PHYSICAL CHARACTERISTICS, GEOLOGIC SETTING, AND POSSIBLE FORMATION PROCESSES OF SPRING DEPOSITS ON MARS BASED ON TERRESTRIAL ANALOGS.

L. S. Crumpler, New Mexico Museum of Natural History and Science, 1801 Mountain Road NW, Albuquerque, NM 87104; lcrumpler@nmmnh.state.nm.us.

Introduction. Spring formation is a predicted consequence of the interaction of former Martian aquifers with structures common to Mars, including basin margins, Tharsis structures, and other structural deformation characteristics. The arid environment and high abundance of water soluble compounds in the crust will have likewise encouraged spring deposit formation at spring sites. Such *spring deposits may be recognized from morphological criteria if the characteristics of formation and preservation are understood.*

An important first step in the current Mars exploration strategy [10] is the detection of sites where there is evidence for past or present near-surface water on Mars. This study evaluates the large-scale morphology of spring deposits and the physical processes of their formation, growth, and evolution in terms that relate to (1) their identification in image data, (2) their formation, evolution, and preservation in the environment of Mars, and (3) their potential as sites of long-term or late stage shallow groundwater emergence at the surface of Mars.

Purpose of this Research. The general geologic diversity of spring deposits and the factors controlling their formation and distribution are poorly constrained and incompletely documented. In addition, the relative importance of concentrated thermal sources (magmatic heat), water heated through deep groundwater circulation, and the mechanisms whereby water may circulate and emerge at the surface have been documented for limited settings. Systematic documentation of the range of spring deposit morphologies and their modes of formation is needed in order to search for spring deposits in the appropriate places on Mars and to be able to identify spring deposits given their wide range of characteristics. A survey of the large-scale morphologic characteristics and the geologic processes of spring deposits from the perspective of aerial identification, surgical processes, and general geologic association is needed in order to provide geologic context for biological, chemical, and *in situ* analyses and resource utilization studies.

Research on spring deposits has focused to date on obvious thermal springs consisting of combinations of carbonates, sulfides, related mineral species, and siliceous sinter, *yet the vast majority of springs are of non-thermal origin and are constructed from low-temperature minerals dissolved in deeply circulated ground water*. This second (low-temperature) type is likely to be important at many sites on Mars where groundwater emergence may be governed by hydrologic gradients more so than simple thermal convection. It is also likely to be more widespread given the limited occurrence of volcanic settings on Mars. The physical processes of mineral spring development, and the importance of an arid environment in preserving and controlling these processes, are not well studied. This study establishes (1) the characteristics by which they can be morphologically recognized to provide additional criteria for high science potential, and the details of spring deposit deposition, and (2) the structure that may relate to accurate identification and interpretation of outcrops at lander and rover scales of observation.

Spring Deposits on Earth. Deposits accumulated at the site of springs have been studied for their economic importance [*1*], and because their chemical and biological origins are significant to understanding both early hydrologic and biotic processes [*2*]. Although it is frequently assumed that spring mound formation is associated with warm ("hydrothermal") springs, many, and arguably most, examples arise from water emerging at or near ambient temperature (**Figure 1**). The observed temperature of most active spring discharges associated with spring mound formation is

Figure 1. Vioew of an ctive travertine spring deposit occurring along the western margin faults of the Rio Grande rift, New Mexico. The source springs are ambient temperature at the source.

deposits that may be applicable.

Characteristics of Spring Deposits. Spring deposits may be as thick as 100 m and cover hundreds of square kilometers. They generally occur in one of five basic morphologies [*3*]: cascades, lake-fill, sloping mounds and fans, terraced mounds, and fissure ridges. In addition to these morphologies, a central vent-like (cratered cone) characteristic of non-thermal mineral springs occurs in a significant number of sites throughout the Southwest. Cratered cone spring morphologies appear similar to small volcanoes in that they constitute distinct cones several hundred meters to over a kilometer in basal dimension that are frequently surmounted by a summit "crater" (**Figure 2**). The differing morphologies arise because the process of volume accumulation is constrained by the variable geometry and dynamics of a point source. The morphology may be sufficient for detection of spring

