

**CO<sub>2</sub>-DRIVEN WATER FOUNTAINS DURING WATER RELEASE EVENTS ON MARS.** Alistair Bargery, Lionel Wilson & Adam Neather Environmental Science Dept., Lancaster University, Lancaster LA1 4YQ, UK

**Aquifer conditions:** Aquifers trapped beneath the cryosphere on Mars may occupy depths between ~4 and 10 km [1] where planetary heat flow [2] maintains temperatures above the melting point and ~5 vol. % porosity allows water presence [3]. The temperature at the top of a pure liquid water aquifer is 273 K (in equilibrium with the base of the cryosphere) and if the geotherm is 20 K km<sup>-1</sup> the temperature at the base of the aquifer, 6 km deeper, will be ~393 K. An estimate of the water temperature is thus the average 333 K, i.e. 60 °C. However, hindered convection in pore spaces occupied by aquifer water [4] probably ~halved the vertical temperature difference across the aquifer so the mean aquifer water temperature is more likely be up to ~303 K, i.e. 30 °C. We consider values in the range 283- 323 K, i.e., 10-50 °C.

**Water Release Conditions:** Water forming outflow channels on Mars was commonly released from graben fractures or multiple fracture systems in areas of chaos. In the case of Mangala Fossa feeding the Mangala Valles, the fracture was  $L = \sim 200$  km long [5] and the water volume flux  $V$  was  $10^7$ - $10^8$  m<sup>3</sup> s<sup>-1</sup> [6] with a typical value of  $2 \times 10^7$  m<sup>3</sup> s<sup>-1</sup>; thus the volume flux per unit length along fracture strike was  $V/L = \sim 100$  m<sup>2</sup> s<sup>-1</sup>. For the Cerberus Fossa graben feeding the Athabasca Valles channels the corresponding values are  $L = \sim 35$  km,  $V = \sim 2 \times 10^6$  m<sup>3</sup> s<sup>-1</sup> [7, 8] and so  $V/L = \sim 60$  m<sup>2</sup> s<sup>-1</sup>. The Aromatum Chaos depression extends ~30 km normal to the strike of the Ravi Vallis channel and with a water discharge rate of  $10$ - $20 \times 10^6$  m<sup>3</sup> s<sup>-1</sup> [10] this implies  $V/L = 500$  m<sup>2</sup> s<sup>-1</sup>, but, there were probably numerous fractures within the chaos releasing water. There are ~10 large subsided terrain blocks on the floor of the chaos and if there were this many fractures we would have  $V/L = 50$  m<sup>2</sup> s<sup>-1</sup>. These three cases together suggests taking  $V/L$  in the range 50 and 100 m<sup>2</sup> s<sup>-1</sup>. Water can be driven from an aquifer through a fracture to the surface either by buoyancy or by an excess pressure, dictated by the lateral gradient of the aquifer [8], by tectonic forces [11], or by downward cryosphere growth [12]. We adopt  $dP/dz = 3000$  Pa m<sup>-1</sup> as typical of the likely range of pressure gradients. Water flow up the fracture is turbulent so the balance of frictional forces against driving forces yields the mean rise speed  $U$  of water of density  $\rho_w$  in a fracture of width  $W$ :  $U = [(W dP/dz)/(f \rho_w)]^{1/2}$  with a friction factor  $f = \sim 0.005$  [8]. Hence  $V/L = (W U) = [(W^3 dP/dz)/(0.005 \rho_w)]^{1/2}$  and if  $V/L = 50$ ,  $W = 1.61$  m and  $U = 31.07$  m s<sup>-1</sup>, and if  $V/L = 100$ ,  $W = 2.55$  m and  $U = 39.15$  m s<sup>-1</sup>. We adopt  $W = 2$  m and  $U = 35$  m s<sup>-1</sup>.

The rise time of water from ~3 km depth is then < 90 seconds and the amount of cooling of water through the fracture walls in a 2 m wide fracture is < 2 K [5].

**Source of CO<sub>2</sub>:** We assume that CO<sub>2</sub> is released from a cooling mafic sill and dissolves into the overlying aquifer water. The magma CO<sub>2</sub> content could be ~0.65 mass % [13]. If a sill 200 m thick (comparable to the 100-200 m thickness found for the sill proposed to underlie Aromatum Chaos [9]) with a density of 3000 kg m<sup>-3</sup> is emplaced beneath an aquifer with a vertical extent of 6 km containing ~5% by volume water [5], the sill releases  $(0.0065 \times 200 \times 3000 =) 3900$  kg of CO<sub>2</sub> per horizontal m<sup>2</sup> of its area, which is absorbed by  $(0.05 \times 6000 \times 1000 =) 300,000$  kg of water per horizontal m<sup>2</sup>, so that a CO<sub>2</sub> mass fraction of ~0.013, i.e. 1.3 mass %, is available to be dissolved. CO<sub>2</sub> will dissolve in the high-temperature, high-pressure water at the base of the aquifer but as convection brings water to the low-pressure, low-temperature top of the aquifer it may become supersaturated and be released. If the overlying cryosphere is impermeable (as it should be if the aquifer is truly trapped) then this CO<sub>2</sub> will form a separate fluid phase. However, fractures may have formed in the cryosphere due to the sill intrusion stresses. Aquifer water should then migrate into, and freeze in, these fractures to restore cryosphere integrity but clearly some CO<sub>2</sub> fluid may also be accommodated in the fractures. When at least one fracture propagates completely through the cryosphere (as must happen if we are to have a water release event) any excess CO<sub>2</sub> fluid will be vented along with the first-emerging water. Clearly, the limit on the maximum dissolved CO<sub>2</sub> content of the bulk of the released water is likely to be the CO<sub>2</sub> solubility at the top of the aquifer, at depth ~3 km, where the ambient pressure is  $\sim(3000 \text{ m} \times 3.72 \text{ m s}^{-2} \times 2500 \text{ kg m}^{-3} =) 28$  MPa. Data on the solubility of CO<sub>2</sub> in water [14] show that at this pressure, with temperatures in the range 10-50 °C, the solubility is ~7 to 8 mass %. Thus the aquifer water is very unlikely to become supersaturated as long as it remains within the aquifer. Indeed, the data show that for a CO<sub>2</sub> content of 1.3 mass %, saturation will not occur until the water has risen to a depth where the pressure is ~1-2 MPa, i.e. 100-200 m below the surface. We use this value, 1.3 mass %, denoted  $n_i$ , for the aquifer water CO<sub>2</sub> content in subsequent calculations and discuss the consequences of assuming smaller values at the end.

