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A case for ancient evaporite basins on Mars

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Abstract. Observations indicate that a Martian analog to the Earth's salt pans and saline lakes of arid regions may have existed in crater-basins during Mars' early (Noachian) epoch. Terraced and channelized crater-basins point to ponding of surface water as well as possible prolonged and evolving base levels. In addition, supportive (evaporite basin) analogs are offered for three other morphologic features of Martian crater-basins. An evaporite basin model for crater-basins on Mars has major implications for the mechanical, chemical, and even biological processes that potentially have operated in Mars' past, and represent a spectrum of potential mineral resources.

Introduction

There is irrefutable evidence for the presence of water ice on Mars. While the surface pressure of the Martian atmosphere is only 0.6% that of Earth, it contains a precipitable 15 μm (in a global layer) of water vapor [*Farmer et al.*, 1977]. The polar deposits today are estimated to include 2 x 10^6 km^3 of water ice [*Carr*, 1986], and variable lines of evidence suggest the presence of ice-rich frozen ground at middle to high latitudes [*Fanale*, 1976; *Squyres*, 1989]. In addition to the possibility of near-surface ground ice today, there is a growing body of work that supports an active role for water in the shaping of Martian landforms during its past epochs [*Squyres*, 1989]. However, since present atmospheric conditions preclude the surface stability of either liquid water at all latitudes or ice at low latitudes, there have emerged two general points of view in attempts to explain the origin of fluvial and other water-related landforms.

One set of interpretations attempts to minimize the need for dramatically different climatic conditions than those found today. The ancient valley networks, documented to exist within the highlands of Mars' southern hemisphere, are seen as most likely related to sapping from groundwater systems [*Pieri*, 1980]. Erosional features in the old southern highlands are typically much too small to be dated accurately by impact crater density, but there is no evidence to suggest that the erosion in the highlands greatly postdates the formation of the cratered terrain during the Noachian epoch on Mars [*Tanaka*, 1986]. The major outflow channels fringing the boundary between the southern hemisphere's highlands and the lowlands of the northern hemisphere can be related to catastrophic flooding [*Baker and Milton*, 1974; *Baker*, 1982] of water possibly released over a prolonged period of time from permafrost-confined groundwater systems [*Carr*, 1979], and surface water lakes, if they existed, were potentially coated with thick layers of ice [*Nedell et al.*, 1987]. Common to these models is the existence of an early Martian geologic epoch with ground water sources (of uncertain origin) that over time have become inactive in low-latitude areas.

From a contrasting perspective, other interpretations require past atmospheric conditions to vary dramatically from those of today, and potentially include the stability of water and ice to equatorial latitudes [*Masursky et al.*, 1977; *Pollack et al.*, 1987; *Baker et al.*, 1991; *Parker et al.*, 1993]. These views which generally beg warmer and wetter climatic models explicitly (or implicitly) invoke mechanisms for recharge directly to the Martian surface, and imply a complex hydrologic cycle once operated on Mars. Ancient valley networks, particularly the degraded ones, are interpreted as runoff channels requiring maintenance of high water tables [*Baker and Partridge*, 1986; Brackenridge, 1990], the outflow channels are visualized as potentially debouching into ancient seas or oceans [*Gulick and Baker*, 1990] and an active hydrologic cycle is seen to potentially persist well beyond Mars' earliest (Noachian) epoch.

Here new observations and arguments are presented, based on morphologic comparisons of Martian crater-basins to terrestrial drainage basins in arid and semiarid areas, and used to advance further the hypothesis for a complex hydrologic cycle in Mars' past that may have included open hydraulic conditions between surface water and groundwater and mechanisms for recharging these reservoirs.

A Case for Base Level and Groundwater-Controlled Drainage on Mars

In the absence of recharge to an unconfined groundwater system, the upper surface of groundwater (i.e., the water table) relaxes to a global minimum equipotential surface, which on Earth is approximated as mean sea level [*Freeze and Cherry*, 1979]. However, the hydrologic processes of precipitation, infiltration, and base flow permit on Earth a dynamic equilibrium between surface topography and the underlying water table. The equilibrium is established by the manner in which the minimum potential of hydraulic head (sea level) is also the base level, below which fluvial erosion cannot occur [*Bloom*, 1978], and inversely, the manner in which local streams, which are responsible for eroding and shaping topography, limit the rise of the water table during recharge periods. On a more regional

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level, the same boundary conditions are applicable to internally drained depressions [*Bloom*, 1978] ,wherein a local base level for fluvial erosion is represented by the corresponding minimum of the water table within the basin.

Partially because of the role of groundwater in determining base levels, streams undergo systematic changes in their channel morphologies from headwater ephemeral regimes (generally without significant floodplains) to base level perennial regimes (with lower gradients and floodplains) [*Leopold et al.*, 1964]. In the latter, periods of climatic and watershed stability (e.g., tectonic quiescence) permit streams to be "graded" or in a state of quasi-equilibrium [*Davis*, 1902; *Mackin*, 1948; *Strahler*, 1952], and it is common during these periods of stability for processes responsible for the lateral migration of channels to be more efficient than the processes of downcutting. The result is the formation of floodplains. Floodplains formed in this fashion, after being subjected to a period of downcutting, are left as terraces or benches along the margins of the valley. Alternative (i.e., nonterrestroid) mechanisms for the formation of fluvial valley terraces on Mars remain possible, perhaps (hypothetically speaking) related in some fashion to changing discharges over an ice-rich permafrost. However, if the ancient valley networks of Mars' southern highlands were produced by fluvial erosion occurring under Earthlike conditions, then similar constraints and conditions can be postulated. One condition of such an analog is that Martian drainage systems would also represent an equilibrium between surface and groundwater systems. The important point being an Earthlike hydraulic coupling between ground water and surface water systems in Mars' past is a plausible hypothesis if geomorphic evidence exists for fluvial drainage under steady base level conditions. Below we describe one ancient Mars drainage basin for which there is evidence in support of fluvial and lacustrine erosion under base level conditions that was sufficiently long-lived in nature to produce what are here interpreted as fluvial and lacustrine terraces.

