Hydrothermal systems on Mars: an assessment of present evidence

Jack D. Farmer

NASA Ames Research Center, MS 2394, Moffett Field, CA 94035-1000, USA

Abstract. Hydrothermal processes have been suggested to explain a number of observations for Mars, including D/H ratios of water extracted from Martian meteorites, as a means for removing CO_2 from the Martian atmosphere and sequestering it in the crust as carbonates, and as a possible origin for iron oxide-rich spectral units on the floors of some rifted basins (chasmata). There are numerous examples of Martian channels formed by discharges of subsurface water near potential magmatic heat sources, and hydrothermal processes have also been proposed as a mechanism for aquifer recharge needed to sustain long term erosion of sapping channels. The following geological settings have been identified as targets for ancient hydrothermal systems on Mars: channels located along the margins of impact crater melt sheets and on the slopes of ancient volcanoes; chaotic and fretted terranes where shallow subsurface heat sources are thought to have interacted with ground ice; and the floors of calderas and rifted basins (e.g. chasmata). On Earth, such geological environments are often a locus for hydrothermal mineralization. But we presently lack the mineralogical information needed for a definitive evaluation of hypotheses. A preferred tool for identifying minerals by remote sensing methods on Earth is high spatial resolution, hyperspectral, near-infrared spectroscopy, a technique that has been extensively developed by mineral explorationists. Future efforts to explore Mars for ancient hydrothermal systems would benefit from the application of methods developed by the mining industry to look for similar deposits on Earth. But Earth-based exploration models must be adapted to account for the large differences in the climatic and geological history of Mars. For example, it is likely that the early surface environment of Mars was cool, perhaps consistently below freezing, with the shallow portions of hydrothermal systems being dominated by magma–cryosphere interactions. Given the smaller gravitational field, declining atmospheric pressure, and widespread, permeable megaregolith on Mars, volatile outgassing and magmatic cooling would have been more effective than on Earth. Thus, hydrothermal systems are likely to have had much lower average surface temperatures than comparable geological settings on Earth. The likely predominance of basaltic crust on Mars suggests that hydrothermal fluids and associated deposits should be enriched in Fe, Mg, Si and Ca, with surficial deposits being dominated by lower temperature, mixed iron oxide and carbonate mineralogies.

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Hydrothermal systems develop wherever a fluid phase coexists with a heat source to drive convective energy loss. Hydrothermal systems consist of spatially confined, warm (~50 °C) to hot (>500 °C) fluids that are in chemical disequilibrium with their host rocks (Pirajno 1992). These fluids alter, leach, transport and subsequently precipitate their primarily metallic mineral load in response to changes in physicochemical conditions. The solutes of hydrothermal systems are derived from primary (magmatic) and secondary (host rock) sources. An actively convecting hydrothermal system consists of a recharge system, a circulation cell, and a discharge system. Hydrothermal minerals are usually deposited at shallow depths in the crust along natural conduits, subsurface channels or fracture systems, and at sites of surface discharge. The history of hydrothermal activity resides in the rock record it leaves behind, although these processes also impact geochemical cycles and the composition of the atmosphere and hydrosphere (Des Marais 1996).

The most compelling evidence for hydrothermal activity on Mars derives from studies of SNC meteorites, objects believed to have come from Mars (see page 300). But in addition, geomorphic features visible in orbital images obtained during the highly successful Viking missions of the late 1970s, as well as the limited infrared spectral data obtained from the floors of rifted basins, or 'chasmata' on Mars are also suggestive of hydrothermal activity. What is presently needed for a definitive evaluation of the importance of past hydrothermal processes on Mars are broadly distributed, high spatial and spectral resolution compositional data that will allow us to identify discrete mineral deposits on the Martian surface.

The goals of this paper are to review evidence consistent with past hydrothermal activity on Mars, and to discuss the broad range of geological features that may have been formed by such processes. The environment and geological history of Mars differ substantially from those of Earth, thereby hindering direct comparative approaches to geological interpretation. However, depositional models derived from studies of ore deposits in similar geotectonic settings on the Earth provide an important starting point for discussing potential differences in hydrothermal mineralization on Mars. For comparative purposes, such models are outlined briefly under discussions of potential Martian hydrothermal features.

Data from SNC meteorites

The SNC (Shergottite, Nakhlite and Chassignite) meteorites comprise a geochemically and isotopically related group of objects that have bulk compositions similar to terrestrial basalts (for review see McSween 1994). With the possible exception of the Alan Hills 84001 meteorite, which has a crystallization age >4.5 Ga, the SNCs are geologically young, falling within the age range 1.3–0.18 Ga. The late crystallization ages and compositional range of the SNC meteorites suggests they were derived from a large thermally active, chemically differentiated, planetary-sized body (Pepin & Carr 1992). Model ages of SNCs indicate that differentiation of the Martian core and mantle were completed by the end of early accretion, and that similarly to the Earth, Mars was hot early in its history. Arguments for a Martian origin are based on the composition of atmospheric gases that were injected into glassy phased during impact. In both relative abundance and isotopic composition, extracted gases precisely match the Martian atmosphere within the measurement errors of Viking (McSween 1994).

Gooding (1992) showed that the SNC meteorites contain trace quantities (<0.01 wt%) of primary hydrous minerals, including amphiboles and micas contained within glassy inclusions of primary igneous origin, as well as post-crystallization alumino-silicate days, sulfates, carbonates, halides and ferric oxides formed through interactions with late-stage aqueous solutions. The post-crystallization assemblage indicates that oxidizing, hydrous solutions were present in Martian crustal environments sometime after 0.18 Ga.

Comparison of the oxygen isotope composition of secondary carbonates in Shergottites and Nakhlites indicates precipitation at low temperatures (see McSween 1994). However, the older Alan Hills 84001 meteorite contains carbonate spherules with $\delta^{13}C$ values of +41‰, suggesting they formed at elevated temperatures from groundwaters that readily exchanged with atmospheric reservoirs (Romanek et al 1994). This is consistent with D/H ratios for water extracted from SNC meteorites, which are enriched more than five times the terrestrial value, an observation attributable to escape to space of the lighter isotope (Watson et al 1994). But, the similarity of D/H values between SNC meteorites and the Martian atmosphere (determined spectroscopically) requires the operation of a highly effective mechanism of crustal—tmosphere exchange (Donahue 1995, Jakosky 1991). Plausible mechanisms include hydrothermal systems associated with intrusives, or large impacts (Jakosky & Jones 1994).

Heat sources for hydrothermal systems on Mars

As on Earth, impacts played a substantial role in shaping early Martian environments. Schubert et al (1992) suggested that impact heating during accretion raised mantle temperatures to near the solidus, and the core above the liquidus. Given the comparatively smaller size and heat capacity of Mars, the energy invested by impacts toward the end of heavy bombardment would have been a major heat source for hydrothermal systems.

On the Earth most internal heat originates by radioactive decay, being dissipated by the upwelling of mafic magmas along diverging plate margins, above deep mantle plumes, or by the production of intermediate and silicic magmas in subduction zones along convergent margins. Although Mars differs fundamentally in this respect (it never developed plate tectonics), crustal magmatism has still played an important role in the thermal evolution of the planet. The abundances of radiogenic isotope abundances (K, U, Th) in SNC meteorites are broadly similar to the Earth (McSween et al 1979) and it is quite possible that radioactive decay provided a longer-term heat source to sustain magmatism. Evidence for shallow magmatism and volcanism is widespread over the planet and, in the absence of crustal recycling, has produced the largest volcanoes in our solar system. Evidence from SNC meteorites indicates that magmatic activity occurred on Mars at least as late as 0.18 Ga (see McSween 1994).

Geological and atmospheric models supporting hydrothermal activity on Mars

In order to assess the importance of hydrothermal processes on Mars, we must also establish how much water was present at different times in the planet's history, What we know of the general hydrological history of Mars has been extensively reviewed elsewhere (Carr 1981, 1996a,b, this volume) and only selected aspects will be discussed here.

