OCEANS IN THE NORTHERN LOWLANDS OF MARS? ASSESSMENT OF DIKE EMPLACEMENT AS A MECHANISM FOR RAPID RELEASE OF A CONFINED SUBCRYOSPHERE AQUIFER.

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Abstract: We show that cracking of the cryosphere by dike injection and subsequent release of water from a confined aquifer can take place fast enough to form an ocean in the northern lowlands of Mars.

Introduction: Although the concept is controversial, various lines of evidence support the presence of ocean-scale bodies of water in the northern lowlands of Mars at several times during its early history ([1] and references therein). According to [1], during the Noachian the cryosphere became global in extent and began to thicken sufficiently to provide a seal inhibiting direct contact of the groundwater table with the surface in the northern lowlands, and prior to this, direct communication between groundwater and the northern lowlands guaranteed a Noachian ocean. After seal development, the Noachian ocean froze and sublimed, and groundwater in and adjacent to the northern lowlands came to be under increasingly greater hydrostatic pressures.

Recent work suggests that the Upper Hesperian Vastitas Borealis Formation, covering much of the northern lowlands, is plausibly interpreted as the sublimation residue of a body of water, emplaced in the lowlands coincident with formation of the major outflow channels, that rapidly froze and sublimed [2, 3]. If so, the boundaries of this unit suggest that the northern lowlands were once filled to a level implying a volume of ~2.3 x 10^7 km^3. Age estimates of the outflow channels thought to have been responsible for filling the northern lowlands show a wide range [see 4], well in excess of the interpreted residence time of a standing body of water [2]. This raises the question of whether there might exist a single mechanism for the rapid flooding of the northern lowlands to the implied depths, one that might have operated over a much shorter time span.

One mechanism known to be effective in forming throughgoing blade-like cracks in the upper crust and cryosphere is the lateral emplacement of giant dikes, for which there is much evidence [7], and there is a very high likelihood that dike emplacement on Mars has led to cryospheric cracking, groundwater release, and abundant water outflow [5-8]. Here we address the following question: Could a single dike emplacement event from the southern uplands (say from Tharsis) create conditions such that groundwater under hydrostatic head could be rapidly released through the cryosphere to fill the northern lowlands to the level of the outer contact of the Vastitas Borealis Formation? If so, what would be the configuration of such a feature? What would be the length of time necessary to fill the basin under these conditions? If a single event is not sufficient to accomplish this, how many such events would be required?

We make the following assumptions: 1) the present topography of the northern lowlands approximates that in the Late Hesperian; 2) the margin of the Vastitas Borealis Formation, and thus the elevation of the edge of the water body, is at an elevation of about -3760 m; 3) a dike was emplaced and approached the surface somewhere at or below this level.

Water release through cryosphere fractures: If fracturing of the cryosphere allows water from an underlying aquifer to rise through a fissure, and if the pressure in the water is close to the hydrostatic weight of the immediately overlying cryosphere (the minimum possible value), then the pressure gradient dP/dh in excess of the static weight of the magma which is available to drive the water motion against wall friction will be given by

$$dP/dh = (\rho_c\, g\, h - \rho_w\, g\, h) / h = g\, (\rho_c - \rho_w) \qquad (1)$$

where ρ_c is the crustal density of the crust, ρ_w is the water density, g is the acceleration due to gravity and h is the depth from which the water rises, i.e. the depth to the top of the water layer. If the crust consists of rock of density ~2800 kg m^{-3} (solid basalt) with 30% pore space occupied by ice with density 917 kg m^{-3}, the value of ρ_c will be ~2235 kg m^{-3} and of course ρ_w = ~1000 kg m^{-3} and g = 3.74 m s^{-2}, so dP/dh will be ~4600 Pa m^{-1}. If, however, cryosphere fracturing occurs in a depression surrounded by higher topography, and the breached aquifer system is continuous into that topography, an additional pressure will be available, essentially equal to ($\rho_w\, g\, h_e$) where h_e is the excess height. The lowest part of the northern lowlands of Mars stands about 1.25 km below the boundary of the putative ocean, making this pressure ~4.5 MPa; if the depth to the top of the aquifer system (i.e. the cryosphere thickness) were ~2 km this would increase dP/dh to ~6900 Pa m^{-1}. We use this value in what follows.