The middle latitude to equatorial region of the southern highlands has been one of the primary areas from which evidence has emerged for Noachian fluvial erosion [e.g., *Baker and Partridge*, 1986; *Pieri*, 1980] and extensive resurfacing [*Jones*, 1974; *Chapman and Jones*, 1977; *Craddock and Maxwell*, 1990, 1993]. Within the Memnonia Northwest quadrangle a segment of a north trending early drainage system, located approximately 200 km south of the highlands/lowlands boundary at 174.6°W, 14.6°S, has been preserved that contains both fluvial and lacustrine features that are interpreted here on geomorphic grounds to support the existence of base level-controlled fluvial

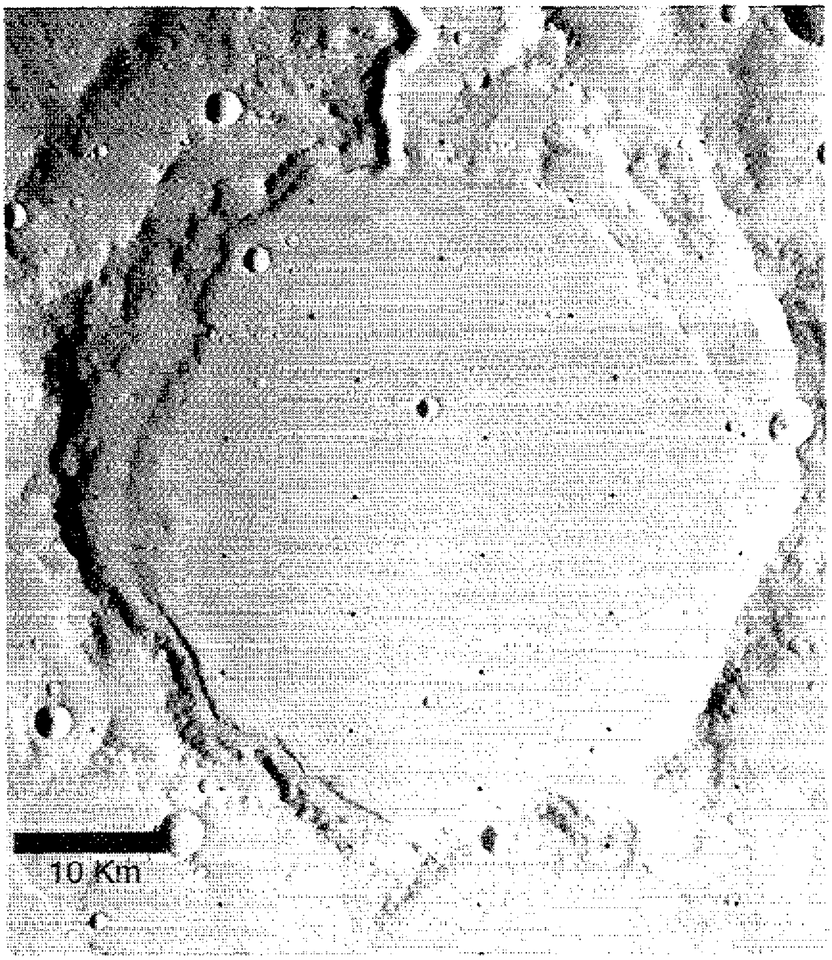

Figure 1a. A terraced crater-basin south of Mars' dichotomy boundary with both an inflowing (lower right) and outflowing (top center) channel. Note the trace of the main terrace up the inflow channel, and the lower level of the outflow channel. Scale bar is 10 km. (Viking Orbiter frame 438S12, centered at 174.6°W, 14.6°S).

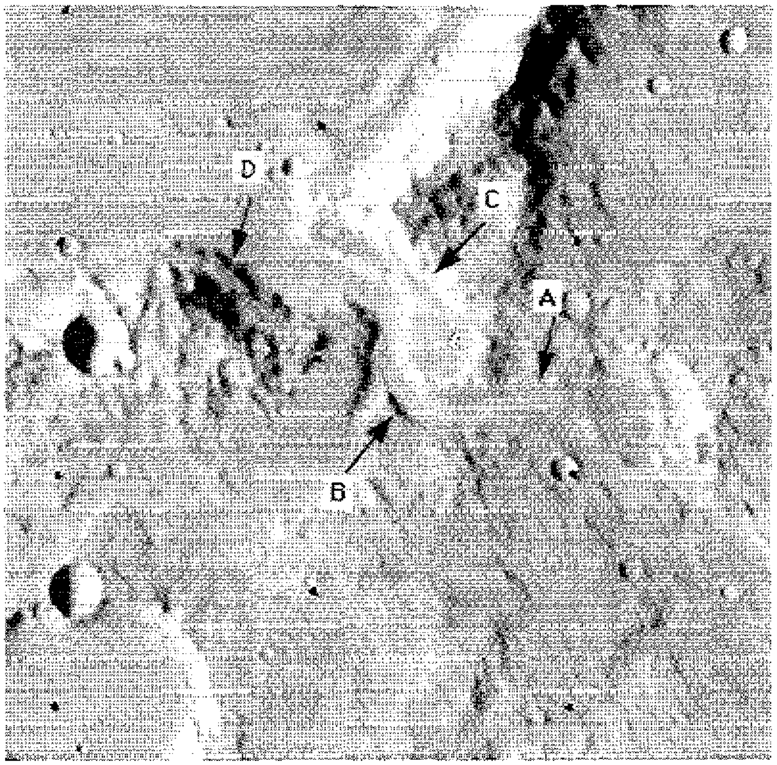

Figure 1b. Closeup of the area of terrace development in the inflowing channel (Viking Orbiter frame 437S15). Localities A - D mark areas near meanders with differential terrace development (see text).

and lacustrine systems. The main fluvial channel can be seen to drain into, and away from, a crater basin. Moderate resolution (63 m/pixel) Viking images of this basin (Figure 1a) shows it to have a polygonal ground plan with an average diameter of approximately 35 km, and a crater rim that, from shadow length measurements, is estimated to rise 0.7 to 1 km above the floor. A prominent terrace or bench, at a height of 200-220 m above the basin floor, is traceable around the entire basin, and extends up into the inflowing channel (Figures 1a and 1b). In addition, an upper smaller bench is traceable just above the main terrace, and two additional, but poorly preserved, erosional benches may exist along the lower slopes (Figure 1c).