Early climate models for Mars (Pollack et al 1987) assumed an atmosphere of 1–3 bars of CO_2. However, more recent models by Kasting (1991) incorporate the effects of reduced solar luminosity which prevailed during early Martian history. Such models apparently do not yield enough greenhouse warming to produce liquid water at the surface. But, atmospheric warming can also be attained by introducing small amounts of alternative greenhouse gases such as CH_4, NH_3 and SO_2 (see Squyres & Kasting 1994), although the short residence times of these compounds in the atmosphere presents a problem for such scenarios (Carr 1996b, this volume).

Loss of a primitive CO_2-rich atmosphere on Mars is generally attributed to the formation of crustal weathering products and the precipitation of carbonate minerals. This idea receives support from geochemical models using a basaltic host rock, a meteoric water source, and low water/rock ratio which indicate that over a broad range of conditions, hydrothermal mineralization could have been a highly effective means for sequestering CO_2 in the Martian crust as disseminated carbonates (Griffith & Shock 1995).

Small, poorly integrated and highly localized channel networks having tributaries with amphitheatre-shaped headwalls, dominate the older, heavily cratered terranes on Mars. Lunar-calibrated cratering chronologies (Neukum & Hiller 1981) suggest that most of the small valley networks were formed toward the end of early bombardment (Carr 1996b, this volume). Most older Martian channels resemble terrestrial features created by spring sapping, and not those formed by surface run-off (Baker 1990). Some of the smallest valley networks visible in Viking images originate near the margins of impact crater melt sheets and have been attributed to hydrothermal outflows (Brakenridge et al 1985).

The localized nature of Martian valleys and their limited integration into drainage networks is difficult to explain by atmospheric precipitation models, which should result in a more uniform distribution over regional terranes (Gulick 1993). The great length of many Martian channels (hundreds of kilometres) requires sustained periods of erosion and a long-term hydrological cycle. But to sustain the headward erosion of valleys there must have been an effective mechanism for recharging local aquifers. Recent climate models for early Mars suggest sub-zero surface temperatures (-10 to $-20°C$) and an extensive subsurface cryosphere. This appears to be inconsistent with extensive recharge through atmospheric precipitation. Alternatively, it has been suggested that recharge of Martian aquifers was maintained by hydrothermal convection (Squyres & Kasting 1994).

Geological evidence suggests that early outgassing of water on Mars was equivalent to several hundred metres depth over the surface (Carr 1996b, this volume). Much of this water may yet remain in the crust as ground ice and permafrost. A variety of geological features at higher latitudes (>40°) have been attributed to the action of ground ice and support the concept of a widespread subsurface Martian cryosphere (Squyres & Carr 1986). Clifford (1993) presented evidence for an extensive global groundwater system capable of sustaining long-term interchanges with the atmosphere. Such interchanges would be significantly enhanced by hydrothermal circulation associated with localized igneous or impact heat sources. As mentioned before, isotopic data from SNC meteorites suggests an on-going mechanism for crustalatmosphere exchange, with hydrothermal systems being a prime candidate (Jakosky & Jones 1994).

A number of geomorphic features on Mars have been attributed to releases of water by the magmatic heating and melting of ground ice. In contrast to the small valley networks which dominate the ancient cratered highlands on Mars, are much larger channels formed by catastrophic outflooding of subsurface water. These features are mostly found in younger Martian terranes, particularly around the margins of the large volcanic complexes at Tharsis (Carr 1981, 1996b, this volume). In the presence of a thick, confining layer of near-surface ground ice, outfloods of subsurface water are likely to have been focused at sites where the cryosphere was thinner because of locally higher heat flow as a result of magmatic intrusions and/or crustal thinning. In fact, many outflow channels originate within chaotic terranes interpreted to have formed where ground ice melted due to localized magmatic intrusions (Masursky et al 1986).

Hydrothermal prospecting on Mars

On Earth, the surface expression of hydrothermal activity varies greatly in relationship to such things as tectonic setting, geothermal gradient, geohydrology and secular variations in climate. We still do not yet understand the relative importance of these factors on Mars and how they have varied through time. Furthermore, with an average atmospheric density of only ~7.5mb and an equatorial temperature range of about −93 °C to +13 °C, liquid water is unstable on the Martian surface and can only exist at depth, beneath a confining layer of ground ice. Thus, if active subsurface systems currently exist on Mars, they are only likely to be detectable at the surface as spatially confined anomalies in surface temperature or atmospheric composition.

The bulk composition of the Martian crust is similar to basalt, and the solutes of Martian hydrothermal systems can be expected to be comparatively enriched in Fe, Mg and Ca (similar to seafloor hydrothermal systems on Earth). Because of higher temperatures, and lower silica and water contents, mafic magmas usually rise to higher elevations in the crust than silicic magmas, a situation favouring near-surface hydrothermal systems. But at 53% of the Earth's diameter and with 38% the gravity, volatile loss and cooling on Mars should also occur with much greater efficiency, particularly in the presence of a porous and permeable megaregolith. Thus, surface hydrothermal temperatures on Mars are likely to have been lower, on average, than for comparable geological settings on Earth, with surface deposits being dominated by lower temperature mineral assemblages.

As noted previously, at this stage in Mars exploration what we can say about hydrothermal processes rests upon a comparatively small number of geochemical observations from SNC meteorites, and interpretations of a select number of geomorphic features observed in orbital images. This stands in marked contrast to the types and amounts of data that are usually available to explorationists searching for hydrothermal deposits on Earth (e.g. elemental abundances, surface mineralogy, magnetic intensities and gravity). Earth-based reconnaissance often begins with broadly-based geochemical sampling and high spatial resolution, hyperspectral, near-infrared mapping (1.0–3.0 μm range). The thermal emission spectrometer (TES) which will be flown to Mars in 1996 will provide useful information within the spectral range of 5–12 μm, although at a somewhat coarse spatial resolution of $\sim$3 km/pixel (Christensen et al 1992).

Targeting specific sites on Mars for high resolution orbital imaging during upcoming missions is especially important because only a small fraction of the Martian surface is likely to be imaged at high resolution. The sites listed in Table 1 were selected to represent a broad range of geological features on Mars that may be shown related to past hydrothermal activity. Potential hydrothermal sites were chosen based on the concurrence of simple channel features (e.g. those formed by sapping, or outfloods of subsurface water), potential heat sources (e.g. impact craters, volcanic constructs, and shallow subsurface igneous intrusives), and/or anomalous albedo features that could reflect local mineralizaton. The discussion which follows is organized around

TABLE 1 Potential hydrothermal features and terranes for Mars

Name	*Location*	*Features*
Hadriaca Patera	32" S, 266" W	Sapping and outflow channels on volcanic slopes and caldera floor deposits
Apollinaris Patera	90° S, 186° W	Sapping channels on volcanic slopes and high albedo features near caldera rim
Cerberus volcanic plains	7" N, 200° W	Volcanic fissures with anomalous albedo features
NW Elysium Mons	25" N, 224" W	NW slope fissure system source for volatile-rich pyroclastics
Ismenius Lacus	35.5° N, 334° W	Small volcanic constructs associated with fretted channels
Aram Chaos	3" N, 20° W	Chaotic terranes and source areas for large outflow channels
Candor Chasma	5" S, 76° W	Rifted basin with albedo features attributed to mineralization
Margaritifer Sinus impact craters	24° S, 8° W	Head reaches of small, flat-floored ravines flanking impact craters

this general geotectonic framework, and provides a summary of pertinent observations for each site type. Where appropriate, brief summaries of depositional models for hydrothermal deposits found in similar geotectonic settings on Earth are included to help draw attention to the potential differences between meteoric/magmatic systems that dominate on Earth and the cryospheric/magmatic systems that seem to have dominated on Mars.

