GEOLOGIC MAP OF THE MTM –15182 AND MTM –15187 QUADRANGLES, GUSEV CRATER–MA'ADIM VALLIS REGION, MARS

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INTRODUCTION

This map is one of a series of large-scale (1: 500,000) geologic maps of Mars initiated by the National Aeronautics and Space Administration to investigate areas of high scientific interest. The Gusev crater–Ma'adim Vallis region includes several potential landing sites for future Mars missions, including those with a focus on exobiology studies and sample return. Channels in the map area span a long age range, cut ancient rocks that may contain important biogenic information, and funneled water into exobiologically important lacustrine basins. The map area is characterized by diverse geologic units representing a variety of endogenic and exogenic proc-esses. The geologic history of this region spans the entire history of the planet.

The base map was compiled from controlled photomosaic maps of the Mars Transverse Mercator (MTM) –15182 and –15187 quadrangles (U.S. Geological Survey, 1992a, b). The map area is in the Aeolis region, which was first mapped from Mariner 9 images at 1:5,000,000 scale (Scott and others, 1978) and at 1:25,000,000 scale (Scott and Carr, 1978). On the basis of Viking data, the area was later mapped at 1: 15,000,000 scale (Greeley and Guest, 1987) and in part at 1:5,000,000 scale (Scott and Chapman, 1995). Recently, the area was mapped at 1:1,000,000 scale by Landheim (1995). This 1:500,000-scale map shows a great diversity of geologic materials and demonstrates a more complete understanding of fluvial processes in the highland plains, the evolution of Ma'adim Vallis, and sedimentation in Gusev crater and in de Vaucouleurs, an ancient 300-km-diameter impact structure west of Gusev crater. Standard photogeologic mapping techniques elucidated by Wilhelms (1990) were used in this work. Viking Orbiter images used to map the area range in resolution from 63 to 70 m/pixel, with small patches at 225 m/pixel.

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The map area (fig. 1) is in the transition zone between the lowlands of the Elysium Planitia to the north and the highland plateau to the south. The elevation of the map area ranges from 0 km in the northwest to 3–4 km in the southeast. Thus, the map area lies at the base of a regional slope that extends from the southeast to the northwest (fig. 2).

Two conspicuous features in the map area are Gusev crater, an impact structure approximately 160 km in diameter, and part of Ma'adim Vallis, a channel that cuts highland terrain and debouches onto the floor of Gusev. Water appears to have exited Gusev along two pathways, including a topographic saddle on the west rim of the crater and a gap in the northwest rim (fig. 2). A second channel, Durius Valles, lies to the west of Gusev. Highland plateau terrain with abundant degraded impact craters and traces of ancient impact basins are found east and south of Gusev (Schultz and others, 1982; Schultz and Frey, 1990). These basins may have had some structural control on the development and location of Ma'adim Vallis. The highland plateau surfaces exhibit morphological evidence of multiple fluvial resurfacing events during the Noachian and Hesperian periods. Heavily cratered and dissected Noachian terrains are dominant in the plateau region adjacent to Gusev (Greeley and Guest, 1987) and are thought to consist mostly of impact breccias and ancient crustal materials (Scott and Tanaka, 1986; Greeley and Guest, 1987). Stratigraphic relations of the geologic units suggest that the area was subject to resurfacing by repeated flooding from the Ma'adim Vallis and Durius Valles fluvial systems, which originate in the highlands to the south. The source of water for these channels appears to have originated in the Sirenum Fossae grabens and chaotic terrain in the Ariadnes Colles area. Water appears to have originated as both surface runoff and ground-water sapping (Cabrol and others, 1997, 1998).

Many small valley networks, mostly of Hesperian age, cut the highland plains and show a general drainage direction to the north. On the highland plains, erosional remnants of likely ancient crustal material are present as scattered mountainous terrain, forming long, narrow ridges or crustal blocks (Scott and Tanaka, 1986). The grabens and fault systems in the area have northwest-southeast and southwest-northeast trends.

The area west of Gusev consists of low-lying plains, with a diversity of geologic units, that occupy the floor of de Vaucouleurs. This basin received sediments by repeated flooding of both Ma'adim Vallis and Durius Valles. The basin opens toward the northwest into the Elysium lowlands, which may have been occupied by a paleolake (Scott and Chapman, 1995). de Vaucouleurs is a topographic embayment of the northern lowlands into the highland-lowland boundary scarp and was a transitory depocenter for Ma'adim Vallis and Durius Valles drainage as it flowed north into the lowland of Elysium basin (Landheim and others, 1994).