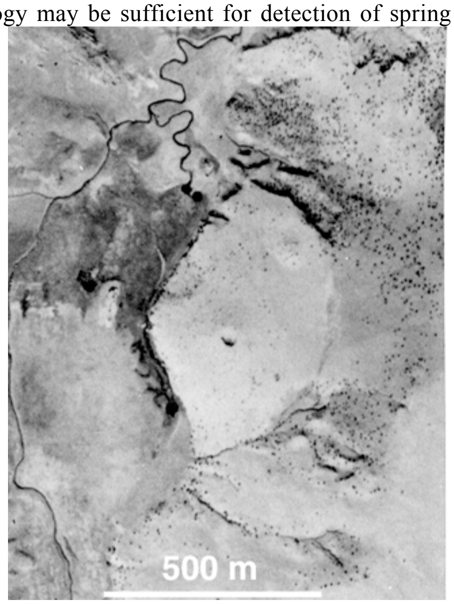

FIGURE 2. Air photo of a typical travertine mound, one of m such mounds consisting of freshwater carbonates associated the emergence of deeply circulated ground water along high-a fault lying down the hydrologic gradient from the Springer volcanic field [*11*].

sites from aerial and orbital image data when combined with knowledge of environments favorable for spring formation, their morphological variability, and factors influencing their morphology. Spring deposits are predicted to occur where there is evidence for long-term emergence of ground water at the surface or where emergence is predicted from considerations of potential groundwater hydrologic gradients.

Mineralogy of Spring Deposits. A significant part of most spring deposits terrestrially is travertine, a form of freshwater evaporite rock formed by both organic and inorganic processes [*3,4*]. $CaCO_3$ is the primary dissolved mineral in terrestrial spring deposits (Fig. 1), but H_2S is also significant in many springs and supports most of the bacterially precipitated deposits [*3*]. It is easy to envision that other water soluble minerals and elements, such as sulfur and sulfur-iron compounds, could be important where these are important constituents of host rocks.

Geologic Setting of Spring Deposits. Three conditions characterize spring deposits
• tectonism (high-angle faults)
• brine concentration (evaporation)
• water-soluble host rocks (mineral-source)

Throughout the southwestern U.S., spring deposits occur where a significant vertical discontinuity interrupts the subsurface flow and forces the groundwater to emerge at the surface. Many spring deposits are therefore associated with tectonic features such as high-angle faults and other prominent upper crustal discontinuities such as anticlines (Fig. 3) and monoclines.