Potential magmatic hydrothermal systems on Mars

Channels on volcanic slopes

Hydrothermal circulation systems associated with large stratovolcanoes on Earth tend to be positioned deep within volcanic edifices. In contrast to Mars, where aquifers are likely to have been recharged by mostly subsurface processes (e.g. melting of ground ice by magmatic intrusions and hydrothermal convection), such systems on Earth are typically sustained by meteoric recharge on volcanic slopes, or by the lateral inflow of groundwater from adjacent areas (Henley 1996, this volume, see also Pirajno 1992). Water, drawn upward toward centrally located intrusives, emerges at high elevations on volcanic slopes, exiting near crater and caldera rims. Rising hydrothermal columns become progressively vapour dominated due to the decreasing influx of groundwater upslope. Because H_2S, CO_2 and other gases dominate the vapour phase, surface systems on high volcanic slopes are characterized by acid-sulfate springs, fumaroles and solfataras. Fumarolic vapours alter volcanic materials to clays and deposit sublimates of various minerals, including chlorides of alkali metals, ammonia and ferric iron, sulfates of various alkali metals and Ca, native sulfur (by oxidation of H_2S), and sulfides of Fe and Pb, with traces of Cu, Mn, Zn, **As,** Hg and Sn. In contrast, springs emerging at some distance from volcanic slopes tend to be neutral chloride or alkaline springs which deposit siliceous sinters, sulfates or carbonates (see Pirajno 1992). Obviously, volcanic slopes and caldera floors (see below) comprise important targets for high resolution infrared remote sensing on Mars. Identification of similarly-zoned mineral assemblages on the slopes of Martian volcanoes would provide compelling evidence for past hydrothermal systems on Mars and aid our understanding of the planet's hydrological history.

Hydrological processes have been invoked to explain incised valleys on the slopes of many Martian stratovolcanoes (Gulick & Baker 1990). For example, Hadriaca Patera (Lat. 32°S, Long. 268°W) is a low-relief highland volcano with a large (—75 km diameter) caldera (Fig. 1, large arrow). The flanks of the Hadriaca Patera are incised by numerous simple, non-branching channel forms, most of which have shallow, trough-shaped floors (Fig. 1, small arrow). The morphology of these channels indicates that volcanic slopes are comprised of layered pyroclastic deposits that are easily eroded. Channels are thought to have been initiated by density-driven pyroclastic flows, but subsequently enlarged by fluvial activity (Crown et al 1992).

Another example is Apollinaris Patera (8°S, 187°W; Fig. 2). This volcano possesses a large (80 km diameter) summit caldera, and a well-defined lobate deposit emanating from a breach in the caldera rim (Robinson et al 1993). Three types of channels are

FIG. 1. The ancient Martian volcano, Hadriaca Patera showing summit caldera (~75 km diameter; large arrow), small flank channels (small arrow) and the large outflow channel, Dao Vallis (~45 km wide; medium arrow).

present on the slopes of Apollonaris Patera (Gulick & Baker 1990): (a) narrowly-incised valleys lacking tributaries which originate outside the caldera rim (1 on Fig. 2); (b) shallow, straight channels carved into the lobate deposit described above (2 on Fig. 2); and (c) a valley network on the NE flank of the volcano which possesses short, stubby tributaries (3 on Fig. 2). Interestingly, Robinson & Smith (1995) have interpreted a high albedo feature located near the caldera rim on the NE rim of the volcano (Fig. 2, arrow) to be a mineral deposit formed by past fumerolic activity.

Dao Vallis (33°S, 266°W) is a broad (>45 km wide) outflow channel that originates from an amphitheatre-shaped source area on the southern flank of Hadriaca Patera (Fig. 1, medium arrow). This channel extends southwest a distance of ~500 km where it enters the Hellas Basin, a large impact crater. Squyres et al (1987) attributed these channels to outfloods of subsurface water released when ground ice was melted by localized subsurface heat sources (e.g. shallow magmatic intrusions). Dao Vallis clearly truncates (post-dates) smaller flat-floored channels that originate on the higher flank regions of Hadriaca Patera, although the period separating their formation is problematic. The floor materials of Dao Vallis suggest extensive modification by fluvial processes and headward growth by the collapse of channel walls (Crown et al 1992). The origin of small mounded features on the floor of Dao Vallis cannot be resolved with Viking images, and we presently lack spectral imaging that could help evaluate mineralogy. Thus, floor deposits near the head reaches of Dao Vallis constitute an important target for high resolution imaging and infrared spectrscopy during upcoming orbital missions (Farmer et al 1993).

Caldera floors

Calderas are enlarged craters that form when the summit area of a volcano collapses following large-scale explosive eruptions. Subsidence occurs when magmatic support is withdrawn from below, causing overlying mass of rock to founder along circular fracture systems, or ring faults.

On Earth, caldera floors are often a locus for magmatic-meteoric hydrothermal systems and focused mineralization (see Pirajno 1992). Terrestrial calderas tend to have shallow, laterally confined aquifers, dominated by meteoric recharge (Henley 1996, this volume). Flat convection cells form above relatively massive magma chambers, and because the convecting column is within easy reach of the surface, alkaline-chloride waters enriched in Na, K, chlorides, silica, bicarbonates, fluoride, ammonia, As, Li, Rb, Cs and boric compounds dominate. Boiling produces a two-phase system (liquid plus steam) in the upper part of the convecting column. H_2S becomes concentrated in the vapour phase and produces fumaroles, solfataras and acid sulfate waters at the surface immediately above shallow instrusives. In outlying areas, cooler, chloride-rich waters (pH 5–9) dominate, and because silica solubility is lower for chloride solutions at an alkaline pH, siliceous sinters tend to be deposited along declining temperature gradients. For areas underlain by limestone or other carbonate-rich rocks, springs tend

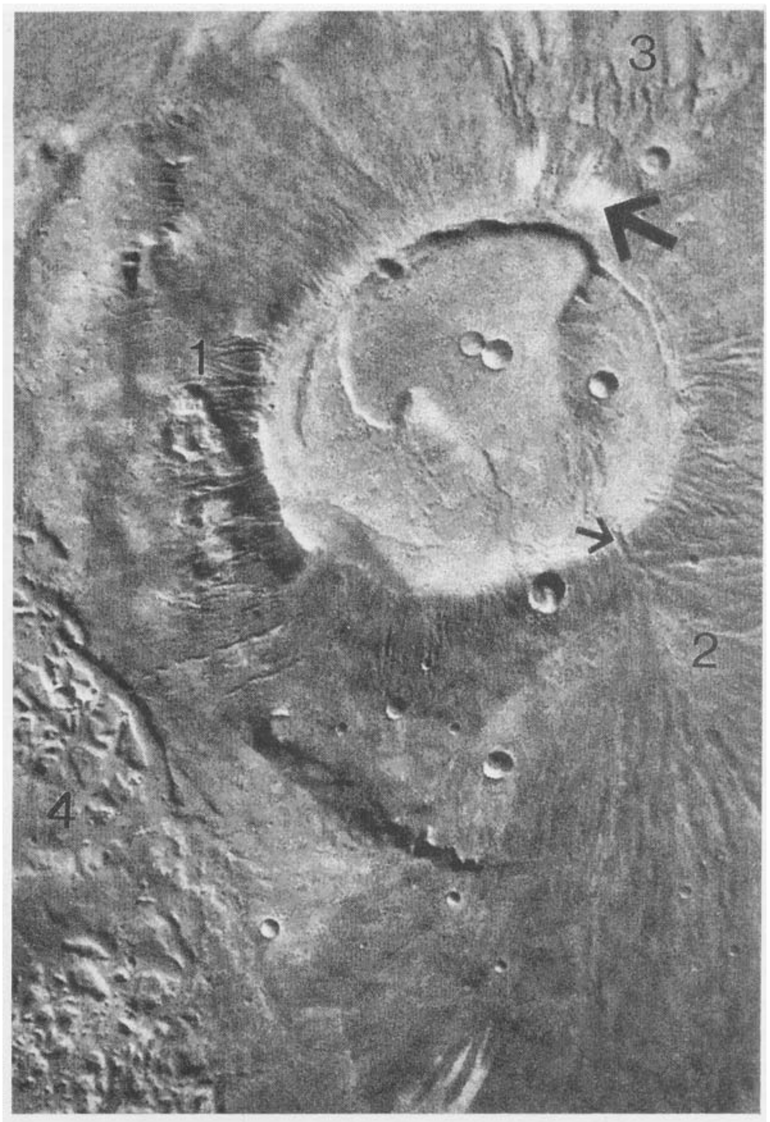

FIG. 2. The ancient Martian volcano, Apollonaris Patera showing summit caldera (~80 km diameter) and high albedo feature (arrow) interpreted to be fumarole deposit. Also visible are several types of channels, including narrowly incised valleys lacking tributaries which originate outside the caldera rim (1), shallow, straight channels carved into a large lobate deposit below a breach in the caldera rim (2), and the upper reaches of a valley network on the NE flank of the volcano which exhibits short, stubby tributaries **(3).**

to deposit calcareous sinters (travertines), while in mafic volcanic terranes, iron-precipitating spring systems dominate.

