerial or subsea environment. Such terrestrial analog environments have been discussed by Brocks (1967) and Barns *et al.* (1994). The preservation of biological information in thermal spring deposits on Mars, as well as related sampling strategies were discussed by Walter and Des Marais (1993). Based on the observational evidence of fluvial erosion on Gale crater's rims, we suggest that potential microbial niches may have been developed underwater. The lake body would have experienced cooling through time. Various microorganisms in the lake may have adapted to physical and chemical changes induced by the modication of the climate (i.e., temperature, pH, salinity). Such changes would in turn have had direct implications on species abundance, diversity, and dominance.

As Gale dried up, resulting playas may have favored the existence of halophiles. Any microbial life that existed in these types settings are likely to have been preserved in mineral deposits, such as carbonates (Schopf 1983, McKay and Nedell 1988), and evaporites (Rothschild 1990), and in the scenario of a volcanic setting, possibly in silica. Each of these fossilization agents have different preservation potentials in the fossil record. In terms of identification, different deposits may be identified through characteristic spectral signatures. As the temperature became progressively cooler, microbes may have retreated from the lake water to subareal habitats and in turn migrated to protected niches in or under rocks on the surface. These types of environments have been identified in some of the Earth's deserts, such as the Dry Valleys of Antarctica (Friedmann 1982, 1986, Friedmann and Koriem 1989). There are also potential martian analogs represented by the perennially ice-covered lakes in Antarctica. These lakes are hosts of microbial mats composed primarily of bacteria, cyanobacteria, and algae that exist without sunlight most of the year (Wharton 1994).

The different environments listed above could all have sustained life that may be still present in the fossil record. The absence of crustal recycling on Mars opens up for the possibility that fossilized life forms from the various ecological niches described could be present right at the surface today, when potential extent life should be searched for underground. The mineral deposits in which life may be preserved would have a good likelihood of being detected with spectral data, such as the Thermal Emission Spectrometer (TES) of the Mars Global Surveyor (Christensen *et al.* 1992). Impact crater lakes must be surveyed through high resolution imagery and spectral data that can assist in further selection of scientifically and biologically promising sites for future surface exploration. The possible ecological niches of Gale crater introduced in this section will be further discussed in a paper currently in progress.

APPENDIX

The survey of Gale has been undertaken using the following data set:

Viking Orbiter images: 631A03, 631A05-10, 631A25-28, 631A30, 631A43, and 631A45.

Topographic Series Maps:

1 : 2M Aeolis Northwest subquadrangle, I-1213 (MC-23NW), 1979.

1 : 2M topographic series Aeolis Northwest, I-2121 (MC-23 NW), 1991.

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