The origins of these terraces are of paramount importance to the interpretation that this channel and basin represent a base level-controlled drainage system akin to terrestrial watersheds. There are two questions related to potential ambiguities to be addressed: (1) Are, in fact, the benches of fluvial and lacustrine origin such that their elevations can be interpreted as former channel floodplain levels, and lake stands, respectively; and (2) does the existence and the levels of the postulated lake benches reflect stands of water controlled by a regional groundwater table? These two questions are addressed separately below.

Erosional benches or terraces can only be produced by two sets of alternative mechanisms. Either the terraces represent levels of lithologic differences within the Martian crust that have, in turn, controlled erosion by whatever means (e.g. eolian, mass wasting, or fluvial), or they have been formed by a water-related mechanism [*Bloom*, 1978]. Fluvial terraces within river valleys can be either degradational (strath terrace) or aggradational (fill terrace) but, irregardless, represent uplifted or undercut floodplains [*Leopold et al.*, 1964].

If the terraces seen in Figure 1 are due to nonfluvial or nonlacustrine processes, then these processes should also operate in surrounding areas free from possible fluvial or lacustrine influences. *Craddock and Maxwell* [1993] have demonstrated that pervasive resurfacing has occurred within a marginal (equatorial) province of the highlands, affecting the Martian crust to a depth of 290 to 2300 m. Yet, despite the evidence for extensive erosion, terraces in the Memnonia NW quadrangle (Figure 1) are restricted exclusively to fluvial valleys and degraded crater basins.

A fluvial or lacustrine origin for the terraces seen in Figure 1 is also supported by three specific attributes of the terraces, which would not be easily explained under other mechanisms. First, the main terrace, which can be traced into, and around, the crater basin, ends abruptly at the outlet, despite the continuing relief along the walls of the valley (Figure 1d, location A). A fluvial or lacustrine origin for the terraces explains this asymmetry, since graded fluvial systems are expected to develop preferentially upstream from a base level. Also note that the outlet channel, which is deeply incised at the outlet, opens up to a broad valley floor (i.e., flood plain) at point B (Figure 1d); again a relationship consistent with the existence of local base level influences. Second, if a river terrace represents a former flood plain, then its width should vary in a consistent manner with its precursory flood plain. The latter would broaden as the channel approaches the local base level. Figure 1b shows a closeup of the inflowing channel. In this image one can see that both the channel floor and terrace levels become systematically narrower upstream. Third, the relationships of the valley terrace to channel meanders suggests that they were formed early on in the development of the valley. At locality B (Figure 1b) one can see that the terrace

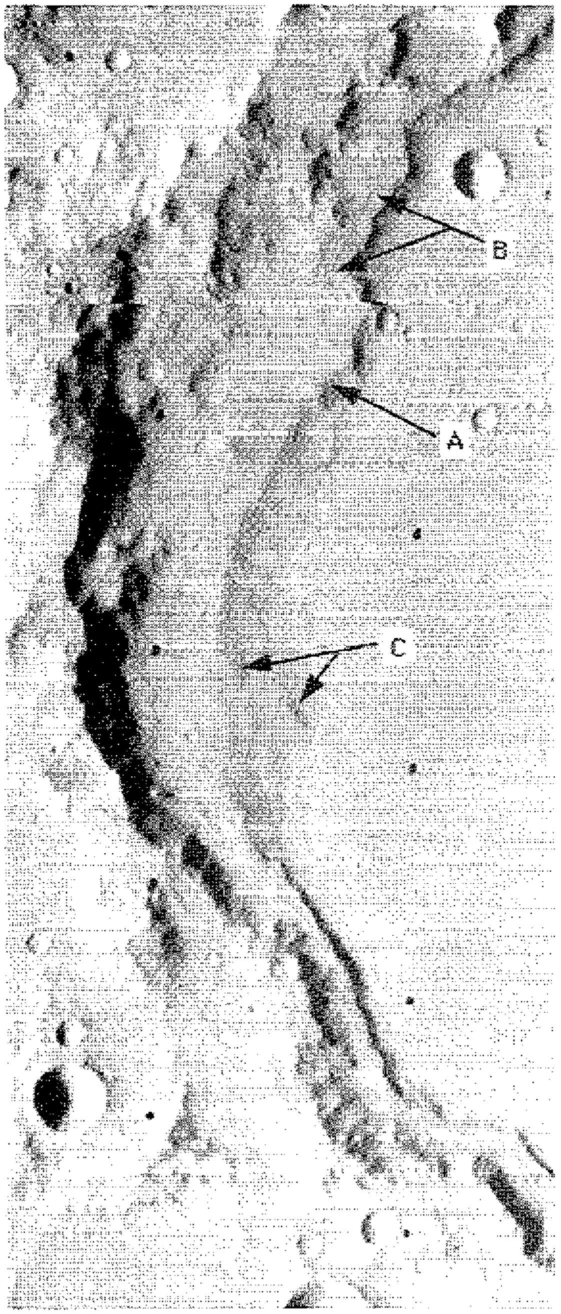

Figure 1c. Closeup of the area of terrace development along the west margins of the basin (Viking Orbiter frame 438S12). Locality A is the uppermost terrace; locality (B) the main terrace, and (C) two other possible lower benches.

does not exist on the outside margin of the meander. Similarly at the next meander, locality C (Figure 1b), the terrace is narrower than it is upstream or downstream. These relationships are expected among river terraces which are incised by later river downcutting. Thus, the terraces described within this system have a number of specific attributes which support a fluvial and lucustrine origin.