Northeast of Gusev, the youngest units of the Medusae Fossae Formation (Aml_1, Aml_2, and Amu; Scott and Tanaka, 1986) are superposed on plains deposited during the last flooding episodes from Gusev. Scott and Tanaka (1986) inferred that the Medusae Fossae Formation was volcanic in origin and likely consisted of pyroclastic material. The boundary between units Aml_{1-2} and $AHgf_1$ forms a prominent cliff, modified by wind erosion (Ward, 1979). A sand dune field (unit Ar) covering an area 30 km by 5 km accumulated near the eastern part of the boundary area and possibly consists of materials derived from units Aml_{1-2} or other older materials.

STRATIGRAPHY

The basic stratigraphic framework for the mapped area is consistent with previous global (Greeley and Guest, 1987) and regional (Scott and Chapman, 1995) geologic mapping. In the present work, units (exclusive of material of impact crater ejecta blankets) of the plateau and high-plains assemblage and the basin and channel-system materials are further subdivided based on morphology and contact relations. The relative ages of the units were established by stratigraphic relations and crater size frequency distributions (table 1, fig. 3).

NOACHIAN SYSTEM

The oldest terrain in the map area is mountainous material (unit Nm) that forms elongate (10–70 km) ridges or crustal blocks of material elevated above the surrounding terrain. The contacts of the mountainous material with adjacent units are commonly bound by steep cliffs, possibly marking the footwalls of normal faults. According to Scott and Tanaka (1986), this unit may consist of impact breccias and ancient volcanic massifs, dating back to the period of heavy bombardment, that subsequently were uplifted by faulting. These mountains rise above the old cratered plains unit of the plateau sequence (unit Npl), which is the predominant geologic unit in the map area. The old cratered plains unit may be of the same composition as the mountainous material, but the material's location in a depositional low adjacent to the mountains leads us to interpret it as a slightly younger unit of later Early–Middle Noachian age. The old cratered plains unit exhibits a rugged, rolling surface with isolated hills, grooves, and fractures (fig. 4). It is characterized by a high frequency of large (>10 km diameter) impact craters and is probably composed of highly brecciated material. The rugged relief may result from a high concentration of impact crater ejecta deposits that have been eroded to varying degrees. In places the surface is dissected by small valley networks that appear to have formed by ground-water sapping (Carr, 1995), perhaps aided by ground ice-magmatic interactions (Brakenridge and others, 1985; Gulick, 1995).

Curvilinear ridges in the western part of the map area have sharp crests and numerous perpendicular grooves. These patches of degraded rim material (unit Nrd) are interpreted to be ancient and may be either fragments of impact crater rims or remnants of volcanic constructs, superposed on older cratered plains. Degraded rim material is embayed by younger

Table 1. *Map area units, number of craters (>D), crater density, and martian epochs (from Tanaka, 1986)*

[Accuracy of crater statistics are limited by the area of units]

Units	Area (km^2)	Number of craters (>D) 2 km	5 km	16 km	Crater density N(D)=no.>D/10^6 km^2 2 km	5 km	16 km	Epoch[1]
Kayne crater ejecta	12,550	4	1	—	318±159	79±79	—	EA–MA
[2]$AHch_3$	9,025	4	—	—	443±221	—	—	LH–EA
[3]$AHgf_{1-2}$	11,075	6	—	—	542±221	—	—	EH–EA
$AHch_1$ and [4]$AHch_2$	6,350	4	—	—	629±315	—	—	EH–EA
$AHbm_2$	7,800	5	—	—	641±286	—	—	EH–EA
$AHbm_1$	5,575	4	—	—	717±358	—	—	EH–EA
Hpld	11,940	9	2	—	754±251	167±118	—	EH–LH
Hcht	5,397	5	—	—	926±414	—	—	LN–LH
$HNpl_2$	13,735	15	6	1	1,092±282	437±178	73±73	MN–EH
$HNpl_1$	6,313	7	2	—	1,109±419	317±224	—	MN–LH
Npl	44,560	78	46	10	1,750±198	1,032±152	224±71	EN

[1]A, Amazonian; H, Hesperian; N, Noachian; E, Early; M, Middle; L, Late.
[2]Data for Ma'adim Vallis floor from 16° S. to 22° S.
[3]Data for area inside Gusev crater.
[4]Data for Durius Valles.

channel- and basin-floor materials and plains materials. The Middle Noachian degraded rim material has been completely buried by these younger materials, and the unit's present exposure is only due to the exhumation of this overlying cover. We base this interpretation on the isolated nature of the hills and their local burial by younger units.

HESPERIAN–NOACHIAN SYSTEMS

An intermediate highland material, subdued cratered plains material (unit $HNpl_1$), appears smoother than the old cratered plains unit (Npl) and contains valley networks that are wider and less distinct than on the older plains. Subdued cratered plains material extends far south of the map area and is the most extensive unit through which Ma'adim Vallis was eroded. This unit was deposited during the Middle Noachian–Early Hesperian and has a smooth subdued surface cut by grooves and valley networks possibly indicating that the unit formed as a result of fluvial sedimentation during widespread flooding from Ma'adim Vallis. Erosional grooves and a small valley network were formed later, perhaps as flood waters receded from the area.

