A MODEL FOR MOUND SPRING FORMATION AND EVOLUTION.

P. A. Nelson,[1] M. Manga,[1] M. C. Bourke, [2] and J. D. A. Clarke[3], [1] Dept. of Earth and Planetary Science, University of California, Berkeley, CA 94720, pnelson@berkeley.edu, manga@seismo.berkeley.edu, [2] Planetary Science Institute, Tucson, AZ 85719 USA, mbourke@psi.edu, [3] Australia/Mars Society, Australia P.O. Box 327, Clifton Hill, VIC 3068, Australia, Jon.Clarke@ga.gov.au.

Introduction: Artesian springs in flat and arid environments are known to produce deposits with a characteristic mound shape, and hence are referred to as 'mound springs' (Fig. 1). Mound springs occur relatively rarely on Earth—they have been described in only a few regions worldwide [1 – 5]. However, recent images of the Martian surface have revealed features with morphologies suggesting an origin as spring deposits [6 – 8]. These features bear a striking resemblance to mound spring deposits on Earth. Thus, developing an understanding of the formation of terrestrial spring mounds may help provide valuable insight on Martian paleohydrology.

Our primary field site for this work is the Dalhousie Mound Complex (DMC), located in the northern part of semi-arid South Australia. The morphology, hydrology, and biology of this region has led some to suggest that it is a suitable analog for Martian valley networks [9].

Model Description: We present below a conceptual model of mound evolution using examples from the DMC field site, which contains spring mounds at various stages of evolution (see also [10]).

Springs initially develop when pressurized groundwater flows through fissures and cracks and emerges at the ground surface. The emergent spring water, which is undersaturated in gypsum, dissolves the bedrock's gypsum cement, forming a collapse depression and then a deeper, wider pool (Fig. 2(a)). The spring water, which is saturated to supersaturated in calcite, precipitates calcite along the pool edges (Fig. 2(b)), where inorganic degassing of carbon dioxide is enhanced as the water flows into an outflow channel [11]. As mineral precipitation along the pool edges continues, the mound grows higher (Fig. 2(c-d)), and the hydraulic gradient driving the flow is reduced, causing the discharge to decrease. As a consequence of this decrease in discharge, which to some extent has been explored experimentally [12], the mound diameter decreases, forming a conical or parabolic shaped deposit. Eventually, the mound becomes high enough that the hydraulic gradient is no longer sufficient to provide flow, and the mound becomes extinct (Fig. 2(e)). This sequence of pool formation, mineral precipitation at the pool edges, decreasing discharge, and eventual extinction may be the way in which all mound spring deposits are created, and may explain why they tend to form in clusters.

Figure 1. *A mound spring deposit at the DMC site.*

Mathematical implementation and model assumptions. The system being modeled is depicted in Figure 3. Discharge from the aquifer into the spring is governed by Darcy's Law:

$$Q = \frac{-\rho g \kappa A_{sub}}{\mu} \frac{dH}{dz} \tag{1}$$

where g is gravitational acceleration, ρ is the density of water, μ is the dynamic viscosity of water, κ and A_{sub} characterize the permeability and areal extent of the region though which the water is flowing, d is the depth to the aquifer, and dH/dz is the gradient of hydraulic head. The quantity $\rho g \kappa A_{sub}/\mu$ can be thought of as a transmissivity of the fracture system or conduit through which water flows from the aquifer to the spring.