The second concern is the possibility that, rather than having an erosional base level defined by a local groundwater depression, it may have been controlled by the existence of a hypothetically impermeable permafrost layer, as envisaged by *Clifford* [1993]. This possibility cannot be ruled out with existing data. However, there are three reasons that support the former hypothesis as being the more plausible alternative in the Memnonia region. There is little doubt that a permafrost zone has existed on Mars, given the abundance and distribution of presumed ice-related geomorphic features [e.g., *Squyres and Carr*, 1986; *Squyres*, 1989] and the estimates of current and past stability of ground ice [*Leighton and Murray*, 1966; *Farmer and Doms*, 1979; *Fanale et al.*, 1986; *Pollack et al.*, 1987b, 1990; *Mellon and Jakosky*, 1993]. However, the hypothesis that a thick permafrost zone could have perched Noachian drainage systems such as the one described above is potentially problematic on three grounds.

First, if permafrost did indeed exist within the southern highlands during the creation of the valley networks, then one should be able to identify features characteristic of geomorphic processes operating in regions with ground ice. As noted above, Mars preserves many geomorphic features in its current polar and midlatitude regions that are interpreted to be related to ground ice (e.g., "terrane softening" of *Squyres and Carr* [1986]). However, ice-free alternatives do exist for some of these geomorphic features [*Zimbelman et al.*, 1989]. The preservation of fluvial features throughout much of the highlands indicates that a sufficient record of past surface processes is available. As pointed out by *Craddock and Maxwell* [1993], the only potential evidence for ice-related processes in the equatorial area are postcrater degradation features (interpreted to be glacial in origin) suggested to be present in some of the more elevated regions by *Baker et al.* [1991] and *Kargel et al.* [1992]. Rampart craters have been cited as possible indicators of subsurface volatiles on Mars, and these craters are present at all latitudes (see *Squyres et al.* [1992] for a detailed discussion). The precise role of volatiles in the rampart crater formation process remains ambiguous [*Squyres et al.*, 1992], but the equatorial rampart craters have been interpreted to indicate that water or ice is present in the subsurface, although at a much greater depth than at midlatitudes [Kuzmin et al., 1988].

Second, while the permafrost zone is commonly described as impermeable, no where on Earth has it been demonstrated that it operates as a pure aquifuge [*Freeze and Cherry*, 1979; *Williams* 1970; *Williams and Smith*, 1989]. While the hydrogeologic literature for permafrost has presented the permafrost zone as impermeable when considering water budgets on timescales pertinent to our understanding of water resources [e.g., *Williams*, 1970], estimates in the laboratory, as well as from field studies, indicate that it is best characterized as an aquitard, or aquiclude, of very low hydraulic conductivity on geologic timescales [*Williams and Smith*, 1989]. The 45 - 50° K difference in the mean annual surface temperatures between the coldest permafrost regions on Earth (-5° to 10°C) and the warmest (equatorial) latitudes on Mars (approximately -55°C) suggest that the hydraulic conductivities of permafrost on Mars under ice-rich conditions would be somewhat lower than that observed for terrestrial conditions. However, the in situ large-scale transmissivities of hydrogeologic units are influenced by both diffuse and nondiffuse flow. Laboratory measurements of the hydraulic conductivity of ice-rich permafrost speak to only the former component.

Third, when surface water persists over permafrost it will have a dramatic affect on the underlying permafrost, producing an extensive zone of thawing both at the top and base of the permafrost zone [*Lauchenbruch*, 1957]. While thermal modelling of these effects for Martian conditions is beyond the scope of this

Figure 1d. Closeup of the outflowing channel where no terrace has been developed (location A), and the incised channel opens up downstream to a floodplain (location B) (Viking Orbiter frames 438S11,-12 and -13).

paper, it should be noted that even within the continuous permafrost regime of Alaska (with permafrost thicknesses of several hundred meters), permafrost is either very deep or absent under lakes and large rivers [*Hopkins et al.*, 1955]. Along the latter there are also frequent, but sporadic, areas of groundwater discharge that produce characteristic "aufeis" or icings [*Williams*, 1970] that may reflect the development of nondiffuse flow conditions within the underlying or surrounding permafrost. The colder mean annual surface temperatures on Mars again could have a mitigating effect on comparisons drawn here to terrestrial permafrost regions. Thus, while the case for a permafrost-controlled base level within the drainage basin described above cannot be unequivocally ruled out, it faces a significant number of challenges to proceed with the case for an interacting groundwater and suface water drainage system in the Memnonia region. Here we prefer to leave the valley network drainage systems in direct contact with a Martian regolith, for which porosity estimates at the surface range from 20 to 50% [*Clifford*, 1993], and permeability estimates range from 10 to 103 darcies [*Carr*, 1979; *MacKinnon and Tanaka*, 1989; *Squyres et al.*, 1992]. Under these conditions a hydraulic connection should exist between surface and ground water systems. In summary, our preferred explanation for the terraces along the drainage system is that they represent erosional base level changes over time associated with a warmer, wetter, early climate, begging a terrestrial watershed analog for such a Martian drainage system.