A younger plateau material, modified cratered plains unit (unit $HNpl_2$), is superposed on the old cratered plains and subdued cratered plains materials (units Npl and $HNpl_1$, respectively) south and southeast of Gusev. The surface of unit $HNpl_2$ is smoother and has fewer superposed craters and valley networks than both the old cratered plains and subdued cratered plains units. Unit $HNpl_2$ may have formed by episodic flooding of old cratered plains and subdued cratered plains due to damming of the lower Ma'adim Vallis by superposed impact craters (Cabrol and others, 1997, 1998).

The cliffs of Ma'adim Vallis and Durius Valles and some steep slopes within the plateau are composed of undivided wall material (unit HNw). Valley walls show a thick series of plateau-forming rocks inferred to be mostly impact breccias and lavas, possibly interbedded with Noachian and Hesperian fluvial and aeolian sediments.

HESPERIAN SYSTEM

The Hesperian System in the map area records multiple episodes of fluvial activity, both on the plateau units and within Ma'adim Vallis and Durius Valles. Dissected plains material (unit Hpld) is the most widespread of the Hesperian units in the map area. This unit is north and northwest of Gusev crater and is partly superposed on the crater rim. The largest exposures of dissected plains material are found in the western part of de Vaucouleurs (immediately west of Gusev). Northwest of the rim of Gusev, dissected plains are superposed on old cratered plains (unit Npl). The same stratigraphic relations are observed in the western part of de Vaucouleurs. Dissected plains material generally forms a smooth and finely pitted surface but in places is dissected by valley networks and sets of small parallel channels. The erosional pattern of the unit appears very similar to friable water-eroded pyroclastic deposits, and dissected plains material could therefore be of volcanic origin. One hypothesis is that the dissected plains material resulted from fluvial resurfacing and erosion of primary pyroclastic deposits from Apollinaris Patera (Robinson and others, 1993). Hypothetical pyroclastic deposits are widespread north of the map area, south and southwest of Apollinaris Patera (mapped as units Ha_3 and Ha_4 by Scott and others, 1993), and could occupy northern parts of Gusev crater and de Vaucouleurs. These so-called pyroclastic deposits formed in the Early and Middle Hesperian (Scott and others, 1993) and are potential candidates for the source materials for unit Hpld.

Chaotic terrain material (unit Hcht) occurs in the northeastern part of the map area and within de Vaucouleurs. This unit is characterized by densely spaced hills that become progressively more isolated toward Apollinaris Patera to the north. According to Scott and Chapman (1995), this unit is of Hesperian age. Stratigraphic relations of chaotic terrain material and crater size frequency distributions suggest that the unit continued to form during the Early Hesperian into the Late Hesperian. Chaotic material may have formed by the degradation of older deposits through melting of ground ice or erosion by outflows from Ma'adim Vallis and Durius Valles. Some parts of the chaotic terrain material appear to have formed by the degradation of dissected plains and older parts of other materials (for example, unit $AHbm_1$, see below). Later, in early and possibly middle Amazonian times the degradation of the chaotic terrain material continued as water was discharged from Gusev during the last intervals of ponding.

The oldest channel material (unit Hch) is Hesperian in age and is found in degraded channels throughout the map area. These degraded channels are superposed on older Noachian and Noachian–Hesperian plains (units Npl, $HNpl_1$, and $HNpl_2$). The northern exposure of the oldest channel material occurs in a discontinuous paleodrainage system east of Ma'adim Vallis; this system is oriented in the same northern and northwestern direction as Ma'adim Vallis. In places, the Hesperian channel material is continuous with the modified cratered plains unit ($HNpl_2$) and may represent a contiguous depositional unit extending to the northwest. Locally, the oldest channel material is associated with shallow tributaries of Ma'adim Vallis and Durius Valles. The unit was deposited in drainage channels between separate, shallow basins that are found on the modified cratered plains unit (unit $HNpl_2$; fig. 5).

The channeled mesa material (unit Hchm) is found in association with a western tributary of Durius Valles at 16.4° S., 189° W. In contrast to the oldest channel material (unit Hch), which is associated with shallow linear depressions, channeled mesa material occurs locally in areas of inverted topographic relief dissected into a branchlike system of linear, plateaulike features (mesas) at the head of the Durius Valles tributary (fig. 6). The unit is superposed on the modified cratered plains unit (unit $HNpl_2$). The general morphology of the channeled mesa material (unit Hchm) resembles a dissected sedimentary delta. The mesas may be capped by a veneer of resistant material, such as outwash gravels from a glacial sheet or perhaps lava. After sublimation of the ice, or erosion of less resistant material, the mesa channels were left as positive relief features. Alternatively, the features might have formed as delta deposits on the floor of an ancient lake that were later dissected by headward erosion of small channels.