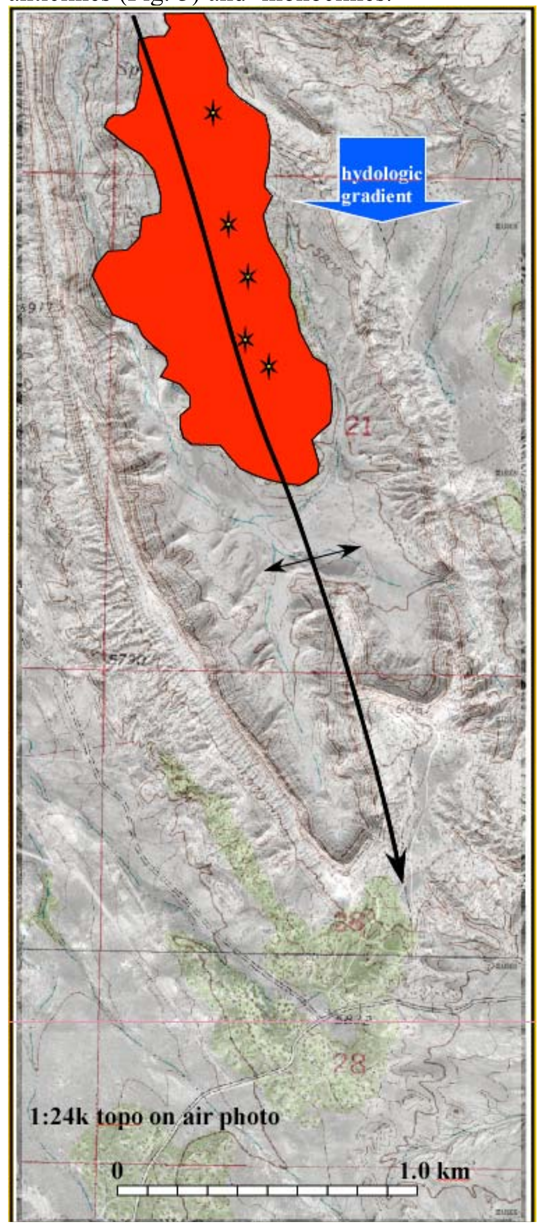

Figure 3. Example of travertine spring deposits (mapped in red) occurring along the axis of a large anticline. Active deposition of spring deposits in the form of conical mounds is occurring from water charged with CO2 and at ambient temperature in this area.

Spring deposits are particularly common in association with high-angle faults (Fig. 4), which act as high hydraulic conductivity conduits for aquifers confined by overlying aquitards and aquiludes. Faults on the margins of basins and other discontinuous structures, such as anticlines, where aquifers are brought in contact with less permeable

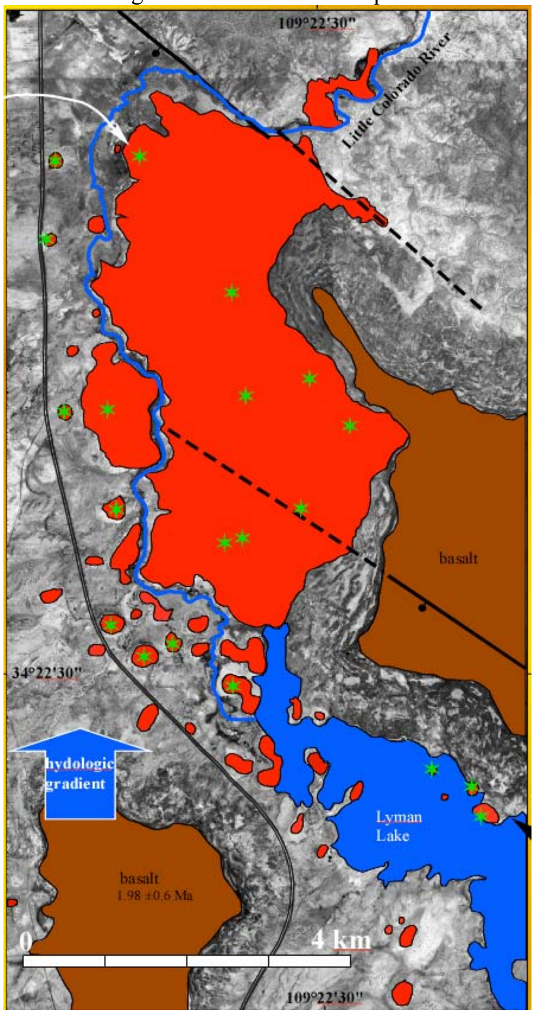

Figure 4a. Active sloping mound and conical mound spring deposits associated with forced convection (high angle fault).

rocks or where an aquifer is abruptly terminated within existing topographic slopes by recent faulting are common sites (Fig. 2, 3). Spring deposits are thus associated with many tectonically active and formerly active areas where evaporation rates and mineral content of spring water are high.

Conditions for Spring Deposit Formation. Based on the observed characteristics of spring deposits discussed above, not all spring deposits are associated with high groundwater thermal conditions. Any physical or chemical condition that results in dissolution of minerals in water and its deposition upon evaporation can result in significant deposits. The morphology of deposits is repeated in many deposits implying that a restricted set of characteristics is common to springs in a wide range of settings.

Results of this study indicate that three conditions are common to all spring deposits: (1) evaporation due to either (a) high temperature or (b) arid conditions; (2) circulation of water vertically within the near surface or upper crust either as a result of (a) free (hydrothermal) convection or (b) forced convection (emergence at a discontinuity); and (3) presence of significant abundances of dissolved minerals: crustal abundance of dissolvable minerals along the hydrologic pathway. On this basis it is suggested that two fundamental types of setting may be identified: (1) thermal type settings and (2) desert type settings.