Morphologic Features of Crater Basins Consistent With Terrestrial Evaporite Basins

The basin described above is not an isolated occurrence; many other basins exist in the southern highlands near the equatorial boundary that may also have been part of comparable surface drainage systems. Some of these have both inflow and outflow channels (e.g. that described above); others have inflow and no outflow channel [*Grant and Schultz*, 1993, figures 8 and 11] and still others have terraces with neither obvious stream inflow or outflow [Figure 2]. In the latter case, water inputs could be purely by base flow, and losses by evaporation and/or sublimation. These conditions are very common in the Atacama desert salars (discussed below). Given that one accepts the arguments presented above for a fluvial or lacustrine interpretation of these terraces, a steady base level must have operated for some significant geomorphic time period for these terraces to form. To maintain these base levels, in the face of either periodic or steady inputs, requires commensurate outputs, either through baseflow or evaporation (or sublimation), to balance the water budget (i.e. conserve mass). But as argued above, maintenance of a base level given the probable hydrogeologic characteristics of the highlands' regolith is problematic without that base level also being the water table. Given that the terraces exist in topographic depressions, groundwater could have provided seepage to these basins, leaving evaporative or sublimative losses as the most likely means of balancing the water exchanges (implied by the geomorphic features). Losses to the atmosphere by evaporation (or perhaps sublimation) within closed basins necessarily leads to saline conditions [*Papke*, 1986; *Stoertz and Eriksen*, 1974]. Thus, many of these crater basins may be akin to the salt flats of the western United States in that their deposits could record a history of progressive desiccation from saline lake to salt pan conditions in time [*Papke*, 1986]. An additional consideration that may influence lake or groundwater salinities under Martian conditions is the exclusion of solutes through freezing.

Figure 2. Crater with a prominent internal terrace and no apparent inflow or outflow channel. Scale bar is 5 km. (Viking Orbiter frame 436S15, centered at 176.5°W, 16.0°S).

In addition to terraced crater-basins, all basins of the highlands with depths beneath a local base level would, like terrestrial basins of arid and semiarid areas, accumulate admixtures of wind, stream sediment, colluvium, and evaporites. On Earth these basins are strongly zoned, with evaporite/loess cores, and marginal facies dominated by salt-cemented clastic units [*Papke*, 1986; *Stoertz and Ericksen*, 1974]. Sharp contrasts in albedo are commonly found at the basin margins, where the albedos of salts or wetted salts stand in sharp contrast to that of the clastic materials composing the fringing alluvial or colluvial fans, bahadas, and piedmonts (Figure 3). Several basins on Mars exhibit a narrow curvilinear marginal fringe zonation involving linear zones with higher and/or lower relative albedos than that observed in upland or central basin floor areas (Figure 4). This suggests the presence of a very narrow basin margin deposit with unique spectral characteristics (e.g., mineralogy; see Table 1). Their analogs on Earth (e.g., Death Valley, Mohave Desert, Salar de Atacama, Atacama Desert) typically mark the location of groundwater seepage and/or paleoshorelines.

A further distinctive feature of Salares (salt pans) in the Chilean parts of the Atacama Desert are marginal salt fingers or channels, developed leeward of marginal seeps or springs toward the prevailing wind direction. Winds passing across the marginal zone, where fresh salt is often found, become charged with salt-laden aerosols and etch linear trails in the prevailing wind direction across the salares (Figure 3 and 5). One Martian crater-basin located at 167.15° longitude, -10.26° latitude, in the Memnonia northwest quadrangle exhibits long and narrow high albedo tracks extending into the basin floor deposit (Figure 5). The features appear morphologically distinct from the array of Martian wind features previously described within craters [*Ward*, 1979; *Peterfreund*, 1981], and have aspect ratios much greater than typical Martian slide features. These linear tracks are good candidates for salt fingers.

A Martian analog to terrestrial salares or sebkhas would predict that crater-basins within the Martian highlands that sat at levels near the regional base level would have filled with admixtures of evaporite, eolian, alluvial, and colluvial materials. Two Martian inselbergs formed of partially exhumed crater-basin deposits exist which have appropriate characteristics for an evaporite facies deposit: "White Rock" [*Ward*, 1979; *Williams and Zimbelman*, 1994], and a similar deposit in the Bequeral crater [*Christensen*, 1983]. Both of these Martian inselbergs have relatively high albedos (see Figure 6), but not as high or white as some of the filtered or processed images might lead one to conclude [*Evans*, 1979]. It is, however, fallacious to suggest that because modern perennially flooded salt flats, such as the Bonnevale Salt Flat of Utah, are white that evaporite facies deposits, in general, should also be white [*Clark and Van Hart*, 1981]. Most of the salt playas on Earth that do not receive a seasonal flooding of surface water have reduced albedos (relative to those seasonally flooded). The driest parts of the Atacama Desert, Altiplano, and Puna, show bright, medium, and dark salar surfaces (Figure 3), and in space shuttle color photography display reddish and brownish hues. Since an exhumed salar evaporite deposit is likely to have clastic, eolian, and salt components, its albedo and color would in part be controlled by the nature of its mixed eolian, clastic, and evaporitic facies, as