AMAZONIAN–HESPERIAN SYSTEMS

Old Amazonian–Hesperian channel floor material (unit $AHch_1$) forms upper level terraces in Ma'adim Vallis and Durius Valles. This unit is thought to represent depositional processes within channels that were later modified by mass wasting (fig. 7). Deposition of unit $AHch_1$ is suggested to have been contemporaneous with the deposition of basin material (unit $AHbm_1$, see below) and appears to correlate with the main episodes of flooding from Ma'adim Vallis. Crater size frequencies (fig. 3) indicate a Late Hesperian to Early Amazonian age for combined old and intermediate age channel floor materials (units $AHch_1$ and $AHch_2$, respectively), suggesting they formed contemporaneously with basin materials (units $AHbm_{1-2}$, see below). Amazonian–Hesperian age fluvial deposits of Ma'adim Vallis include old and intermediate channel floor materials and young channel floor material (unit $AHch_3$), which comprise the lower terraces and floor of Ma'adim Vallis, respectively (Cabrol and others, 1997). Durius Valles only contains old and intermediate channel floor materials. The absence of young channel floor material in Durius Valles suggests that the fluvial activity of Ma'adim Vallis lasted longer than Durius Valles and possibly continued into the Early Amazonian.

Basin floor unit 1 (unit $AHbm_1$) forms rough terrain and is found on the eastern third of the Gusev crater floor and as isolated patches in de Vaucouleurs. Generally, the eastern parts of the unit within Gusev are superposed on the oldest, intensely degraded crater material (c_1), whereas the western parts form terraces inside the crater and in the western part of de Vaucouleurs. In all locales, this unit is bordered by erosional cliffs on one side (fig. 8). Outside of Gusev, the unit embays and is superposed on dissected plains material and old cratered plains material (units Hpld and Npl, respectively); it is topographically higher than chaotic terrain material (unit Hcht), young basin floor material (unit $AHbm_2$), and etched plains material (unit Aetpl). Because basin floor unit 1 ($AHbm_1$) formed only within topographically high parts of Gusev and de Vaucouleurs, we consider the unit to consist of deposits formed during an early stage of flood ponding by Ma'adim Vallis and Durius Valles. At this time, the old cratered plains and dissected plains units (between the two basins) were subjected to erosion. Basin floor unit 2 (unit $AHbm_2$) only occurs in de Vaucouleurs and lies at a lower topographic elevation relative to unit 1. Both basin materials (units $AHbm_1$ and $AHbm_2$) are interpreted to be fluvio-lacustrine materials deposited during the final periods of flooding from Durius Valles when intermediate channel floor material (unit $AHch_2$) was formed. Concurrently, erosion within unit $AHbm_2$ formed scattered groups of small low hills. Possible agents of erosion include both glacial and fluvio-lacustrine processes. Massive and hilly deposits with sinuous lobatelike edges (shown by detached lobe pattern) lie within Gusev and are superimposed on unit $AHbm_1$. These deposits are interpreted as debris flows that consist of materials from the inner slopes of the crater rim.

Member 1 of the Gusev Crater Formation (unit $AHgf_1$), interpreted to be fluvio-lacustrine material, covers a large area of the floor of Gusev. This unit persisted into the Early Amazonian and may have formed by ponding in the crater (Goldspiel and Squyres, 1991). This unit is correlative with fluvial activity in Ma'adim Vallis and with the deposition of intermediate channel floor material (unit $AHch_2$). Water may have exited Gusev by one or more paths, including a gap in the north crater rim toward Elysium Planitia and a deep topographic saddle in the west rim of the crater that enters de Vaucouleurs. In both cases, flooding from Gusev (together with flows through Durius Valles) may have been responsible for the deposition of sedimentary deposits in de Vaucouleurs. These materials are represented by basin floor unit 2 (unit $AHbm_2$). The same flooding episode was apparently responsible for continued degradation of chaotic terrain material (unit Hcht).

The final stage of fluvial activity through Ma'adim Vallis occurred in the Late Hesperian to possibly Middle Amazonian and is represented by member 2 of the Gusev Crater Formation (unit $AHgf_2$). This unit forms a smooth, tonguelike lobe with sinuous margins. We infer that the last depositional events in Gusev were water or ice-rich debris flows from the mouth of Ma'adim Vallis.