The rise speed of water through the fissure, u, is related to the average width of the fissure, w, and dP/dh by the standard fluid dynamics result for turbulent flow, always relevant here:

$$u = [(w\, dP/dh) / (\varphi\, \rho_w)]^{1/2} \qquad (2)$$

with a friction factor φ of order 10^{-2} for crustal fractures [9]. The water flux per unit length along strike of the fissure, F, is equal to ($u\, w$), so that

$$F = w^{3/2}\, [(dP/dy) / (\varphi\, \rho_w)]^{1/2} \qquad (3)$$

There is a minimum speed at which water can rise through the fissure, set by the need for the rising water not to undergo significant freezing against the fissure walls. Finding the time taken for a wave of cooling to penetrate through the ice and the laminar boundary layer of the flowing water to the center of the fissure, and using this time to relate the flow speed to the distance travelled, leads to:

$$u_{min} = (\lambda\, \kappa\, h) / w^2 \qquad (4)$$

where κ is the thermal diffusivity of the ice, about 1.1 x 10^{-6} m^2 s^{-1}, w is the average width of the dike, and λ is a constant which a similar analysis [9] for rising magma in fissures suggests to be ~5. The minimum water flux per unit length along strike of the fissure corresponding to this minimum speed is therefore F_{min} given by $F_{min} = (u_{min}\ w) = (\lambda\ \kappa\ h) / w$. This relationship can be rewritten to define a maximum depth of origin, h_{max}, for any given volume flux:

$$h_{max} = (w F) / (\lambda\ \kappa) \qquad (5)$$

Table 1 shows values of u, F and h_{max} (and the Reynolds number of the motion) for a range of values of w. The variation of h_{max} with w is dramatic; if we assume that aquifers or other water reservoirs on Mars are at depth of at least a few km, then prolonged water release can only occur if fissure widths are greater than about 0.07 m with corresponding water fluxes of at least 0.7 $m^3\ s^{-1}\ m^{-1}$.

Subsequent water flow on the surface: Water released from a fissure and flowing away as a flood with depth d will travel downslope across pre-existing topography with mean slope α at a speed v given by

$$v = [(2\ d\ g \sin \alpha) / \varphi]^{1/2} \qquad (6)$$

and the flux per unit width of the flow, Q, will be equal to ($v\ d$), i.e.

$$Q = d^{3/2}\ [(2\ g \sin \alpha) / \varphi]^{1/2} \qquad (7)$$

where we plausibly use the same friction coefficient as for flow up a fissure. There are two criteria that must be satisfied for the flow to travel to a maximum lateral distance X: it must not freeze, and it must not evaporate into the atmosphere. The main control is the evaporation rate, a function of water temperature and atmospheric pressure. If the atmospheric pressure is less than the vapor pressure of the water at its release temperature, water molecules will be lost at a rate corresponding to a mass flux per unit area of

$$dm/dt = \beta\ P\ [M/(2\ \pi\ G\ T)]^{1/2} \qquad (8)$$

where P is the temperature-dependent saturation vapor pressure, M is the molecular weight of water, G is the universal gas constant, T is the absolute temperature, and β is a constant ~ 0.94. dm/dt is ~0.6 kg $s^{-1}\ m^{-2}$ at temperatures just above the freezing point T = 273 K. Dividing by the water density ρ_w this corresponds to water being lost fast enough to cause the flow to get shallower at a rate of $dd/dt = 0.6 \times 10^{-3}$ m s^{-1}.