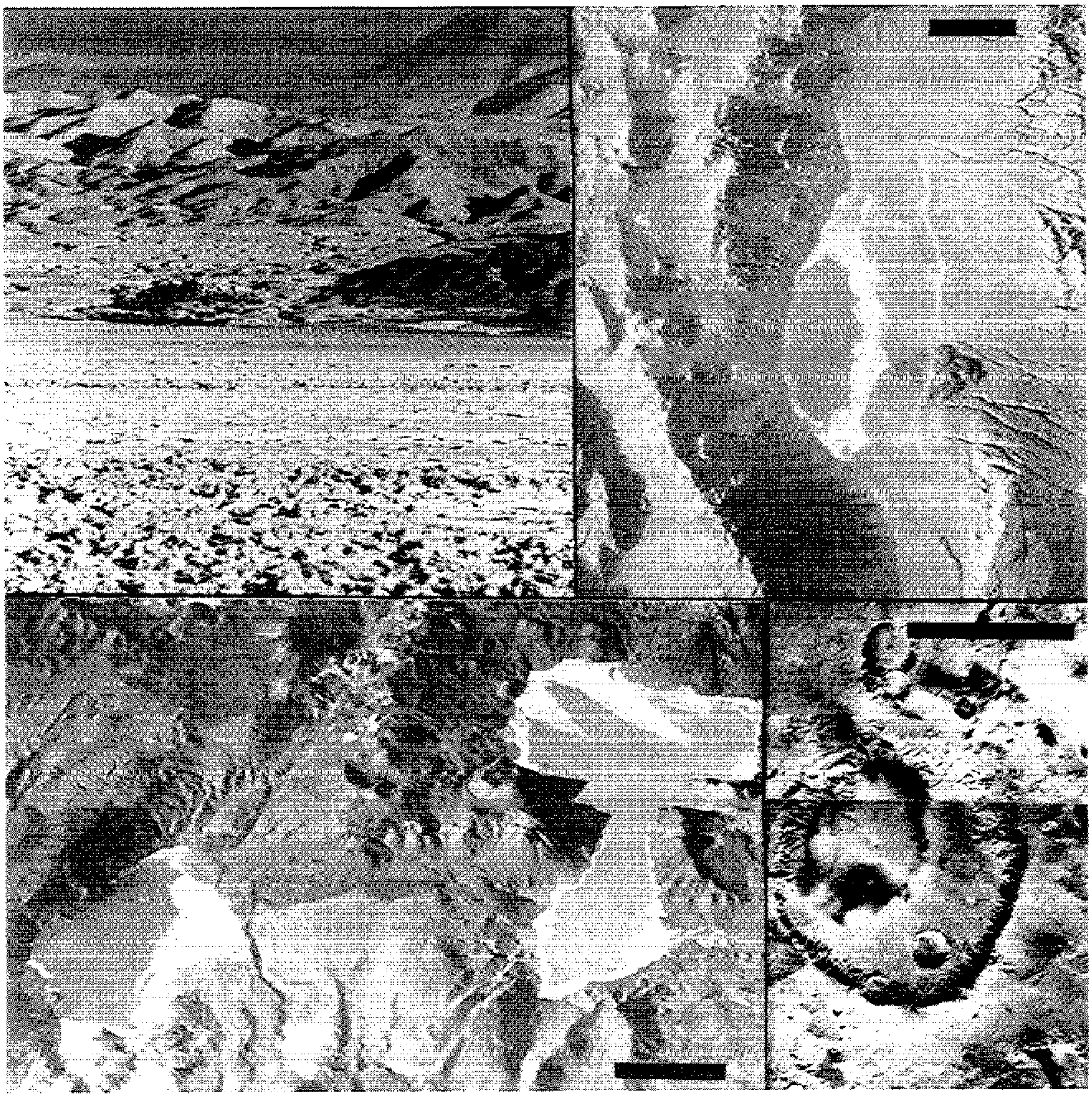

Figure 3. (Top left) Ground photo of the brown to white salt-encrusted surfaces of the Salar de Atacama, northern Chile (68.3°W, 23.5°S), Oasis of Paine in middle ground, Altiplano in background (RDF, taken July 1982). (Top right) Hand-held space shuttle view of the Salar de Punta Negra, Chile (69°W, 24.5°S, NASA 61C-45-018), with bright outer rim of salts and core of dark salt facies. Scale bar is 10 km. (Lower left) Hand-held space shuttle view of evaporite basins in northern Chile with dark central salt facies and bright rims (68.8°W, 25.7°S, NASA STS-23-38-050). (Lower right) Martian crater basin with flat lying dark internal basin fill with a surrounding pediment apron (Viking frames 618A33 and -A35, centered at 322.0°W, 9.0°S). Scale bar is approximately 100 km.

well as the superimposed effects of secondary erosion and weathering of the exhumed deposit. Radiometric data for White Rock indicate higher than Mars-average albedo [*McEwen*, 1987], with red filter reflectivities higher than blue [*Evans*, 1979], consistent with that of many terrestrial evaporite facies deposits.

Terrestrial (nonmarine) evaporite basin deposits are generally well bedded. As such, aerial and space imagery of partially exhumed deposits (Quidham Basin, western China; Tanerouft Basin, southcentral Sahara; Salt Ranges, Atacama Desert) exhibit a fine concentric to convoluted structure produced by the erosional sculpturing of the internal bedding. A similar fine and convoluted layer structure can also be observed in the Bequeral deposit (Figure 6, lower right). Stereo images of White Rock also reveal that the upper erosional surface has a vertically stratified structure [*Williams and Zimbelman*, 1994]. The variation of bedding facies in a nonmarine terrestrial evaporite basin can be used to explain an additional attribute of the Martian inselbergs. Both are relict mounds of basinfill deposits isolated