AMAZONIAN SYSTEM

Amazonian units in the map area are represented by plateau and plains materials (units Aps, Aml_1, Aml_2, Amu, and Ar) and by channel- and basin-floor materials associated with Gusev crater and de Vaucouleurs (Aetpl, Aft, and Achp). Smooth plains material (unit Aps) forms a featureless surface covering the floors of most old craters in the map area. This unit was formed during the Amazonian primar-ily by fluvial, mass-wasting, and aeolian processes (Scott and Chapman, 1995).

Etched plains material (unit Aetpl) covers a low-lying area in the central part of de Vaucouleurs. The unit is interpreted to have formed by fluvial erosion of dissected plains material, chaotic terrain material, and basin floor units (units Hpld, Hcht, and $AHbm_{1-2}$), perhaps accompanied by ground-ice melting from geothermal heating (Squyres and others, 1987) or possibly sapping of water by volcano ground-ice interactions (Allen, 1979, 1980; Mouginis-Mark, 1985, 1990). Similar processes could have produced the fretted terrain material (unit Aft) within de Vaucouleurs found within networks of intersecting, flat floored, and slightly sinuous channels. During the Late Amazonian the channels were mantled by windblown material, which accumulated in places to form dunes resembling mega-ripples (fig. 9).

The youngest channel associated with fluvial plains material (unit Achp) is found in the northwestern part of the map area. We suggest that the water, which deposited etched plains material, fretted terrain material, basin floor units, and member 1 of the Gusev Crater Formation (units Aetpl, Aft, $AHbm_{1-2}$, and $AHgf_1$, respectively), might have percolated through deposits of chaotic material (unit Hcht) and breached the Gusev crater rim, leading to the formation of the fluvial plains (unit Achp). During the Late Amazonian, the surface of the plains was mantled with windblown material similar to that occurring on fretted terrain (unit Aft).

Three units of the Medusae Fossae Formation are found along the highland-lowland boundary northeast of Gusev. Two lithofacies (units Aml_1 and Aml_2) compose the lower member of the Medusae Fossae Formation, and the upper member is represented by unit Amu. These materials have been interpreted to be ash-flow tuff (Scott and Tanaka, 1982), pyroclastic or aeolian material (Greeley and Guest, 1987), or paleopolar deposits (Schultz and Lutz, 1988). The contacts of the units with older plains materials are associated with erosional features such as yardangs, which formed by wind erosion (Ward, 1979). The eroded materials may have accumulated as dune fields near the edge of lithofacies 2 of the Medusae Fossae Formation (unit Aml_2) and covered parts of member 1 of the Gusev Crater Formation ($AHgf_1$). Ridged material (unit Ar), the youngest unit in the map area, forms local aeolian dunes that are deposited on member 1 of the Gusev Crater Formation in the northeastern part of the map area.

GEOLOGIC SUMMARY

Early and Middle Noachian—Formation, modification, and degradation of the heavily cratered materials that form much of the highland plateau along the transition zone between the highlands and lowlands; fluvial dissection of the cratered unit by ground-water sapping with runoff (perhaps induced by ice-magmatic interaction); widespread flooding from source areas south of the map area, prior to the formation of Ma'adim Vallis.

Late Noachian—Fluvial sedimentation on inter-crater plains of the highland plateau during episodes of flooding from the precursor to Ma'adim Vallis. This flooding was responsible for the formation of the oldest fluvio-lacustrine sediments in Gusev crater and de Vaucouleurs. At this time, water derived from small valley networks on the eastern and southern crater rims may have ponded within Gusev.

Early Hesperian—Eruptions of Apollinaris Patera emplaced pyroclastic deposits and lava flows north and northwest of Gusev; canyons of Ma'adim Vallis and Durius Valles were carved; local flooding from the highland plains may have resulted in episodic ponding of the lower reaches of Ma'adim Vallis as a result of superposed impact craters; development of a discontinuous drainage system within the plateau plains and tributaries of Ma'adim Vallis and Durius Valles; origin of older deltaic deposits in the lower reaches of Durius Valles; continued fluvio-lacustrine sedimentation within Gusev and de Vaucouleurs from drainages on the bordering highland plains; fluvial erosion of the pyroclastic deposits from Apollinaris Patera and formation of chaotic material within de Vaucouleurs.

Late Hesperian—Continued fluvial modification of volcanic deposits from Apollinaris Patera and development of upper level terraces of Ma'adim Vallis and Durius Valles; continuous deposition of fluvio-lacustrine sediments within Gusev and de Vaucouleurs; continued development of chaotic terrain within the crater basin; filling of older impact craters in the highland plateau by fluvial and mass-wasting processes.