Calderas are widespread features of Martian volcanic terranes (Crumpler et al 1996) and they have been identified as high priority targets for exopalaeontology because of their potential for focused hydrothermal mineralization (e.g. Walter & Des Marais 1993, Farmer & Des Marais 1994). An objective of upcoming orbital missions to Mars should be to look for zoned patterns of mineralization on the floors of calderas.

Volcanic fissures

Many ancient Martian volcanoes (e.g. Hadriaca, Apollinaris and Tyrrhena Paterae and Elysium Mons) were apparently dominated by pyroclastic eruptions, suggesting that higher volatile abundances prevailed during earlier periods of Martian volcanic activity. This is in contrast to the dominantly effusive (lava-prone) volcanism of younger Martian volcanoes, such as those at Tharsis. The volcanic plains northwest of Elysium Mons (25°N, 214°W) consist of lobate deposits with well-defined medial channels (Granicus Valles, Fig. 3 small arrows) that originate from a fissure trough on the NW flank of the volcano (Fig. 3, large arrow). Because their estimated volume is 10–100 times larger than the fissure system from which they originated, these flows have been interpreted to be 'lahars', or volcanic mud flows formed when pyrodastic materials incorporated water by melting subsurface ground ice (Christiansen 1989). The surfaces of these pyroclastic flows and the trough fissure systems from which they were erupted are potential targets for hydrothermal and fumarolic activity.

Dark-coloured fractures occur on the Cerberus volcanic plains which are a part of a regional system that encircles the ancient Martian volcano, Elysium Mons (7°N, 200°W). In some cases, down-wind drifts of dark materials appear to originate from fractures. In other cases, symmetrical zones of lighter albedo are observed adjacent to fissures (Fig. 4, arrows). These lighter albedo features could be due either to fumarolic mineralization, or to systematic variations in the grain size of pyroclastics erupted from the fissures. Deciding between these alternatives will require high resolution orbital imaging, accompanied by information about mineralogy and grain size.

Fretted channel terranes

Carruthers (1995) cited evidence for volcano–ground ice interactions in association with an unnamed system of fretted channels and closed canyons located within the southern Ismenius Lacus terrane of Mars (35.5°N, 334°W). The fretted channel segment identified by the arrows in Fig. 5 lies between two features interpreted to be eruptive centres. At one end is a dark-coloured mound that is interpreted to be pyroclastic cone (Fig. 5, bottom arrow). At the other is an irregular, closed depression —40 km in diameter that is interpreted to be a Maar-type crater (Fig. 5, top arrow). At higher resolution, lobate deposits interpreted to be pyroclastic surge or debris flow deposits are visible on the flanks of the Maar crater. These deposits are cut by 400–800 m wide channels up to 20 km long which are arrayed radially around the cone.

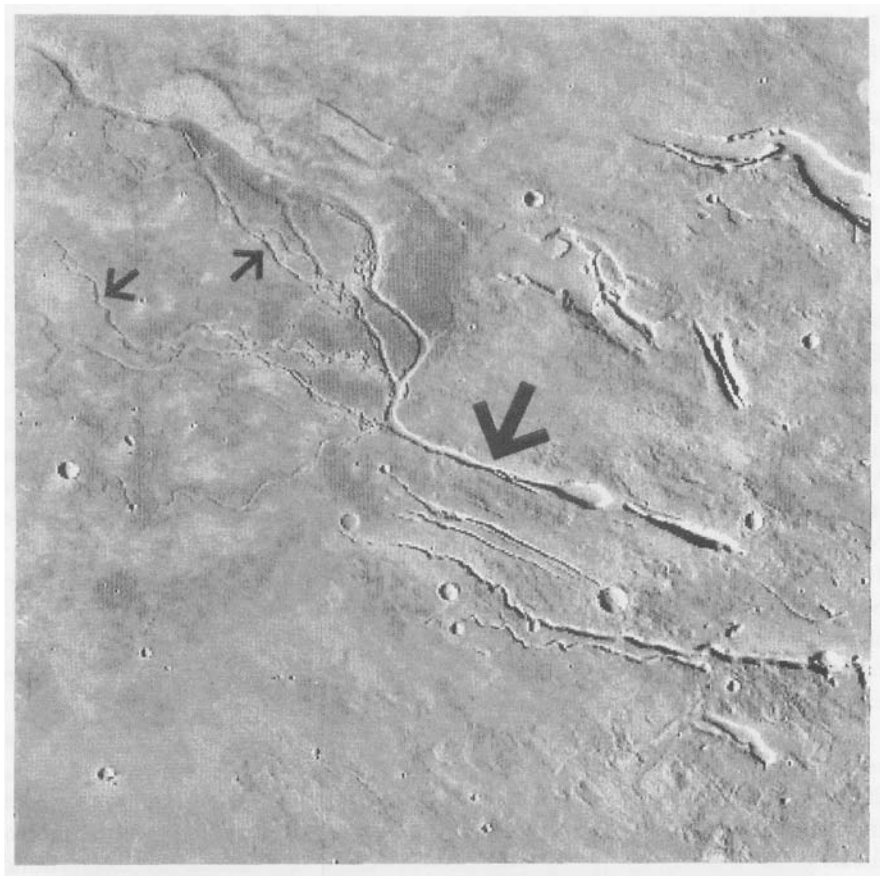

FIG. 3. Sinuous channels of Granicus Valles (small arrows) crossing the surface of lobate deposits that comprise volcanic plains northwest of the Martian volcano, Elysium Mons. These deposits, which originate from a trough fissure system on the NW flank of the volcano (large arrow), are interpreted to be 'lahars', or mud-flows formed when pyroclastics were erupted within an ice-rich terrane. Area shown is about 300 km across.

Small volcanic centres are widespread in many ice-rich, high latitude terranes on Mars (Hodges & Moore 1994), and such features are obvious potential targets for small-scale hydrothermal systems. But the spatial coincidence of small volcanic features with closed canyons, depressions and channel junctions suggests that shallow magmatic processes may have played an important role in the origin of some fretted terranes. Carruthers (1995) suggested a generalized model for fretted channel growth whereby ground ice is melted and vaporized by shallow intrusives, escaping to the surface through fractures and small vents. Channels initiated by phreatic explosions are