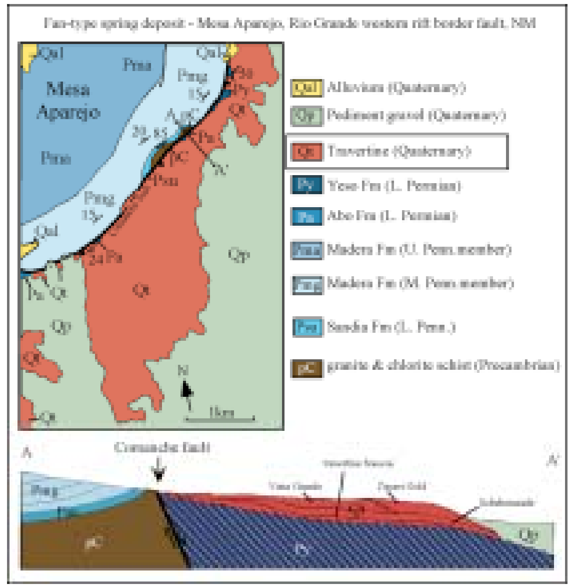

FIGURE 4b. Geologic map of a commercial sloping mound-and-fan type spring (travertine) deposit near Belen, New Mexico. Spring deposits at this site are one of many that are forming where de-watering of the elevated Colorado Plateau geologic section is occurring and water is emerging along one of the western boundary faults of the Rio Grande rift. Spring waters are relatively low-temperature and carbonate-charged. Active deposition is limited to relatively small areas that continually migrate leaving behind inactive deposits. Map after [*12, 13*].

Application to Mars. The upper few kilometers of the Martian crust are likely to be highly fractured [*5, 6*] and thus permeable to fluid flow and aquifer development [*7*]. If water is present in the subsurface as a fluid, it will accumulate within the permeable zone and, under the force of gravity, flow from topographically HIGH regions to regions of discharge at topographically low regions. At that point it is either discharged or accumulated in the subsurface. The gradient on the upper surface of the water-saturated region defines the top of the water table [*8, 9*]. The relief on the water table, or the potenti_ometric surface controls the flow, which is generally a subdued reflection of the surface topography. At the largest scales, we may expect that water in a Martian aquifer of regional extent will flow from high elevations, such as the highlands to lowlands or local basins.

An example setting would be on the margins of basins. Faults and other discontinuous structures, including antiformal and graben type structures, may be common sites where aquifers are brought in contact with less permeable rocks, or where an aquifer is abruptly terminated within existing topographic slopes by faulting. Sulfur, sulfides, and related iron-rich materials may be important water-soluble materials that could constitute spring deposits on Mars. Given the deeply brecciated nature likely for the highlands and the widespread distribution of atmospherically transported volatiles and dust, including volcanic and impact-generated aerosols, the crust is likely to be liberally mixed with compounds that are unstable in water.

There are many physical features over the surface of Mars that are similar to the morphologies typical of terrestrial spring mounds. For example, large areas of pitted mounds, generally interpreted as hydro-magmatic (e.g., "pseudo-craters", *Frey et al., 1979)* or ice-related phenomena (pingos), bear many of the characteristics of summit-pitted spring mounds (**Fig. 5a**). Other anomalous mounds in non-volcanic terrain occur around basin margins (**Fig. 5 b**). these frequently occur in young basins or around the margins of basins.