Early Amazonian—Continued fluvio-lacustrine sedimentation within Gusev and de Vaucouleurs to the west related to flooding of Ma'adim Vallis and Durius Valles; continued erosion of chaotic material within de Vaucouleurs; formation of lower level terrace within Ma'adim Vallis and floor deposits within Durius Valles; beginning of the final episode of fluvio-lacustrine sedimentation within Gusev and de Vaucouleurs, accompanied by glaciation; dissection of de Vaucouleurs by melting of ground ice (thermokarst processes) and ground water sapping; water erosion and fretting processes within de Vaucouleurs; formation of local debris flows within Gusev and on the highland plains; initial deposition of Medusae Fossae Formation northeast of Gusev.

Middle and Late Amazonian—Continued deposition of Medusae Fossae Formation and subsequent erosion by wind; end of fluvial activity in Ma'adim Vallis and fluvio-lacustrine sedimentation within Gusev; continued fluvial resurfacing in the northern part of de Vaucouleurs; extensive aeolian (erosion and deposition) activity within Gusev and surrounding areas; mantling of old crater floors by veneers of aeolian material.

EXOBIOLOGICAL IMPORTANCE OF THE GUSEV STUDY

Major goals of exobiology in Mars exploration are to (1) determine whether a biosphere presently exists on Mars or has existed at some time in the past; (2) define the nature of early martian environments, especially those regarded as favorable for the origin and subsequent development of life; and (3) understand the geochemistry of the biogenic elements (C, N, O, S, and P) and organic compounds. These goals require a broad-based approach to Mars exploration and interface naturally with the goals of other planetary science disciplines aimed at understanding martian crustal evolution, climate, and volatile history.

Water is regarded as a fundamental requirement for the origin and continued existence of life. Thus, the question of the history of liquid water on Mars and the duration of hydrological systems is a fundamental goal in exploring for evidence of a past or present martian biosphere. Substantial geological and climatological evidence exists to support the presence of abundant water on the martian surface early in its history (Carr, 1995 and references therein). If life originated on Mars and persisted for a time within surface environments, it is likely to have left behind a fossil record. On Earth, the record of past microbial life tends to be preserved in a comparatively small number of geological environments that share in common rapid rates of deposition that produce low permeability host rocks of stable mineralogy (Farmer and Des Marais, 1994; Farmer, 1995a, b). The most favorable host rocks for long-term preservation are fine-grained, clay-rich sediments and chemical precipitates formed in aqueous environments. In this context, the most important targets for Mars include lacustrine shale, marls, or water-lain ash deposits, evaporates (inclusive of carbonates), and hydrothermal deposits, including those formed in subaerial environments (thermal springs) and shallow subsurface (epithermal) environments below the upper temperature limit for life (+120 °C for terrestrial life).

The early pre-biotic steps in evolution that eventually led to life on Earth have been lost on our planet due to extensive crustal recycling, weathering, and erosion. But Mars lacks a plate tectonic cycle, and the hydrological cycle involving liquid water appears to have been arrested there very early. The age of martian meteorite ALH84001 (>4.5 Ga) suggests that the crust of the ancient, heavily cratered highlands of Mars is likely to extend back to the very earliest periods of planetary evolution (McKay and others, 1996). So even if life did not develop on Mars, the prebiotic chemistry that developed on the early Earthlike surface of Mars may provide fundamentally important insights in the origin of life on our own planet (Farmer and Des Marais, 1994). The same kinds of deposits that are the best for preserving a fossil record are also the best for preserving a record of prebiotic chemistry. These ancient rock sequences are likely to contain important information about the biogenic elements that were present on Mars early in its history, while providing information about the surface environments that prevailed and other factors that determine the assembly of simple organic compounds into complex forms required for life.

Site selection is regarded as critical for implementing a strategy to explore for evidence of martian life or prebiotic chemistry. Specifically, we must discover the locations of surficial deposits that were formed in the aqueous sedimentary environments identified above, those that have the properties favorable for the long-term preservation of biosignatures or prebiotic chemistry. A site selection effort for Mars Exopaleontology was initiated in 1994 using Viking data (Farmer and others, 1994). This research resulted in the identification of 25 landing sites of exopaleontological interest (see Greeley and Thomas, 1994). One of the highest priority sites identified in that study was the Gusev crater–Ma'adim Vallis system in the Aeolis region. This site was subsequently targeted for more detailed regional studies to further assess the potential as a site for future missions to explore for past life (Landheim, 1995; Landheim and others, 1994; Cabrol and others, 1994, 1997). Important exobiological questions that have provided a focus for these regional studies include the duration of hydrological systems in the area and the range of depositional environments favorable for capturing and preserving a record of past life or prebiotic chemistry.

Some conclusions regarding the exobiological potential of the mapped area include the following: Our geologic interpretations suggest that Gusev crater is one of the few large basins on Mars that had a prolonged, but episodic, hydrological history, beginning in the Early Noachian and lasting into the Middle Amazonian. During the periods of fluvio-lacustrine deposition, conditions were probably favorable for life within surface environments. The most widespread environments for life probably included lakes and streams, or their ice-covered equivalents. In the absence of compositional data, it is difficult to assess the possibilities for hydrothermal mineralization processes associated with impact craters, chemical sedimentation (evaporates, spring deposits, and so on) within basins, or the precipitation of sedimentary cements which, based on Earth analogs, would be of primary importance in capturing and preserving a microbial fossil record. However, on the basis of present evidence, fine-grained detrital sediments probably were deposited in distal deltaic environments and on the deeper parts of basin floors during periods of inferred fluvial-lacustrine sedimentation. Such fine-grained deposits are likewise regarded as favorable targets in the exploration for a fossil record, and in particular where they have been well-cemented. The distribution of finer grained detrital sediments can be predicted to some extent by the overall facies interpretations and geologic relations implied by our interpretations, and with higher resolution data obtained during future orbital missions, such depositional models may serve as a framework for testing our hypotheses. However, an important key for constraining interpretations and for identifying the best sites to explore for a fossil record is mineralogy. Therefore, it is important that Gusev crater be given priority as a target for high spatial resolution photography and compositional mapping on future orbital missions.

REFERENCES CITED

Allen, C.C., 1979, Volcano-ice interactions on Mars: Journal of Geophysical Research, v. 84, p. 8048–8059.

———1980, Volcano-ice interactions on Earth and Mars: NASA Technical Memorandum 81979, p. 163–264.

Brakenridge, G.H., Newson, H.E., and Baker, V.R., 1985, Ancient hot springs on Mars—Origins and paleoenvironmental significance of small martian valleys: Geology, v. 13, p. 859–862.

Cabrol, N.A., Landheim, R., Greeley, Ronald, and Farmer, J.D., 1994, Fluvial processes in Ma'adim Vallis and the potential of Gusev crater as a high priority exobiology site [abs.], *in* Abstracts of papers submitted to the Twenty-fifth Lunar and Planetary Science Conference, Houston, March 14–18, 1994: Houston, Lunar and Planetary Institute, p. 213–214.

Cabrol, N.A., Landheim, Ragnhild, and Grin, E.A., 1997, Ma'adim Vallis paleocourses [abs.], *in* Abstracts of paper submitted to the Twenty-eighth Lunar and Planetary Science Conference, Houston, March 17–21, 1997: Houston, Lunar and Planetary Institute, p. 195–196.

Cabrol, N.A., Grin, E.A., Landheim, Ragnhild, Kuzmin, R.O., and Greeley, Ronald, 1998, Duration of the Ma'adim Vallis/Gusev crater hydrogeologic system, Mars: Icarus, v. 133, no. 1, p. 98–108.

Carr, M.H., 1995, The martian drainage system and the origin of networks and fretted channels: Journal of Geophysical Research, v. 100, p. 7479–7507.

Farmer, J.D., 1995a, Mars exopaleontology: Palaios, v. 10, no. 3, p. 197–198.

——— 1995b, Site selection, *in* An Exobiological Strategy for Mars Exploration: NASA Special Publication 530, p. 42–50.

Farmer, J.D., and Des Marais, D.J., 1994, Exopaleontology and the search for a fossil record on Mars, *in* Abstracts of papers submitted to the Twenty-fifth Lunar and Planetary Science Conference, Houston, March 14–18, 1994: Houston, Lunar and Planetary Institute, p. 367–368.

Farmer, J.D., Des Marais, D.J., and Klein, H., 1994, Mars site selection for exobiology—Criteria and methodology, *in* Greeley, Ronald, and Thomas, P.E. (eds.), Mars landing site catalog (2nd ed.): NASA Reference Publication 1238, p. 11–16.

Goldspiel, J.M., and Squyres, S.S., 1991, Ancient aqueous sedimentation on Mars: Icarus, v. 89, p. 392–410.

Greeley, Ronald, and Guest, J.E., 1987, Geologic map of the eastern equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1802–B, scale 1:15,000,000.

Greeley, Ronald, and Thomas, P.E. [eds.], 1994, Mars Landing Site Catalog (2nd ed.): NASA Reference Publication 1238, 392 p.

Gulick, V.C., 1995, Low-temperature hydrothermal system on Mars [abs.], *in* Abstracts presented at the 27th Annual Meeting of the Division for Planetary Sciences, Kona, HI, October 9–13, 1995: Bulletin of the American Astronomical Society, v. 27, no. 3, p. 37.