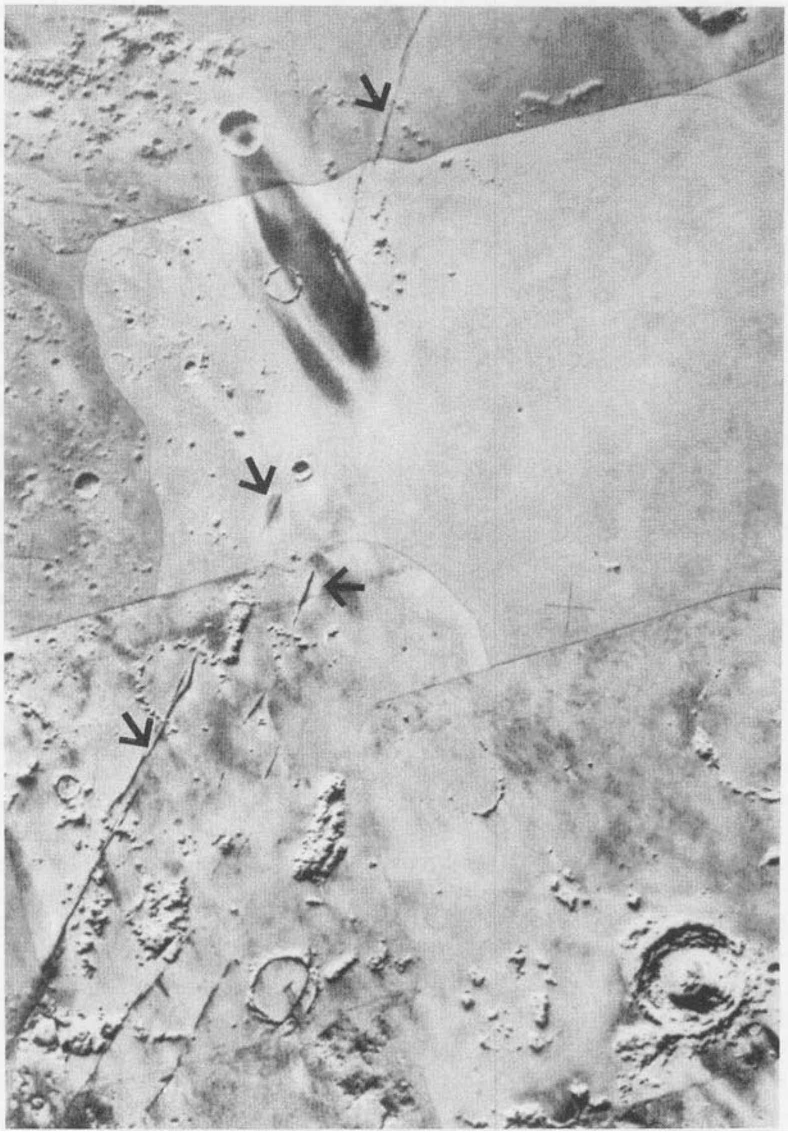

FIG. 4. Cerberus Volcanic Plains located south of Elysium Mons. Dark fractures are a part of the regional fracture system surrounding Elysium Mons. Some fractures exhibit symmetrical zones of lighter albedo (arrows) which could be due either to fumarolic mineralization, or to systematic variations in the grain size of pyroclastics erupted from the fissures. Impact crater at lower right of image is —50 km in diameter.

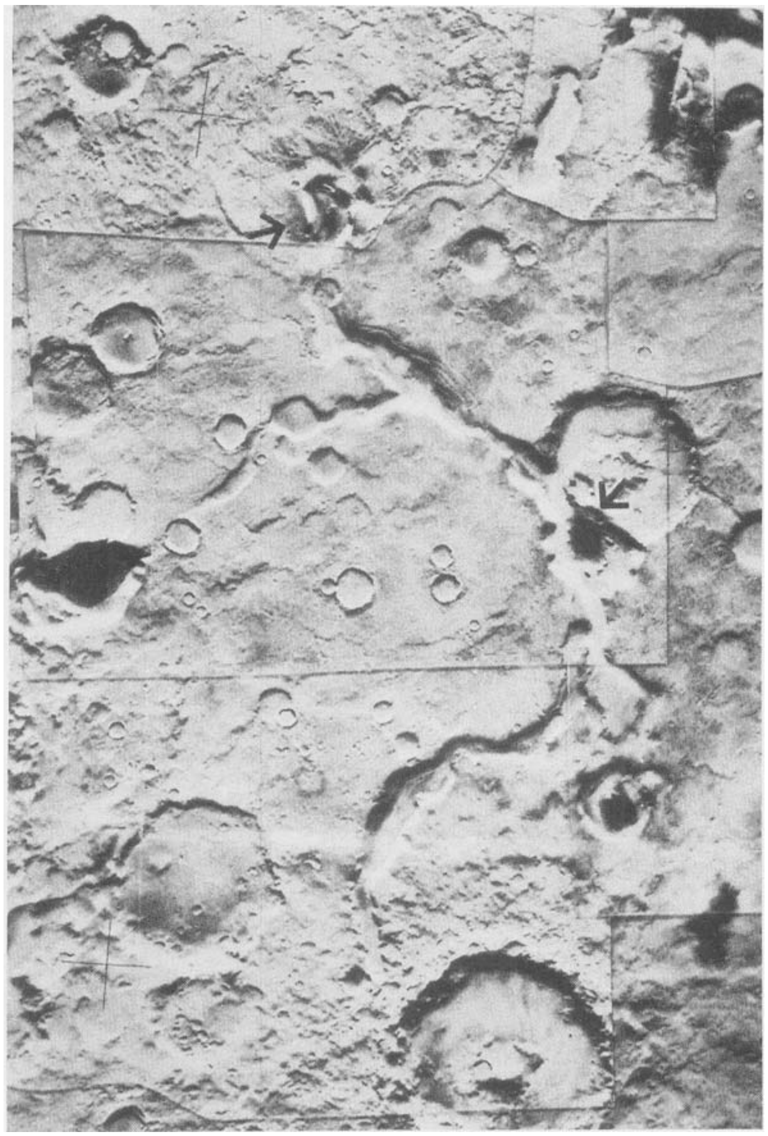

FIG. 5. Fretted channels and closed canyons located on southern Ismenius Lacus, Mars. The channel segment lying between the arrows ($\sim$100 km long) is bounded by features interpreted to be small eruptive centres, including a dark-coloured mound (bottom arrow) and closed depression believed to be a Maar-type crater (top arrow).

enlarged by subsurface sapping, wall collapse, along with erosion by down-channel ice-rich debris flows. Under such conditions, the floors of fretted channels and closed depressions could have also been sites for hydrothermal mineralization.

Chaotic terranes and associated outflow channels

Most outflow channels on Mars occur in younger Martian terranes around the large volcanic complex at Tharsis. Outflows northeast of Vallis Marineris originate from highly fractured, elongate to circular collapsed zones called chaotic terranes (Baker et al 1992). These regions consist of irregularly-broken and jumbled blocks apparently formed by the withdrawal of subsurface ice and/or water (Mars Channel Working Group 1983). Masursky et al (1986) suggested a thermokarst origin for the chaos source regions of many Martian outflow channels. Outfloods of water would have occurred by the melting of water ice stored in the Martian regolith. The favoured mechanism is heating by shallow intrusives. This suggests that shallow hydrothermal systems could have developed and persisted for some time prior to and following major outflooding events. Small channels on the flanks of circular collapsed terranes, such as Aram Chaos (3°N, 20°W; Fig. 6, arrow) are logical sites for concentrating the surface deposits of hydrothermal systems (Farmer et al 1995). In addition, the walls of collapsed blocks could also expose zones of shallow epithermal mineralization.

Rifted basins

On Earth, rifted basins are often associated with a variety of sediment-hosted (stratiform) and exhalative base metal sulfide deposits (Pirajno 1992). Crustal attenuation during rifting is usually accompanied by an increase in regional heat flow and igneous activity, particularly along basin margins. In such settings, hydrothermal convection transports water from the deeper parts of the basin toward its margins. Hydrothermal fluids usually ascend along basin-bounding normal faults, and invade adjacent aquifers, forming exhalative sulfide deposits at or below the sediment–water interface. In rifted basin lakes, stratiform ore deposits may form either from diagenetic, low temperature, metalliferous brines formed during compactional dewatering, or from high temperature hydrothermal systems associated with basin margin faults (Robbins 1983). Hydrothermal fluids originate from meteoric waters that are heated by intrusives at depth, picking up CO_2, H_2, N_2, and biogenic H_2S and CH_4. In addition, the Na and Cl content of saline lakes in such settings often reflects substantial hydrothermal inputs.