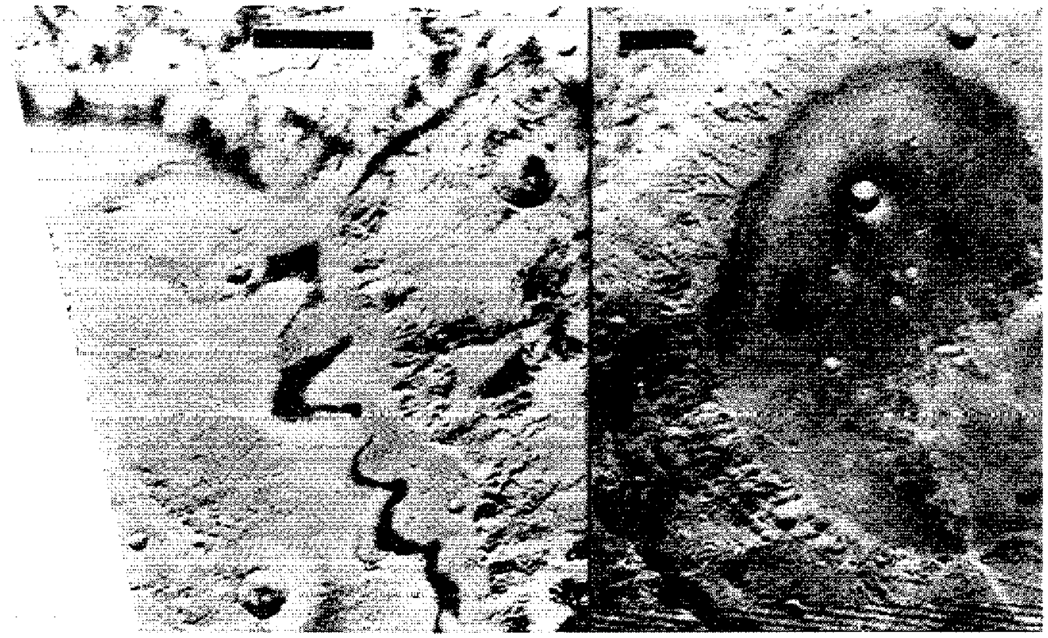

Figure 4. (Left) Margin of a Martian crater-basin with sharp albedo contrasts in the transition zone from the flat lying central facies to the marginal colluvial pediments. Scale bar is 25 km (Viking frame 321A38, centered at 341.8°W, 5.8°S). (Right) Martian crater-basin with a fine bright fringe developed approximately 1 km inward from the basin floor/crater wall margin. Scale bar is 5 km (Viking frame 212A05, centered at 10.2°W, 19°N).

by erosion from the crater-basin margins. Salt-cemented rock (salcrete), while unstable under humid conditions, becomes very stable under arid conditions, and for example, in the hyperarid areas of the Atacama Desert have been used for buildings and roads. Central parts of basins have cores of salt-rich evaporite facies strata originally surrounded by a salt-poor, and clastic-rich, marginal evaporite basin facies, which could have been preferentially left behind as winds deflated these basins over time.

Discussion

An evaporite basin analog for ancient crater-basins on Mars has several implications for future research and exploration efforts. First, from a climatic perspective, the existence of paleolakes and possible large accumulations of evaporite deposits in small basins (e.g., White Rock) reinforces the interpretations that an equilibrium may have existed between surface, groundwater, and atmospheric water reservoirs. This is

Table 1. Authigenic Minerals of Nevada Playas and Atacama Salars [*Papke*, 1976; *Stoertz and Ericksen*, 1974]

	Mineral	Chemical Formula		Mineral	Chemical Formula
Chlorides	Halite	$NaCl$		Natron	$Na_2CO_3 \cdot 10(H_2O)$
	Sylvite	KCl		Thermonatrite	$Na_2CO_3 \cdot H_2O$
Sulfates	Gypsum	$CaSO_4 \cdot 2(H_2O)$		Pirssonite	$Na_2Ca(CO_3)_2 \cdot 2(H_2O)$
	Basanite	$CaSO_4 \cdot 1/2(H_2O)$		Strontianite	$SrCO_3$
	Anhydrite	$CaSO_4$		Nahcolite	$NaHCO_3$
	Mirabilite	$Na_2SO_4 \cdot 10(SO_4)$	Borates	Borax	$Na_2B_4O_7 \cdot 10(H_2O)$
	Thenardite	Na_2SO_4		Tincalconite	$Na_2B_4O_7 \cdot 5(H_2O)$
	Glauberite	$Na_2Ca(SO_4)_2$		Ulexite	$NaCaB_5O_9 \cdot 8(H_2O)$
	Epsomite	$MgSO_4 \cdot 7(H_2O)$		Colemanite	$Ca_2B_6O_{11} \cdot 5(H_2O)$
	Aphthitalite	$NaKSO_4$		Searlesite	$NaBSi_2O_6 \cdot (H_2O)$
	Bleodite	$Na_2Mg(SO_4)_2 \cdot 4(H_2O)$	Nitrates	Soda Niter	$NaNO_3$
	Celestite	$SrSO_4$	Others	Fluorite	CaF_2
Carbonates	Calcite	$CaCO_3$		Phillipsite (other zeolites)	
	Aragonite	$CaCO_3$			
	Dolomite	$CaMg(CO_3)_2$		PotassiumFeldspar	$KAlSi_3O_8$
	Gaylussite	$Na_2Ca(CO_3)_2 \cdot 5(H_2O$		Burkeite	$Na_6CO_3(SO_4)_2$
	Magnesite	$MgCO_3$		Hanksite	$Na_22KCl(CO_3)_2(SO_4)_9$
	Trona Na3	$H(CO_3)_2 \cdot 2(H_2O)$			

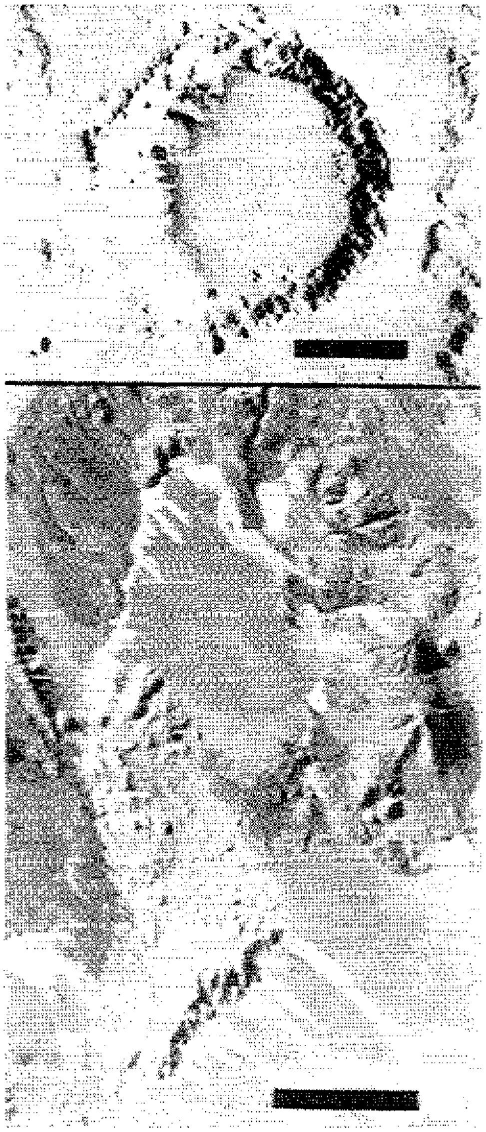

Figure 5. (Top) Mosaic of Viking frames 442S02-4 (centered at 167.15°W, 10.27°S). Along left margin of basin floor bright linear trails of salt are developed inward from the wall. Scale bar is 10 km. (Bottom) Hand-held Space Shuttle photo shows similar linear trails in the Atacama salt basins (67.6°W, 24.3°S), where field work [*Stoertz and Ericksen*, 1974] demonstrates their formation by saltetching. Scale bar is approximately 10 km.