Kuzmin, R.O., Greeley, Ronald, Landheim, Ragnhild, and Cabrol, N.A., 1997, Geologic mapping of Gusev crater–Ma'adim Vallis region, Mars [abs.], *in* Abstracts of papers submitted to the Twenty-eighth Lunar and Planetary Science Conference, Houston, March 17–21, 1997: Houston, Lunar and Planetary Institute, p. 779–780.

Landheim, Ragnhild, 1995, Exobiology sites for Mars exploration and geologic mapping of Gusev crater–Ma'adim Vallis: M.S. thesis, Tempe, Arizona State University, 167 p.

Landheim, Ragnhild, Cabrol, N.A., Greeley, Ronald, and Farmer, J.D., 1994, Stratigraphic assessment of Gusev crater as an exobiology landing site [abs.], *in* Abstracts of papers submitted to the Twenty-fifth Lunar and Planetary Science Conference, Houston, March 14–18, 1994: Houston, Lunar and Planetary Institute, p. 769–770.

McKay, D.S., Gibson, E.K., Thomas-Keprta, K.L., Vali, H., Romanek, C.S., Clemett, S.J., Chillier, X.D.F., Maechling, C.R., and Zare, R.N., 1996, Search for past life on Mars—Possible relic biogenic activity in martian meteorite ALH84001: Science, v. 273, p. 924–930.

Mouginis-Mark, P.J., 1985, Volcano/ground ice interactions in Elysium Planitia, Mars, Icarus, v. 64, p. 265–284.

———1990, Recent water release in the Tharsis region of Mars: Icarus, v. 84, p. 362–373.

Robinson, M.S., Mouginis-Mark, P.J., Zimbelman, J.R., Wu, S.S.C., Ablin, K.K., and Howington-Kraus, A.E., 1993, Chronology, eruption duration, and atmospheric contribution of the martian volcano Apollinaris Patera: Icarus, v. 104, p. 301–323.

Schultz, P.H., and Lutz, A.B., 1988, Polar wandering of Mars: Icarus, v. 73, p. 91–141.

Schultz, P.H., Schultz, R.A., and Rogers, R., 1982, The structure and evolution of ancient impact basins on Mars: Journal of Geophysical Research, v. 87, p. 9803–9820.

Schultz, R.A., and Frey, H.V., 1990, A new survey of multiring impact basins on Mars: Journal of Geophysical Research, v. 95, p. 14,175–14,189.

Scott, D.H., and Carr, M.H., 1978, Geologic map of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1083, scale 1: 25,000,000.

Scott, D.H., and Chapman, M.G., 1995, Geologic and topographic maps of the Elysium paleolake basin, Mars: U.S. Geological Survey Miscel-

laneous Investigations Series Map I–2397, scale 1:5,000,000.
Scott, D.H., Dohm, J.M., and Applebee, D.J., 1993, Geologic map of Science Study Area 8, Apollinaris Patera region of Mars (special MTM –10186 quadrangle): U.S. Geologic Survey Miscellaneous Investigations Series Map I–2235, scale 1:500,000.
Scott, D.H., Morris, E.C., and West, M.N., 1978, Geologic map of the Aeolis quadrangle of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1111, scale 1:5,000,000.
Scott, D.H., and Tanaka, K.L., 1982, Ignimbrites of the Amazonian Planitia region on Mars: Journal of Geophysical Research, v. 87, p. 1178–1190.
———1986, Geologic map of the western equatorial region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–1802–A, scale 1:15,000,000.
Squyres, S.W., Wilhelms, D.E., and Moosman, A.C., 1987, Large-scale volcano-ground ice interactions on Mars: Icarus, v. 70, p. 385–408.
Tanaka, K.L., 1986, The stratigraphy of Mars, *in* Proceedings of the Seventeen Lunar and Planetary Science Conference, Houston, March 17–21, 1986: Journal of Geophysical Research, v. 91, p. E139–E158.
U.S. Geological Survey, 1991a, Topographic map of the Aeolis northeast quadrangle (MC–23 NE) of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2118, scale 1: 2,000,000.
———1991b, Topographic map of the Aeolis southeast quadrangle (MC–23 SE) of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2119, scale 1:2,000,000.
———1992a, Controlled photomosaic of the MTM –15182 quadrangle, Ma'adim Vallis region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2256, scale 1:500,000.
——— 1992b, Controlled photomosaic of the MTM –15187 quadrangle, Ma'adim Vallis Region of Mars: U.S. Geological Survey Miscellaneous Investigations Series Map I–2257, scale 1:500,000.
Ward, A.W., 1979, Yardangs on Mars—Evidence of recent wind erosion: Journal of Geophysical Research, v. 84, p. 8147–8166.
Wilhelms, D.E., 1990, Geologic mapping, *in* Greeley, Ronald, and Batson, R.M. [eds.], Planetary mapping: Cambridge, U.K., Cambridge University Press, p. 208–260.