MAGHNUM – A NUMERICAL SIMULATOR FOR NON-ISOTHERMAL FLOW AND TRANSPORT PROCESSES IN THE MARTIAN REGOLITH AND OTHER PERMEABLE MEDIA.

B. J. Travis[1], J. Palguta[2], C. Barnhart[3], M. McGraw[4], W. C. Feldman[5], Computational Geosciences Group, Los Alamos National Laboratory, MS-F665, Los Alamos, NM 87545, bjtravis@lanl.gov; [2]Earth and Planetary Sciences Dept., UCLA; [3]Earth Sciences Dept., U. California, Santa Cruz; [4]U. Montana, Missoula, MT; [5]Planetary Science Institute, Tucson, AZ.

Introduction: There is an extensive body of physical and chemical evidence for the action of liquid water on the surface and in the near surface of Mars in the past. For example, a recent study [1], using THEMIS data, has found evidence of chloride salt deposits associated with a number of features on the surface of Mars, primarily in the southern hemisphere. Based on their interpretation of the data, precipitation from briny aquifers and surface ponds is a likely source of those salts. Other studies indicate high hydrogen content (and by inference, water content) at the surface of Mars in certain locales [2], even at the equator.

MAGHNUM model: To address dynamics of water, ice and salts in the Martian regolith, we developed the MAGHNUM numerical simulator. MAGHNUM provides a numerical solution of the governing partial differential equations for 1, 2, or 3-D, time-dependent non-isothermal fluid flow and reactive species transport in permeable media. Heterogeneous media (structured, or random/stochastic, or a mix), single liquid phase or two fluid phases (liquid and gas/vapor) plus an ice phase, determined by local thermodynamics, are model capabilities. Dependence of ice melt temperature on salt concentrations, changes in permeability/porosity due to mineral precipitation and dissolution, and hydrothermal-mineral alterations, are model features. It even has a microbial metabolic module.

Previous applications: A previous simulation study of aquifer dynamics in the Martian subsurface, using MAGHNUM, considered only pure water aquifers [3]. It found that hydrothermal convection develops for a range of geothermal gradients, for reasonable regolith properties. Despite a uniform surface temperature, uniform heat flux at depth, and uniform porosity/permeability structure, a non-uniform subsurface ice distribution can develop due to hydrothermal convection in the permeable subsurface. A subsequent, combined experimental and numerical study [4] considered both pure water and salty aquifer dynamics in response to a geothermal gradient. Salts not only depress the freezing point, but can add an unsteady characteristic to hydrothermal convection. Experiments of hydrothermal convection under cold conditions provided testing of the code, as well as measurements of viscosity vs temperature and salt concentration for subzero conditions (Fig. 1). Further experimental testing of hydrothermal circulation in brines under Martian conditions is needed.

Brine aquifers: The dominant Cl-containing salts in Martian subsurface aquifers are likely to be $CaCl_2$ and NaCl [5]. The NaCl eutectic point is about -22 ^oC, while for $CaCl_2$, the eutectic point is -52 ^oC. Geothermal gradients on Mars have been estimated to be in the range of 20 to 40 mW/m^2, with considerably higher values earlier in Mars' history, and possibly even now in certain areas such as the Tharsis region.

We are applying MAGHNUM to study dynamics of brine aquifers [6] having depth-dependent permeability and porosity and a high initial salt content ($CaCl_2$ at about 1 mole/liter) in the pore water, with surface temperature of -60 ^oC, and bottom heat flux of 30 mW/m^2. Using these values, the system convects; that is, the geothermal gradient drives an upward flow of brine through the soil pores. A downward return flow occurs in very narrow channels, "drainage pipes", that are essentially at the eutectic concentration and are completely liquid (see Fig. 2). The narrow "drainage pipes" lead to a non-uniform pattern of ice near the surface; there are icy lenses separated by liquid brine regions. The aquifer between the surface and a depth of about 400 m is partially frozen; fluid motion is still possible. The salinity at the top of the aquifer increases and then water begins to freeze out. Water ice fills the pores of the topmost 50 m of the aquifer, but there are also salt precipitate inclusions in the ice. Other simulations using higher heat flux result in locations where liquid brine is carried to the surface.

Considerable salt precipitates out in the ice layer, about 7.6 cm of pure salt per meter thickness of ice lens, on average for the lower geothermal gradients, and about 15.1 cm per meter for a shallow high heat flux case. If the lens ice evaporates over time, salt deposits will be left behind. Several 3-D geometry simulations have also been made; results are similar to the 2-D cases, but the near-surface pattern of ice is roughly polygonal. The "drainage pipe" features occur at the vertices of the polygons.