consistent with the interpretations drawn from studies of the Noachian degraded valley networks [*Baker and Partridge*, 1986; *Gulick and Baker*, 1990].

The potential presence of evaporite deposits on Mars would suggest that, at least locally, groundwater conditions reached saline conditions [*Zent and Fanale*, 1986]. The possible existence of saline groundwater has major chemical and mechanical consequences on the surface processes that have operated in the past. The densities of salt-saturated brines can be approximately 20% heavier, and their dynamic viscosities twofold higher than that of distilled water. The mechanical impact is an increase in the driving forces for mass wasting of slopes, and an increase in the internal bulk dynamic viscosity of "flows". While the effects of salts on surface and shallow subsurface processes have been discussed [e.g. *Clark and Van Hart*, 1981; *Malin*, 1974; *Zent and Fanale*, 1986], these have generally not acknowledged the possible presence of localized evaporite facies deposits. As such, a salt karst alternative has not been included along with discussions of thermo- and carbonate-karst alternatives for many of the sapping-related features and terrains.

The evaporite basin hypothesis can be tested by several means, both with existing data and with improved data from future missions. XRF results from the Viking landers are interpreted to indicate the presence of various chloride salts on Mars (*Banin et al.*, 1992), and the present work would suggest that a salt signature might be strongest in the Memnonia region. Even with the limited spatial resolution available to Earth-based instruments, the great spectral resolution now available might be able to detect regional variations in some evaporite concentrations. Viking image data of the cratered highlands outside of Memnonia need to be searched systematically to assess the global distribution of possible fluvial terraces on Mars.

Future missions, particularly the Mars Global Surveyor spacecraft which will refly a large portion of the Mars Observor instruments to Mars, hold great potential for providing further tests to the hypothesis. The 1.4-m resolution of the Mars Observor camera [*Malin et al.*, 1992] may detect deflation pits associated with the "salt finger" weathering, as is observed on evaporite basins in South America, or layering associated with

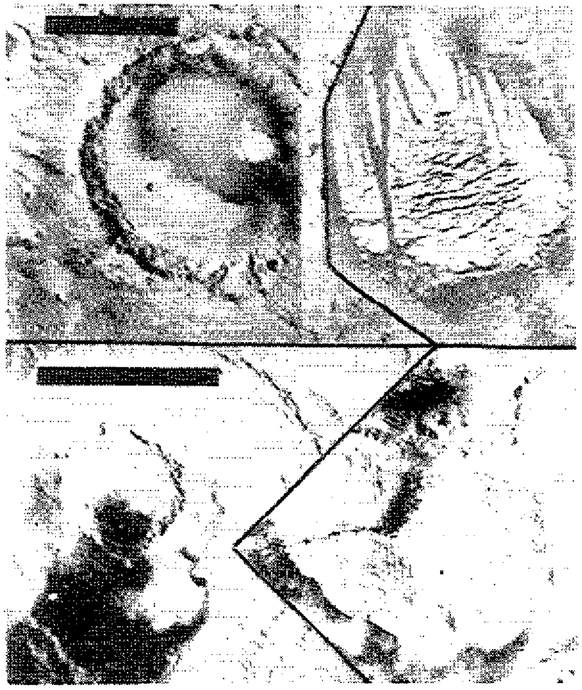

Figure 6. (Top) Views of "White Rock," a relatively high albedo deposit in an unnamed crater southeast of Schalaparelli Impact basin in the Sinus Sabaeus region of Mars. Scale bar is approximately 50 km. Viking Orbiter frames 618A11 (top left) and 826A34-36 (top right), located at 335°W, 8°S. (Bottom) Views of the residual inselberg of a crater-basin deposit within the Bequerel Basin. A convoluted pattern of lines within its surface suggests differential erosion of thinly bedded deposits. Scale bar is approximately 50 km. Viking Orbiter frames 829A37 (bottom left) and 209A07, 9 (bottom right), located at 7.0°W, 21.3°N.

the evaporite deposits themselves. The combined spatial and spectral resolution of the thermal emission spectrometer [*Christensen et al.*, 1992] may be able to detect evaporites at basin margins where eolian erosion has exposed variable albedo materials. Finally, the greatly improved topography which should result from the Mars Observor laser altimeter (*Zuber et al.*, 1992) should be able to determine if terraces within the large crater basins conform to a geopotential surface, as would be expected for a fluvial origin. These new data are crucial to testing a variety of hypotheses related to the history of Mars, such as the evaporite basin hypothesis presented here.

The possible existence of evaporite deposits may at some point in the future have major practical importance for a long-term manned base on Mars. On Earth these deposits contain wide arrays of authigenic sulfates, chlorides, carbonates, borates, and nitrates (Table 1) and are economic sources of sodium chloride, borax, sodium carbonate, sodium sulfate, and lithium, and are potential sources of potash, magnesium, calcium chloride, fluorine, tungsten, uranium, zeolites, nitrates and clays. They may also form basic construction materials for buildings or roads under a hyperarid climatic condition. Finally, in our future efforts to search for past life on Mars, the postulated evaporite basin deposits would be a natural target for paleontologic study.

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