Candor Chasma (5°S, 76°W; Fig. 7) is a semi-enclosed structural trough ~525 km long by ~150 km wide that is part of the Vallis Marineris Canyon system, a large system of steep-walled, canyons formed by extension along east–west trending radial fracture systems associated with the Tharsis volcanic province (Plescia & Saunders 1982). Viking Orbiter multispectral images of the western end of Candor Chasma reveal two 20 km-long depressions of anomalous albedo. These features are located near the margins of interior layered deposits on the chasma floor which have been interpreted to be

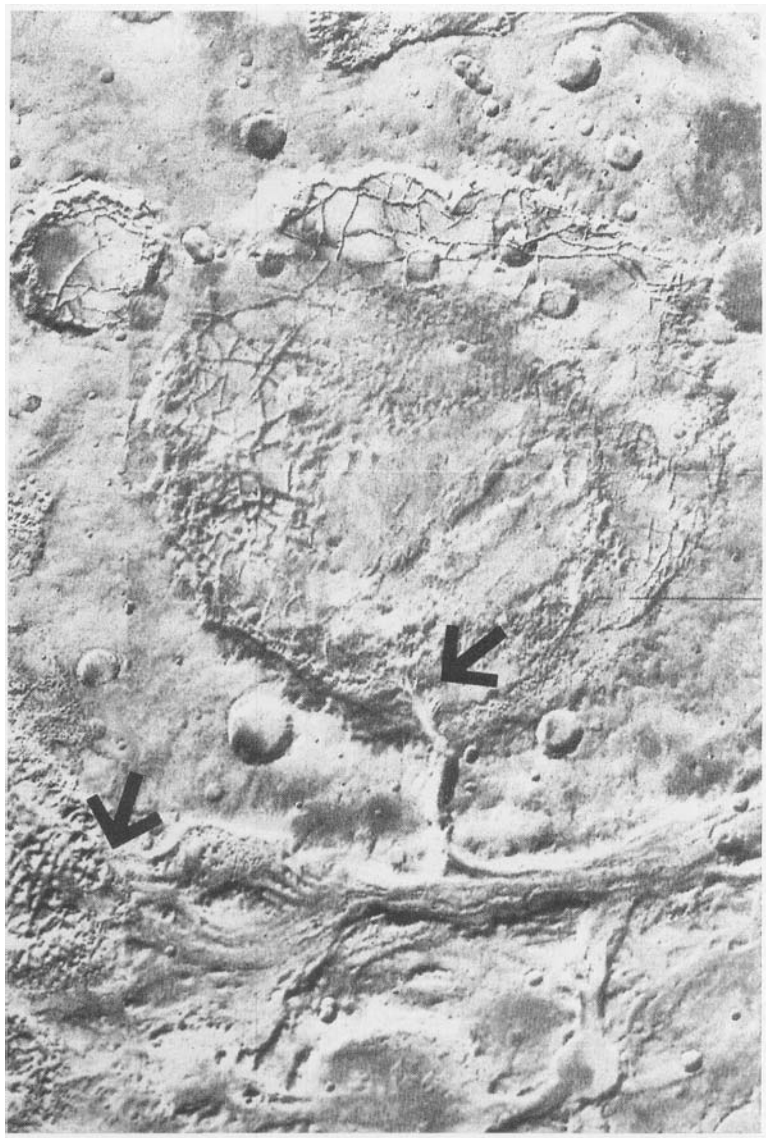

FIG. 6. Aram Chaos is a semi-circular collapse feature (~300 km diameter) located near the upper reaches of Ares Vallis outflow channel. Chaotic terranes are thought to have formed where magmatic intrusions melted ground ice. Under such conditions, near surface hydrothermal systems may have developed near the head reaches of small valleys, or on valley floors (arrows).

FIG. 7. The floor of Candor Chasma, a semi-endosed structural trough (~150 km wide) that is part of the Vallis Marineris Canyon system. **An** anomalous spectral unit on the chasma floor is interpreted to be due to the presence of aqueously-deposited ferric oxides, oxyhydroxides and hematite.

ancient lake deposits (Nedell et al 1987). Combined analysis of Viking multispectral data and high spatial resolution infrared reflectance data obtained by the ISM imaging spectrometer on the Russian probe, Phohos 2, suggest a local enrichment in ferric oxides and oxyhydroxides, and a small increase in crystallinity due to hematite (Geissler et al 1993). The anomalous spectral unit is confined to the chasma floor (Fig. 7 arrow), and suggests that mineralization and alteration is restricted to low areas, possibly as a result of groundwater seepage and subaqueous alteration of pre-existing, iron-rich rocks. The tectonic setting and restricted nature of the mineralization suggests that the spectral unit could he hydrothermal in origin, but further evaluation of this hypothesis will require more detailed mineralogical information (Geissler et al 1993).

Channels surrounding impact craters

Newsom (1980) suggested that impact-related hydrothermal systems were widespread on early Mars. Impact melting of volatile-rich crustal materials is likely to have set up hydrothermal systems that would have emerged at the surface along the margins of impact melt sheets. Brakenridge et al (1985) identified two classes of small, sapping valleys associated with impact craters formed just prior to the end of heavy bombardment, —3.8 Ga. These channels include some of the smallest valleys visible in Viking images — small, flat-floored ravines oriented subparallel to the slopes flanking craters. One group of valleys occur near the margins of impact crater melt sheets and are thought to have been formed by hydrothermal outflows (Fig. 8). The headwall regions of this smaller class of valleys (ravines) adjacent to impact crater melt sheets (e.g. Fig. 8, arrow) are a particularly compelling target to explore for hydrothermal mineralization.

Brakenridge et al (1985) also recognized a second class of larger and more widespread valley systems within inter-crater plains areas. These flat-floored branching valleys are thought to have formed through the interaction of impact, volcanism and erosion.

Given the complex, overlapping events at the end of late bombardment, it is possible that hydrothermal mineralization was widespread within heavily cratered ancient highland terranes. Wilhelms & Baldwin (1989) suggested that magmatism played a role in the origin of small valley systems in some upland terranes of Mars as a result of the widespread emplacement of shallow sills into an ice-rich crust during later periods of Martian history. In terrestrial settings, loosely consolidated sediments and/or pyroclastics marginal to dikes and sills, undergo porosity reduction during magma emplacement, expelling substantial amounts of pore water. For example, it is estimated that an area of 2 km^2 intruded by sills can expel up to $40 \times 106 m^3$ of water (Einsele et al 1980). Under such conditions, temperatures adjacent to intrusives can exceed 400 °C, and near surface pore waters may reach the boiling point. In permeable country rocks, symmetrically-zoned alteration halos usually form adjacent to tabular plutons as a result of convecting hydrothermal fluids. Water can also be channeled upward along faults and discharge as hot springs at the surface.