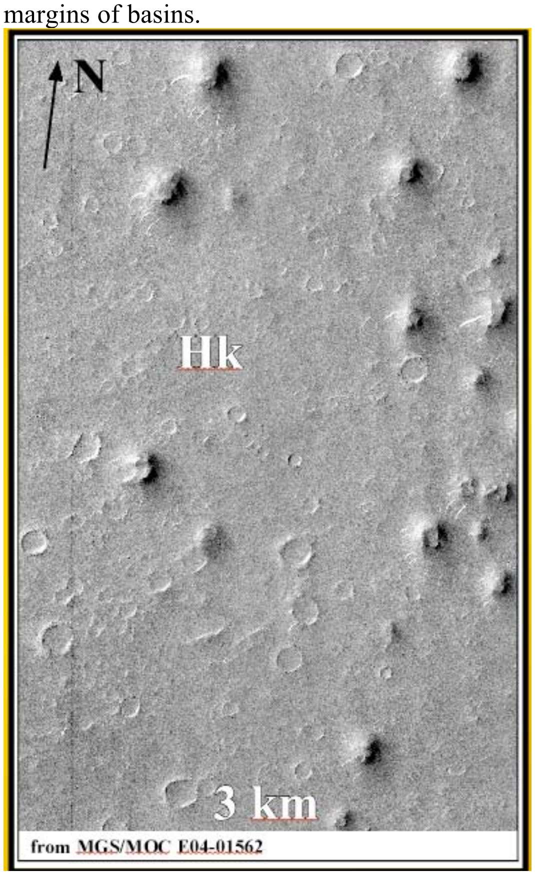

Figure 5a. Pitted mounds within the Isidis basin, long interpreted as possible volcanic conbes, may equally epresent the surface expression of volatile release from the subsurface analogous to spring deposits.

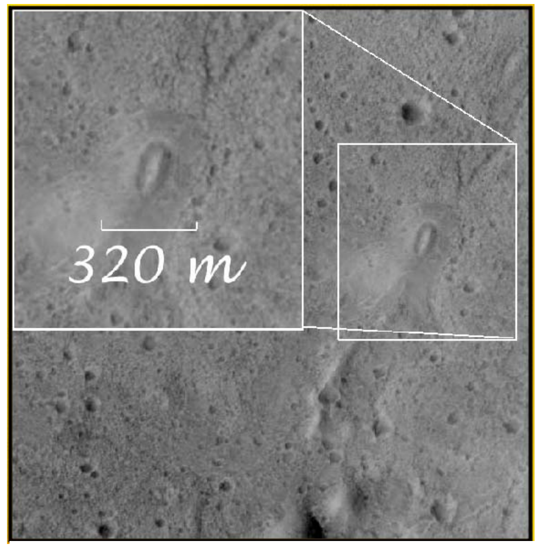

Figure 5b. Anomlous cone located on structure in an otherwise non-volcanic highland region.The area is down-gradient from significant valley network concentrations.

formed from carbonates appear relatively unlikely on Mars because there is as yet little evidence for extensive carbonate in the surface. Nonetheless many minerals are soluble in water and will respond similarly to dissolution, transportation, and deposition during desiccation. The abundant of dissolvable compounds in the Martian crust must be great. Given the deeply brecciated nature likely for the highlands and the widespread distribution of atmospherically transported volatiles and dust, including volcanic and impact-generated aerosols, the crust is likely to be liberally mixed with compounds that are unstable in water. Sulfur, sulfides, and related iron-rich materials may be important water-soluble materials that could constitute spring deposits.

This research is supported by the Mars Fundamental Research Program, NASA.

References. [1]Austin and Barker, . New Mexico Geology, New Mexico Bureau of Mines and Mineral Resources, **12**, 49-58, 1988; [2]Fisher, Unpublished M.S. thesis, New Mexico Institute of Mining and Technology, 152 pp, 1979; [3](Chafetz and Folk, . J. Sed. Petrology, **54**, 289-316, 1983; [4] Julia, Travertines. in Carbonate Depositional Environments, P. A. Scholle, D. G., Bebout, and C. H. Moore, eds., AAPG Memoir **33**, 63-72, 1983; [5]Fanale, Icarus, **28**, 179-202, 1976; [6] Carr, J. Geophys. Res., **84**, 2995-3007, 1979; [7]Clifford, . J. Geophys. Res., **98**, 10973-11016, 1993; [8] Hubbert, . Am Assoc. Petrol. Geol. Bulletin, **37**, 1954-2026,1953; [9]Freeze and Cherry, Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey, 604p., 1979; [10] Mars Exploration Payload Group and Committee for Planetary Exploration, Science Planning for Exploring Mars, , Smithsonian Institution, Washington, D.C. JPL Publication 01-7, 2001; [11] Crumpler, New Mexico Geol. Soc. Field Conference Guidebook, 45th Field Conference, Mogollon Slope, 147-164, 1994; [12] Kelley and Wood, : *U. S. Geol. Survey, Oil and Gas Investigation, Prelim. Map* 47, scale 1:63,360. 1946; [12] Cooper, Unpublished Report to Ultra Marbles Inc., ALbuquerque, 66pp, 1964.