We assume a constant artesian pressure head, P_{art}. We further assume that there is a characteristic velocity in the pool U which can be approximated as $U = R/T$, where T is the average residence time of water in the pool ($T \approx R^2h/Q$). Because the existence of a pool depends upon the ability of the flow to remove sediment (which may be supplied through aeolian processes or upwelled from the subsurface) as suspended load, we assume that the pool dimensions will be set by this characteristic velocity such that it is equal to the settling velocity W_s of the largest particles evacuated from the pool: $U = W_s = Q/Rh$. If we assume the

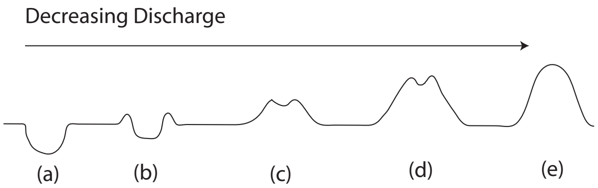

Figure 2. *Schematic of mound spring evolution.*

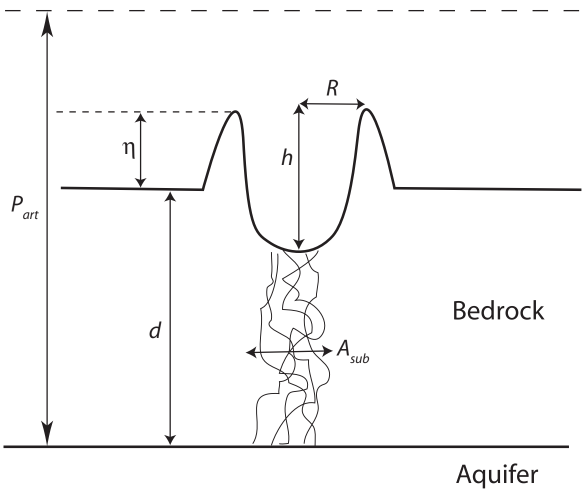

Figure 3. *The modeled system.*

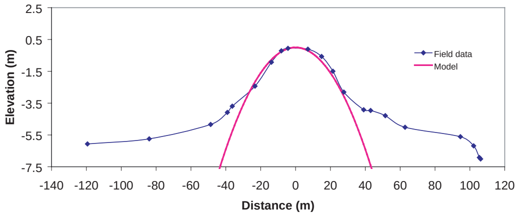

Figure 4. *Example model calculation ((*P_{art} *–* d*) = 0 m,* A *= 0.004 m*$^{-1}$*) plotted against field data from a DMC mound.*

pool retains a self-similar shape throughout the evolution of the spring, such that the depth-to-width ratio remains constant, i.e. $h/R = \beta$, where β is a constant, we can arrive at an expression for the height of the mound η as a function of pool radius R:

$$\begin{cases} \eta(R) = (P_{art} - d) - AR^2 \\ A = \dfrac{W_s \mu \beta d}{\rho g \kappa A_{sub}} \end{cases} \qquad (2)$$

It should be noted that since this model is a physical description of processes that occur chemically (e.g. precipitation of calcite) and because these chemical processes are temperature-dependent, we are neglecting the effects of temperature on precipitation and therefore are assuming isothermal conditions. We examined this assumption by developing a model relating spring outflow temperature with discharge. The model calculates the heat lost from the spring to the surrounding rock as the water flows to the surface. Results from this model suggest that the DMC springs' discharges are large enough to remain essentially isothermal throughout most of their evolution.

Application to Mars and Future Work: Modeling exercises indicate that the parabolic shape predicted by the model does a reasonable job approximating the top and upper slopes of extinct mound springs surveyed at the DMC field site (Fig. 4). The field data suggest that further refinements to the model incorporating evaporation and mineral precipitation on the side slopes of mounds may improve its performance. We are continuing to adjust the model design in accordance with insights gained from field data collected at DMC and other mound springs in New Mexico, USA.

Using only surface topographic data and a few assumptions about soil hydraulic properties, this model is able to infer a region's hydrogeological history. It therefore has potentially useful applications on Mars. Although Martian features are unlikely to be carbonate deposits like most of the spring mounds on Earth, they may represent other water-soluble minerals such as sulfur, sulfides, or other iron-rich minerals [8] for which the generic processes described by this model still apply. With the continuing acquisition of relatively high resolution topography and imagery, we intend to apply this model to some of the Martian features that have been hypothesized to be spring deposits. This will allow us to estimate the hydrologic discharges and hydraulic potentials that would have been necessary to create these features.

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