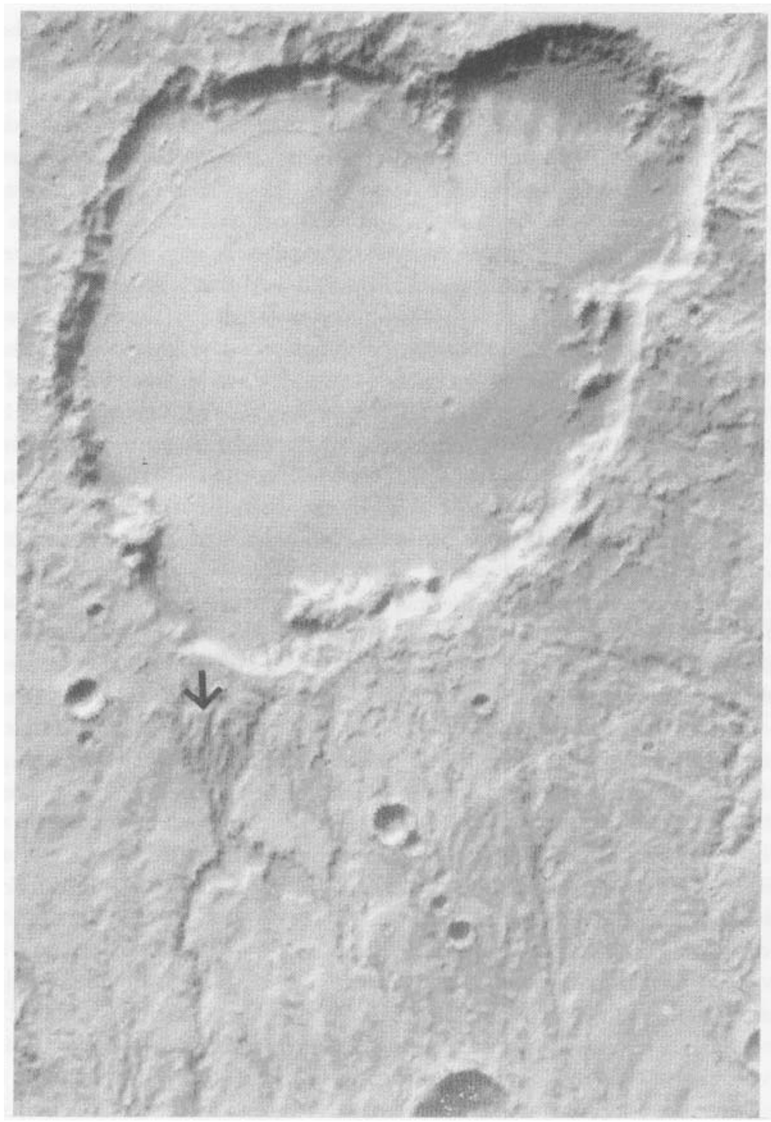

FIG. 8. Small, flat-floored ravines, originating near the margin of an —70 km diameter impact crater in the Margaritifer Sinus region of Mars. Crater rims have been removed by erosion leaving a flat, smooth crater floor interpreted to be an impact melt sheet. Such valleys often comprise higher order tributaries of small valley networks within ancient cratered highland terranes of Mars and are interpreted by some authors to have formed by surface outflows of hydrothermal systems formed by impact heating.

Summary discussion

The interpretation of geomorphic features on Mars is presently challenged by the lack of spatially-resolved orbital imaging and information about surface mineralogy. Interpretations are also complicated by differences in the present Martian surface environment and uncertainties about how geological and climatic processes have varied through time. But, there are a number of independently-derived observations that are consistent with past hydrothermal processes on Mars and this framework provides the basis for preliminary evaluations.

Thermodynamic models indicate that hydrothermal mineralization could have been an effective means for sequestering atmospheric CO_2 in the early Martian crust. Thus, hydrothermal systems may have played a prominent role in loss of the early atmosphere (Griffith & Shock 1995). This is consistent with isotopic data from the Mars-derived SNC meteorites which indicate there has been an active and ongoing process of crustal–atmosphere exchange throughout Martian history (see McSween 1994). Hydrothermal convection provides the most compelling mechanism for such exchanges (Jakosky & Jones 1994). The young age of the SNCs suggests that hydrothermal systems could still be active on Mars, but given the instability of liquid water at the surface, their expression is likely to be limited to localized anomalies in surface temperature or atmospheric composition.

The selection of potential hydrothermal sites on Mars is presently based on the concurrence of water-carved geomorphic features and potential heat sources (e.g. volcanic centres or suspected magmatic intrusions). In some instances, suspected hydrothermal features are accompanied by albedo or spectral anomalies that suggest focused mineralization. These potential hydrothermal sites are regarded as important for Mars exopalaeontology and should be targeted for high resolution orbital imaging and mineralogical mapping during upcoming missions (see Farmer et al 1993, Farmer & Des Marais 1994).

Perhaps the most convincing geomorphic evidence for hydrothermal activity on Mars is the observation of simple channel systems along the margins of impact craters in ancient cratered highland terranes on Mars (Brakenridge et al 1985, Newsom 1980). In addition, the presence of iron-rich deposits of possible hydrothermal origin observed on the floors of some chasmata (Geissler et al 1993) suggests intriguing similarities to the stratiform ore deposits of many rifted basin settings on Earth. More controversial are numerous examples of small channel systems on the slopes of Martian stratovolcanoes. Although a variety of processes (density-driven pyroclastic flows, sapping processes, and/or surface run-off) may have been involved in their formation, subsurface water appears to have played a key role in many instances (Gulick & Baker 1990).

The visible concentration of channels on volcanic slopes, within terranes where they are otherwise absent, provides important circumstantial evidence for the thermal focusing of hydrological activity. And the presence of anomalous, high albedo features near the crater rims (e.g. Apollinaris Patera; Robinson & Smith 1995) compares favorably to fumarolic deposits found in similar locations on terrestrial volcanoes.

Widespread magma–cryosphere interactions are suggested by chaotic source terranes associated with the large outflow channels surrounding Tharsis (Masursky et al 1986), by volatile-rich pyroclastic fissure eruptions on the plains west of Elysium Mons (Christiansen 1989), and by the association of fretted channels, closed depressions and small volcanic centres in some areas of the northern plains (Carruthers 1995).

Present evidence suggests that classical meteoric systems of the type described for volcanoes on Earth are probably not directly applicable to Mars. Climate models suggest an early cool Mars with surface temperatures below the freezing point. Thus, atmospheric precipitation and meteoric recharge may have been minimal. However, the aquifer recharge needed to sustain channel erosion could have been provided by hydrothermal convection (Squyres & Kasting 1994). In many cases, features of the adjacent terrane suggest that ground ice was widespread prior to volcanism, and that a subsurface cryosphere could have provided a source of water for hydrothermal systems. Numerical modeling of hydrothermal systems developed adjacent to a 500 km^3 intrusion suggest that discharges of water exceeding 1.0×10^{13} m^3 during the cooling history (Gulick 1995). This volume is probably sufficient to carve the small valley networks on Mars even in the presence of a subsurface cryosphere. Planetary-scale hydrological models for Mars support the presence of a global groundwater system that is capable of replenishing long term losses of ice and water to the atmosphere by such surface outflows (Clifford 1993).

In conclusion, under cooler climatic conditions, the shallow portions of hydrothermal systems on early Mars would have been dominated by magma-cryosphere interactions and the effects of declining atmospheric pressure. Given the greater efficiency of volatile outgassing and magmatic cooling afforded by the lower gravity of Mars, the attenuated atmosphere, and a permeable megaregolith, hydrothermal systems are likely to have had lower average surface temperatures than comparable geological settings on Earth. Compositionally speaking, the predominance of basaltic host rocks on Mars suggests hydrothermal fluids and associated deposits relatively enriched in Fe, Mg, Si and Ca, similar to hydrothermal deposits in mafic volcanic terranes on Earth. Thus, surficial hydrothermal deposits are likely to be dominated by lower temperature, mixed iron oxide and carbonate mineralogies.

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DISCUSSION

Jakosky: Why do you think the structure in Fig. 8. is **an** impact crater?

Farmer: Because of the general circular morphology. The crater rim was removed by erosion, and the flat crater floor is interpreted to be an impact melt sheet. Brakenridge et al (1985) used this as an example in their paper. I wonder if Mike Carr would be willing to comment?

Carr: When you go back to the earliest history of Mars, you see impact craters in all stages of degradation. This one, for example, is a rimless depression, but it is simply an end-member of a continuous series of craters degraded to different degrees.

Jakosky: I have seen many impact craters, and this one looks distinctly different.

Carr: It is obviously a dual crater.

Davies: Has the rim eroded away?

Carr: Yes. There was a dramatic change in erosion rates at the end of heavy bombardment, around 3.8 Ga, such that these old craters look extremely eroded, whereas younger craters are barely eroded at all.

Davies: So was there a much thicker atmosphere then?

Carr: Yes, I think so.

Farmer: How do you feel about the idea of impact-crater-related hydrothermal systems?

Carr: I think that is very plausible. What I do not accept, with respect to the effects of hydrothermal activity, is that under the present climate conditions the water could ever get back in the ground. That's a part of the Gulick and Baker story.

Davies: Where does it all go?

Carr: Various places. Some was lost to space, some was frozen out at the poles, and some formed permanent ice deposits at high latitudes.

Knoll: In years gone by, a paper on this subject would have discussed at length the evidence for standing water: what is the present thinking on this issue?

Farmer: My feeling is that if standing water was present at all, it was probably only for short episodes.

Carr: If you look at the size of some of those large channels, you can calculate the volumes of water must have gone through them. They must have formed small lakes. I see no problem in having small lakes that then freeze over, leaving a permanent ice deposit. My perception is that we're seeing an equilibration process whereby the water at high regions of the planet ends up in low regions where it forms permanent ice deposits. Others have proposed the multiple formation of oceans, but this hypothesis has so little backing and causes so many problems in terms of the mechanisms involved that I can't accept it.

Knoll: That is important, because if what you say is true, hydrothermal systems on Mars would be the only suitable environment for life.

Jakosky: I didn't want to let Mike's comment about the problem of getting water brought to the surface by hydrothermal systems back down again pass completely unchallenged. The problem, of course, is that temperature is too cold for liquid water to be stable at the surface, but I think there are a couple of ways by which you might be able to do it. One is under different climatic conditions with different orbital elements, because the obliquity changes dramatically: if you can put enough CO_2 in the atmosphere, you can raise the temperature enough to let the water dribble back. The other is the exchange near the surface of hydrothermal water with ground ice. It is not clear that either of these will work, but I think it's premature to rule out exchange.

Davies: If there was continued episodic bombardment of Mars, would that raise the temperature sufficiently so that for a short period of time the water could be re-liquified and go back?

Jakosky: I don't know.

Pentecost: Most of Earth's hydrothermal travertines are fault-guided and in many areas you can see alignments of travertine deposits. It may be worth looking for alignments on Mars.

Farmer: We would need much better spatial resolution than we currently have to get to the observational scale that you are talking about. The lineaments along which travertine deposits in Yellowstone National Park are aligned are only hundreds of metres long and would not be visible on the most of the Viking images. The only features I have looked at that might be fissure-related are those I showed on the Cerberus volcanic plains south west of Elysium which have black lineaments with halos of lighter albedo. Those could be due to hydrothermal alteration, or to variations in grain size of pyroclastics erupted from fissures. It is hard to say without additional data.

Pentecost: If one has hot water flowing up from a spring onto a surface, is it possible to model how long that water will remain water, given the discharge and the temperature?

Farmer: Dr Virginia Gulick, a National Research Council Postdoctoral Fellow at Ames, has been doing this kind of model-based work. Perhaps the most interesting models involve the incorporation of a confining layer of near-surface ground ice. The bottom line is that from a small igneous intrusion she can sustain thermal systems for a very long time. Even with the presence of confining ground ice, these systems can apparently be sustained for periods long enough to carve the kinds of channels that we see.

Henley: It occurs to me that whilst those channel ways are impressive, the amount of water that is actually being mobilized compared to the amount of water that over time **is** convecting within the system is actually very small. So down below, there is a convective system, but only a small amount of water discharging at the surface.

Trewin: I have no experience of the surface of Mars, but it looked as though the rims of the large channel (~45 km wide; Dao Vallis) were raised. The morphology looks very similar to the bottleneck slides that occur on delta fronts in the Mississippi, with slurry and debris flow in the channels. Is it possible that it is not water that was flowing down those channels, but something with viscous strength, for instance a mixture of ice and whatever?

Carr: That has been suggested. With respect to the large flood features, the water interpretation is pretty secure. We have lots of analogies. One can take the largest flood features that we know on earth (the Chuja Basin flood of Siberia and the Channeled Scablands of Eastern Washington) and they match feature for feature these on Mars. There are very plausible mechanisms for generating these large floods. There are many other indicators of ground water, and in my paper I discuss the mechanisms for getting the water out of the ground (Carr **1996,** this volume).

Powell: Mars is about half the size of the Earth. On Earth, hydrothermal systems seem to have a standard size. Why are the systems on Mars much larger than their counterparts on Earth, despite its smaller size?

Farmer: It seems as if all the geological features on Mars are large by Earth standards. But if you think of it in terms of integrating a single process over a long time and then not destroying the landform (there's no turnover of the crust), then you can perhaps account for the very large volcanoes and channel systems on Mars.

Nisbet: I lived in Saskatchewan for many years, and so I got quite used to temperatures of −40 °C. Even as cold as this, ice disappears quite fast by ablation, especially if there's some wind. Presumably the Martian ice-covered lake would have disappeared pretty fast, unless it was covered in dust?

Curr: If the lake forms at low latitude, it disappears. But at high latitudes, where the mean annual temperature is well below the frost point, it is permanent. You can calculate what the sublimation rates are. If you simply cover the lake with a thin layer of dust, it lasts forever.

Nisbet: My second question is about finding fluorine, which goes back to Jim Lovelock's old idea of releasing CFCs into the atmosphere (and maybe we could add some methane too), in order to warm up the surface of Mars. Presumably, finding supplies of chlorine and fluorine would be a secondary target of any exploration. I was interested that you mentioned the evidence for maars on Mars. Have you looked for places, such as this sort of volcano, where you might find fluorine and chlorine, particularly fluorine?

Farmer: Not specifically.

Nisbet: Presumably it remains a real, if distant possibility that you could make a million tonnes of CFCs and turn some of the CO_2 into methane by creating ponds and bogs colonized with methanogenic communities. **As** a long-term option Lovelock has a point: we could think of warming up the planet. It's well within our power, even now. Would it be worth doing? Or ethical? Deep ecologists would prefer it barren of life, I suspect, or would argue that as long as there is a chance of indigenous life, we should not add our own biology.

Huntington: One thing that interests me about these pictures of the surface of Mars is that there's little evidence of any brittle failure. **Is** this a correct perception, or is it all masked by the ejecta from the craters? There is all this erosion, sapping and these channels, but one never sees intersecting brittle structures.

Carr: You do, it's just the region we're looking at here. There is a vast system of faults; in this particular area you don't see much of them.

Farmer: There are certainly vertical faults; I don't know about lateral shear zones.

Carr: 99% of the faults we see are normal faults, but there are huge fault systems. There is a big bulge on the equator. It is 4000 km across and 10 km high at the centre. Around this bulge is a radial set of fractures that extend perhaps over a third of the planet. There is a complementary set of ridges that are compression features, and they are circumferential around this structure. The fracture pattern and the compressional ridges are consistent with the present load being carried by the lithosphere.

Duvies: With the early hydrothermal systems on Earth, the moon would have been closer then and the tides would have been enormous. There are two reasons why this might be important. First, the huge changes in the sea level and, consequently, pressure; second, the dissipation of energy in the Earth's crust, heating it. Is this at all relevant?

Jakosky: Tidal heating is negligible.

Duvies: Even with the moon much closer?

Jakosky: Yes, there's just not much energy.

Duvies: What I've heard this afternoon doesn't make Mars in the past sound any better suited to life than Mars today. Why did we all think it was a better place for life *3.5* Ga ago than it is now?

Curr: For one thing, the evidence for water: when we go back as far as we can look, about 3.8 Ga, the evidence is that water is far more abundant. There are more channels and valleys. Another factor is that modelling of the heat flow would suggest that when Mars emerged from the end of heavy bombardment about 3.8 Ga, the heat flow was five times as high as at present, so there should have been more volcanism.

Duvies: Has all volcanism now ceased? Presumably there is still a heat outflow and processes such as the liberation of water could continue.

Curr: With time, volcanism has become much more restricted to one or two areas of the planet. But early on there was much more extensive volcanism.

Stetter: **Is** there anything known about the driving forces of volcanism on Mars?

Curr: The source of most of the heat is accretional energy. Schubert et al (1990) have modelled the convective systems that you might expect in a planet the size of Mars. With the appropriate starting points from the current models, they showed a very small number of convective cells which is consistent with the very localized distribution of volcanic action on Mars.

Farmer: Radiogenic element concentrations in the SNC meteorites are comparable to abundances on earth, so radiogenic heating should be an equally effective way of providing internal heat.

Curr: Yes, but the dominant factor is accretional energy. In fact there is somewhat more potassium on Mars than in the Earth, so radiogenic heating may be somewhat larger.

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