A TWO-LAYER HYDROLOGIC MODEL FOR THE IMPACTED MARTIAN CRUST
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Hydrologic conditions in the Chryse region of Mars leading to catastrophic breakout of ground water have been modeled by Carr [1]. He proposed a subsurface aquifer having variable depth, thickness, and hydraulic head, a porosity of 10%, and a permeability of 1000 darcies; he based these hydrologic conditions on the assumption that the aquifer was moderately brecciated volcanic crust. This model permits high rates of discharge through breakout areas such as the chaotic terrain. We find, however, that in addition to catastrophic outbreak, many canyon, chaos, and channel features document the development of debris flows [2,3] that are formed more readily from material that is of low rather than high permeability. Thus the Martian crust must have been hydrologically heterogeneous. We suggest that, at the end of heavy bombardment, it consisted of impact ejecta about 2 km thick underlain by a basement structurally disturbed by impacts. We further suggest that ground-water release from the ejecta and fractured basement can explain most canyons, chaos, and channels in the Chryse region.

Because the crustal structures of the cratered terrains of the Moon and Mars are probably similar, we base our suggestion of Mars' crustal stratigraphy on a recently proposed model for the lunar highlands [4]. The model consists of (from top to bottom) a regolith, ejecta deposits, a structurally disturbed zone, and a fractured basement. The Martian regolith probably consists of impact ejecta, which may have been further comminuted by endogenic processes of erosion during the heavy bombardment [5]. However, unlike the lunar case [4], the Martian regolith thickness is insignificant compared with the thickness of the underlying ejecta in what has been referred to as the large-ejecta zone [4], composed of volcanic and impact-melt clasts. According to a recent stochastic model [6], the thickness of the Martian ejecta zone exceeds 2 km over 60% to 70% of the planet, depending on the total impact density at the end of heavy bombardment. The underlying structurally disturbed zone [4] is composed of fractured blocks that remained largely unmixed [7]; this zone is inferred to extend to a depth of about 10 km, similar to that inferred for the Moon [4]. The structurally disturbed zone is thought to grade downward into a fractured basement [4], which likely extends to a depth of about 25 km. Impact-melt sheets and interlayered volcanics probably accounted for a small volume of the impact breccia crust at the end of heavy bombardment.

We infer that the porosity and permeability of the ejecta zone are determined by the hydraulic properties of finer grained materials that fill the pore spaces between the larger clasts. We base this inference on (a) measured size frequencies of ejecta fragments from terrestrial and lunar impact craters and terrestrial explosions [8], (b) packing theory [9,10], (c) observations that ejecta deposits tend to be very poorly sorted [11], and (d) our porosity measurements of mixtures of fragments with a size-frequency distribution similar to that of impact materials. These measurements and observations suggest that Mars' ejecta zone had an average porosity of about 20% and a permeability of probably much less than 10 darcies.
Because of the intermediate gravity of Mars, an upper porosity value of about 10% for the top of the fractured zone has been inferred from indirect measurements of porosity beneath large craters on the Earth (4%) [5] and on the Moon (20%) [12]. But the permeability cannot be determined directly from the porosity unless either fracture width or fracture density is known [13]. As an example, for a porosity of 10% and a cubic distribution of fractures 1 m apart [13], we calculated a fracture width of 3 cm and a permeability far exceeding what can be calculated by Darcy's Law [13]; although we cannot realistically calculate permeability, we agree with Carr [1] that permeability values may be high (about 1000 darcies). The porosity and permeability of the fractured zone would decrease with depth as the density and width of fractures decrease. In summary, our two-layer model consists of a fractured zone about 10 km thick of low porosity (less than 10%) and of high permeability (about 1000 darcies), overlain by an ejecta zone > 2 km thick of moderate porosity (about 20%) and low permeability (less than 10 darcies).

After complete or partial saturation of their pore space, the ejecta and fractured zones may have become hydrologically unstable, producing various types of mass-movement, collapse, and outflow features. The ejecta zone's clast distribution may have been similar to that of a matrix-supported debris flow [10]; if it was noncohesive, this zone could be readily fluidized. If exposed scarps of the ejecta zone were weakly lithified and wet, shaking produced by impacts and earthquakes may have destabilized them and generated debris flows [2,14]; exposures that were more strongly lithified may have developed sapping features. In the fractured zone, a variety of geologic processes may have increased pore pressure, leading to breakouts [1] and flooding. These processes may have included freezing of pore water in the ejecta zone, increase in hydraulic head caused by tectonic uplift, geothermal heating, and through-going fracturing from the surface. Although we have not examined all possibilities, our two-layer hydrologic model has a stratigraphy consistent with the early history of Mars [1], and its physical and hydraulic properties account for a broad range of geomorphologic features attributed to ground water.

References Cited: