N92-10770

ROLE OF GROUNDWATER IN FORMATION OF MARTIAN CHANNELS

Alan D. Howard, Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903

A global 3-D model of groundwater flow [1] has been used to investigate possible behavior of groundwater on Mars and its role in creating fluvial features. This report supplements and expands on conclusion drawn from an earlier 2-D groundwater model [2], and is organized into topical headings:

Timescales of groundwater flow: Results from the 3-D model [1] confirm the timescales for draining of near-surface aquifers inferred from the 2-D model [2]. The modeling indicates the difficulty of sudden mobilization of large quantities of groundwater to create outflow channels as suggested by Carr [3]. Aquifers with high permeability (e.g., 10^3 darcies) would tend to drain to the lowest available discharge point within 10^4 years, probably shorter than timescales for development of confining permafrost. If this water were confined by a coherent permafrost, highest artesian gradients would not be in the location of outflow channels but in the lowest basins on Mars, including those in the northern plains and especially Hellas (Fig. 1).

Because of the distributed nature of inputs, recharge of aquifers from surface infiltration from rain, snowmelt, or permafrost degradation occurs very rapidly, with timescales for equilibration with a constant recharge rate of 1 to 10 cm/yr being on the order of 10^5 to 10^4 years. Spring-fed streams and groundwater sapping processes would become active during relatively brief periods of climatic amelioration due to orbital variations, volcanic activity, or impact events or due to regional changes in geothermal heat flux due to volcanism.

"Wet" Areas on Mars and location of outflow channels: The global simulations imply which areas were likely to have been characterized by the presence of near-surface waters or groundwater efflux during past epochs. The groundwater model utilizes present topography (Fig. 1), except that most simulations conceptually fill in fluvial channels in order to examine flow conditions contributing to their formation. An accompanying abstract [1] argues that the present topography can be considered to be indicative of conditions during channel development.

Figure 2 shows areas that have steady-state water levels less than 200 meters below average land surface elevations under for areally uniform recharge and for a variety of values of the recharge to permeability ratio (Q/k). Although the assumption of surface recharge may be invalid for most or all of Mars' history, the simulations still show the likely flow patterns, relative depths, and exit locations of water introduced into regional aquifers from any source, including melting of surficial permafrost layers. Potential wet areas are primarily located in the lowest portions of the planet (Hellas and low portions of the northern lowlands) but also in moderate-depth regional depressions (e.g., Argyre). Wet areas also occur along lower portions of regional slopes, particularly in low areas intruding into highlands; such areas are generally also locations of strong groundwater discharge. Outflow channels and some larger valley networks are generally located in such areas (Fig. 1), such as Al Qahira, Ma'adim, lower Kasei, Maja, and Vedra Valles, the possible source of Kasei adjacent to Hebes Chasma, and the chaotic terrain of Margaritifer Sinus and associated outflow channels. The major exceptions are the channels emptying into Deuteronilus and Protonilus Mensae (Auqakuh and Huo Hsing Valles and Deuteronilus channel) which according to present topographic maps are near the crest of the upland-lowland scarp, and Mangala Valles, which is indicated to flow across a topographic nose.

Implications for Valley Networks: By contrast with the outflow channels, concentrations of valley networks (stippled in Fig. 1) generally occur on high portions of the cratered uplands and thus in areas that are relatively "dry" (Fig. 2). That is, any recharge or release of water by melting of regolith ice would tend to migrate vertically to a deep water table and then flow laterally to exit in the "wet" areas of Mars. This implies that the suggestions of a sapping origin to these channels [4,5,6,7] are unlikely unless the surface aquifer is very shallow (e.g. perched on permafrost or a duricrust) or water is released locally by melting of permafrost due to volcanic intrusions [6] or impact-generated heat [7,8]. However, the amount of surficial materials eroded during formation of the networks suggests that more volume of water was required than could be stored in the regolith at levels above the channels [2,9,10]. Thus the channels may have originated by runoff erosion (or sapping erosion from perched aquifers) during a warmer and moister Noachian climate [2,11].

The enigma of Hellas: The bottom of Hellas is the lowest location on Mars by a margin of about

2 km. It would therefore be the ultimate base level for global groundwater and regional surface flow. A variety of evidence has accumulated that the northern lowlands has served as a sink for sediment eroded from the highlands-lowlands boundary with corresponding water, mud, or ice-covered seas, and features suggestive of shorelines have been identified [12]. Valles Marineris has layered deposits that may represent subaqueous deposition [13]. The bottom of Hellas also has deposits that could be fluvial or lacustrine, and it has received drainage from two outflow channels. However, cursory inspection of images of the Hellas basin does not reveal the prominent shorelines that should have been formed if Hellas has served as the baselevel for local and planet-wide groundwater flow. A variety of explanations could be devised for the absence of lacustrine features (particularly impermeable rocks on the flanks of Hellas, rapid evaporation, obliteration of shorelines by mass-wasting or eolian erosion, etc.), including the possibility that pronounced regional groundwater flow has never occurred on Mars except under special circumstances such as by geothermal melting of permafrost.

Absence of fluvial or periglacial features on Syrtis Major: Most of the strongly sloping highland-lowland scarps exhibit either development of outflow channels or periglacial features such as fretted terrain [14]. The absence of either on the strong Syrtis Major slope is problematical, particularly because Syrtis Major is a major re-entrant of the highland-lowland scarp, which in other circumstances has generally encouraged formation of channels. One explanation might be the absence of late-Hesperian or Amazonian volcanism, which has been argued to be instrumental in melting of ground ice to form the circum-Tharsis outflow channels [3,15]. However, Syrtis Major has a very small contributing upland area, and much of the subterranean water could have been diverted to the nearby and lower Hellas (Fig. 1). In fact, the simulations show that "wet" conditions are mostly limited to Isidis Planitia (where features suggestive of a former periglacial and/or lacustrine environment abound [16]) and do not extend far up the regional slope onto Syrtis Major (Fig. 2). The presence of thick volcanic plains in Syrtis Major may also have contributed to a deep water table.

Development of chaotic terrain and associated outflow channels: A role of artesian groundwater in development of chaotic terrain and its associated outflow channels has been suggested by Carr [3]. Carr's model, involving rupture of an artesian groundwater reservoir confined by permafrost, requires very high regolith permeability, but this model has deficiencies discussed above. Chaotic terrain has also been compared to collapse features resulting from permafrost degradation or to sudden mobilization (liquefaction) of sediments with high void ratios [17]. These models require mechanisms for generation of large ice contents in the regolith. A mechanism is suggested here which combines aspects of the Carr [3] and Nummendal and Prior [17] models. The chaotic terrain lies near the base of the highland-lowland boundary in the Chryse trough (Fig. 1). This is a potentially wet area under unconfined conditions and an area of high artesian pressures if confined by permafrost, as pointed out by Carr. Although permafrost is in long-term disequilibrium in equatorial areas [18], import of water from groundwater flow would easily compensate for slow dehydration by water vapor diffusion to the surface through the regolith. Thus a coherent permafrost is likely to have formed in this area. Furthermore, segregated ice would probably have been formed during permafrost growth, and intrusions of ice sills and laccoliths may have occurred due to the artesian conditions. Thus the role of artesian groundwater may not have been a direct dewatering of a large aquifer, but more indirect through slow development of thick ice layers which might then have melted due to intrusions or enhanced geothermal heat flow. Another possibility is slow intrusion but sudden breaching of water laccoliths emplaced at the base of the permafrost. In either case the need for very high aquifer permeability is avoided.

Structurally-controlled valley networks: Some martian scarps are dissected by long, narrow, reticulate valleys that are obviously structurally controlled. The best examples occur in and around the bend of Kasei Valles at 10-33°N 70-80°W, including the Sacra Fossa and the arborescent network dissecting the floor of Kasei. The angle, ψ, included between the tapering sidewalls is a function of the ratio, R, of the scarp backwasting rate along the fracture to that of inter-fracture areas:

$$\text{Sin } \psi/2 = 1/R \text{ .}$$

Measurements in Sacra Fossa suggests R values from 5 to more than 35. Recharge-fed sapping valley networks on the Colorado Plateau show much less extreme structural control, even where fracture control is best developed [19]. The very strong structural control may be due to sapping by artesian upwellings

along fractures. This area may have been characterized by artesian groundwater capped by permafrost with water derived from the Lunae Planum uplands [14]. The spacing between enlarged fractures (ca. 25 km) is probably much larger than the characteristic spacing of fractures in the plateau material, suggesting control by flow through only the widest fractures coupled with inhibition of erosion along intervening fractures due to drawdown effects of those fractures that have been enlarged. The eroded debris could either have been removed by fluvial flow (although the valley walls lack the sinuous undercutting that characterizes valleys such as Nirgal) or by ice flow, analogous to the fretted terrain.

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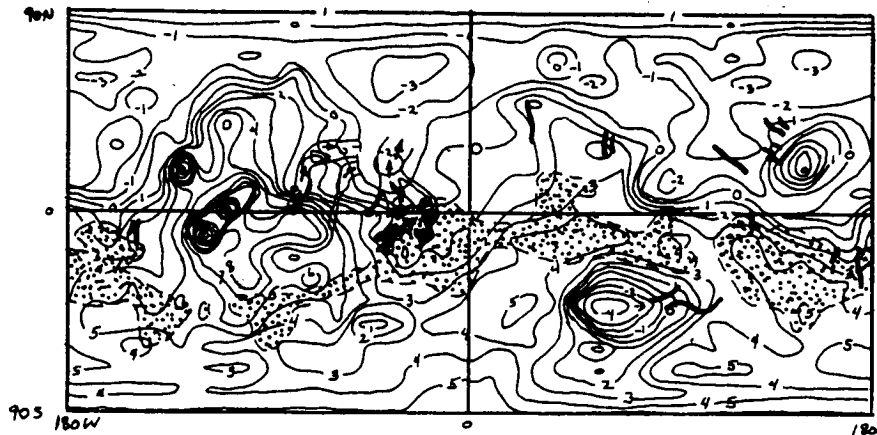
Fig. 1. Contours of generalized mars topography (kms) with areas of abundant small valley networks stippled (from [20]), major outflow channels as heavy lines or thin lines with arrows (Chryse region), and chaotic terrain (cross-ruled).
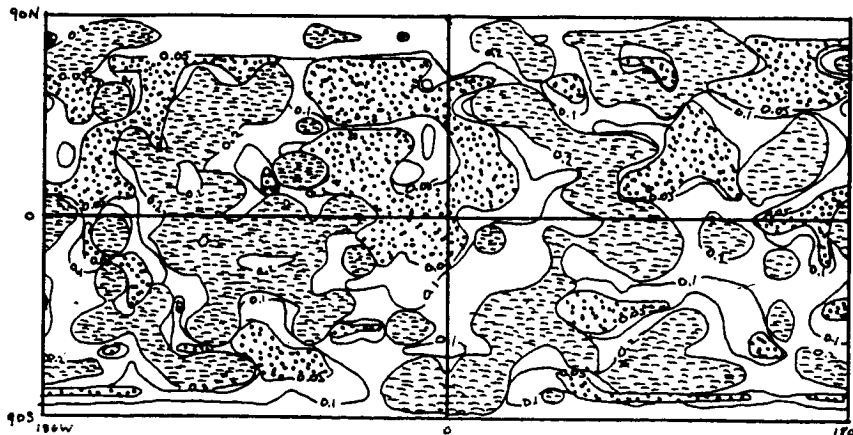

Fig. 2. Wet and dry areas of Mars. Contours show areas with groundwater at steady state within 200 m of ground surface (including saturated areas) for various values of the ratio of vertical recharge, Q (in cm/yr), to intrinsic permeability, k (in darcies). Particularly "wet" areas are stippled ($Q/k \leq 0.5$) and "dry" areas shown by dashed pattern ($Q/k \geq 0.2$ for near-saturation conditions).