We utilize this result as follows. We initially assume that water released from a fracture neither spreads laterally nor is confined by topography as it flows downslope away from the source fissure. Q in eqs. (7) is then the same as F in eq. (3). So, for each fissure width in Table 1 we can find the flow depth d from eq. (7) and the flow speed v from eq. (6). Dividing d by dd/dt gives the time τ required for complete evaporation of the flowing water, and multiplying τ by the flow speed v gives the maximum potential travel distance of the water, X. Table 1 shows the values of d, v, τ and X for a surface topographic slope of 1.25 km in 2000 km, an average value for water flow within the northern lowlands of Mars. The implication is clearly that to have water discharges travel for hundreds of km, the case if the cryosphere were breached near the edge of the northern lowlands, fissures must be at least ~5 m wide. Allowing for focussing of flow by local topography or unconstrained lateral spreading might change the required fissure width by a factor of order 2-3 but would not change the order of magnitude.

However, if filling of the northern lowlands commenced with cryosphere breach near the middle of the region, all that would be required would be for the water depth to increase faster than the evaporation rate until a stable ice-raft had formed on the rising water surface. The ice surface would cool, and because the evaporation rate decreases rapidly with falling temperature the growing ocean could continue to deepen and spread until the water supply was exhausted. The required ice thickness is ~ 0.2 m, since the pressure under this thickness of ice is enough to suppress water vapor nucleation, and this thickness would only require that water flow laterally on a $\sin \alpha$ = 0.0006 slope for ~300 m, thus requiring a fissure width of only 0.04 m (see Table 1) and a water flux of ~0.2 $m^3\ s^{-1}\ m^{-1}$. This is less than the minimum flux (0.7 $m^3\ s^{-1}\ m^{-1}$) to avoid water freezing in the fissure, and so this mechanism is clearly viable. For normal Darcy flow through the aquifer, the minimum flux could readily be achieved for an intrinsic permeability of ~4 x 10^{-8} m^2, similar to that of coarse gravel. At this rate a single 1000 km long fissure would require a few thousand years to fill the ocean; multiple dike injections on this time scale would drastically speed up the process.

Summary: We conclude that dikes propagating northward from areas (such as Tharsis) in the southern uplands, and interacting with and breaching the cryosphere, could have led to flooding of the northern lowlands of Mars to levels limited only by the hydrostatic head and the ultimate equilibrium level.

References: [1] S. Clifford & T. Parker, Icarus, 154, 40, 2001; [2] M. Kreslavsky & J. Head, JGR, 107, 5121, 2002; [3] M. Carr & J. Head, JGR, in press, 2003; [4] K. Tanaka, JGR, 91, E131, 1986; [5] J. Head & L. Wilson, Geol. Soc. SP-202, 2002; [6] L. Wilson & J. Head, Geol. Soc. SP-202, 2002; [7] L. Wilson & J. Head, JGR, 107, 1-10, 2002; [8] D.M. Burr, J.A. Grier, A.S. McEwen & L.P. Keszthelyi, Icarus, *159*, 53, 2002. [9] L. Wilson, L. & J.W. Head, JGR, 86, 2971, 1981.

Table 1: See text for parameter definitions.

w/m	u/(m s^{-1})	F/($m^3\ s^{-1}\ m^{-1}$)	h_{max}/km	d/m	v/(m s^{-1})	τ	X/km
0.01	2.6	0.30	0.05	0.12	0.23	3.2 min	0.04
0.03	4.6	0.14	0.74	0.35	0.39	9.6 min	0.23
0.1	8.3	0.83	15.10	1.15	0.72	32.1 min	1.38
0.3	14.4	4.32	235.43	3.46	1.25	1.6 hr	7.19
1	26.26	26.27	4775.97	11.54	2.27	5.3 hr	43.78
3	45.49	136.49	74450.05	34.63	3.94	16.0 hr	227.49
10	83.07	830.66	1510295.25	115.42	7.20	53.4 hr	1384.44