Impact crater outflow: Barnhart et al [7] are using MAGHNUM to investigate surface processes associated with impact hydrothermal systems. Fig. 3 shows the distribution of simulated water/rock ratios due to focusing of outflow towards the center of an impact crater, as a result of the cold surface and ice formation. Residual impact energy causes hydrothermal convective circulation below the crater floor, resulting in a non-uniform w/r ratio distribution.

Chemistry: MAGHNUM has been coupled to the PHREEQC chemical speciation code [8]. To date, it has been used for studying possible chemical reactions and hydrothermal circulation inside planetesimals, but it could just as well be applied to aqueous chemistry in the Martian regolith. We are also coupling the MAGHNUM code to FREZCHEM [9], a chemistry package designed specifically for chemical equilibrium reactions under cold conditions. This will allow us to model complex salt solutions and more accurately determine salt precipitate stratification and near surface mineral alteration.

Other applications: Several other Mars-related studies in progress include dark streaks as unsaturated flow in surface soils, planet scale hydrology, and seepage below polar caps. Non-Mars applications of MAGHNUM include planetesimals [10], hydrothermal convection in Europa's mantle, Enceladus [11], and permafrost on Earth.

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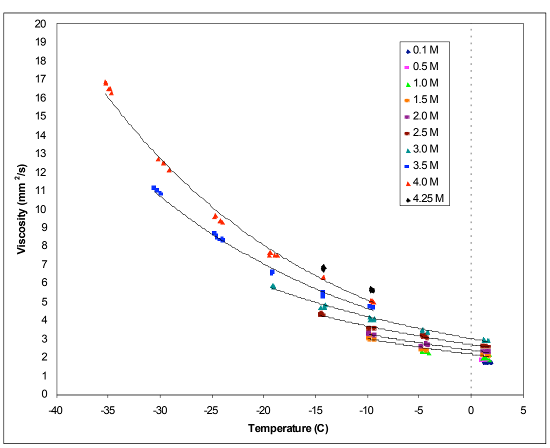

Fig. 1 Measured viscosity of $CaCl_2$ brine vs. temperature and salt concentration for subzero conditions. Viscosity increases by about an order of magnitude near the eutectic point compared to values at 0 ^oC.

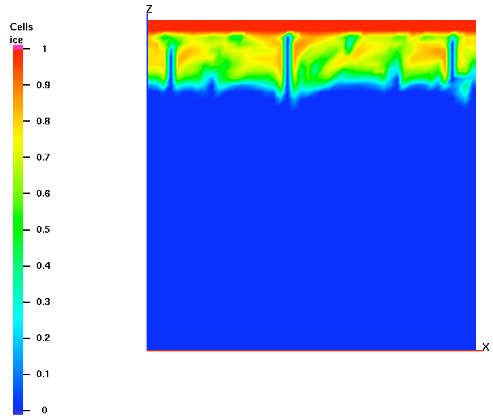

Fig. 2 Distribution of ice fraction on a vertical section through a brine aquifer after quasi-steady state has been established (~3000 yrs). The dimensions of the system shown are 2 km across by 2 km deep. "Ice fraction" here means fraction of pore water that is frozen. The upper 400 m are partially frozen. A roughly 50-100 m thick ice lens has developed at the surface. Narrow "drain pipes" form, that transport completely liquid brine back to the deeper aquifer. If salt were not present, the entire domain would be frozen.

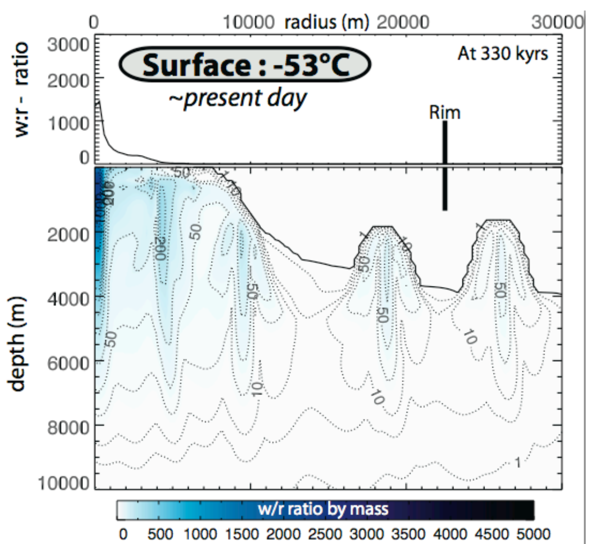

Fig. 3 Water/rock ratios after 330 kyrs after impact, below the floor of the impact crater (image from [7]). The cold surface and ice formation focuses outflow towards the center. The w/r = 1 contour marks the interface between ice and liquid water. The high w/r regions indicate hydrothermal upwelling locations.