**Thermodynamics of water ascent:** If (see above) we can neglect heat exchange with the surroundings

then water rising through a fracture as a result of a pressure gradient and emerging into the low pressure atmosphere will cool adiabatically, and either begin to freeze or begin to nucleate vapor bubbles. Using eq. 6 in [15] and converting pressures to lithostatic depths, the adiabatic cooling in water rising through a fracture on Mars will be  $\sim 0.12 \pm 0.09 \text{ K km}^{-1}$ . Thus from 3 km depth the amount of cooling should be much less than 0.5 K and we can regard the water release process as isothermal. The water vapor pressure  $P_v$  in Pa is given as a function of temperature  $T$  in  $^{\circ}\text{C}$  up to  $50^{\circ}\text{C}$  by  $P_v = 610.5 + 60.44 T - 0.168 T^2 + 0.0728 T^3$ . Then using 700 Pa for the martian atmospheric pressure, we can find the depths at which vapor bubble nucleation begins as a function of water temperature. At temperatures of 10, 20, 30, 40 and  $50^{\circ}\text{C}$  the depths are  $\sim 0.05, 0.18, 0.38, 0.72$  and  $1.25 \text{ m}$ , respectively. The key issue is then whether water boiling or  $\text{CO}_2$  exsolution dominates the emergence of the water at the surface.

**CO<sub>2</sub> release during water ascent:** Data in [14] and [16] give the solubility of  $\text{CO}_2$  in pure water as a function of temperature, pressure and salt content. At pressures  $< \sim 5 \text{ MPa}$ , the dissolved mass fraction,  $S$ , is  $S = (7.61 \times 10^{-3} + 1.85 \times 10^{-5} T - 8.5 \times 10^{-7} T^2) P (1 - 0.2001 M + 0.01858 M^2)$  where  $T$  is in  $^{\circ}\text{C}$ ,  $P$  is in MPa and  $M$  is the NaCl concentration as a mole fraction. The types of metal salts in aquifers on Mars are uncertain, but if we assume, say, the equivalent of 1 molar NaCl, we have  $S = 0.78132 (7.61 \times 10^{-3} + 1.85 \times 10^{-5} T - 8.5 \times 10^{-7} T^2) P$  and using a crustal density of  $\sim 2500 \text{ kg m}^{-3}$  we can find the depth at which  $\text{CO}_2$  vapor bubbles should start to form as a function of water temperature. For temperatures of 10, 20, 30, 40 and  $50^{\circ}\text{C}$  the depths are 178, 180, 186, 197 and 215 m, respectively, all  $>100$  times larger than the depths at which water boils, and so clearly  $\text{CO}_2$  exsolution completely controls the final  $\sim 200 \text{ m}$  of water ascent. The formation of  $\text{CO}_2$  bubbles in water causes it to rise faster, partly because of the added vapor volume and partly because vapor expansion provides energy. By analogy with ascending silicate magmas, the speed increase is not large until the point where the vapor bubble volume fraction becomes  $\sim 0.8$ , i.e. 80% of the volume, so that the continuous liquid (here water) disrupts into a spray of droplets suspended in vapor. The large reduction in frictional force at the fracture wall that this causes allows a rapid acceleration, and vapor continues to exsolve and expand until the surface is reached. A good approximation to the energy released,  $E$ , [17] is  $E = [(n_s Q T)/m] \ln(P_s/P_{\text{atm}}) + [(1 - n_s)/\rho_w] (P_s - P_{\text{atm}})$  where  $n_s$  is the mass fraction of vapor with molecular weight  $m$  ( $44 \text{ kg kmol}^{-1}$  for  $\text{CO}_2$ ) exsolved at the point of spray formation,  $P_s$  is the pressure at which this oc-

curs,  $P_{\text{atm}}$  is the surface atmospheric pressure (700 Pa as before),  $Q$  is the universal gas constant and  $T$  is the absolute temperature. Spray formation is located by decreasing the pressure  $P$  below the initial bubble nucleation pressure and tracking the volume fractions of vapor  $q_v = [(n_c Q T)/(m P)]$  and liquid  $q_l = [(1 - n_c)/\rho_w]$  until  $q_v = 4 q_l$  (80% vapor). As the pressure decreases, the mass fraction of vapor exsolved,  $n_c$ , equals the total amount initially dissolved in the water,  $n_s$ , minus the amount still dissolved given by the formula for  $S$  above. The final exit speed,  $U_f$ , of the spray of water droplets and released  $\text{CO}_2$  at the surface is found by adding to  $E$  the initial kinetic energy of the water,  $0.5 U^2$ , and equating this to  $0.5 U_f^2$ . The maximum height,  $H_f$ , of the fountain that forms above the fracture is then given by  $H_f = U_f^2/(2g)$  where  $g = 3.72 \text{ m s}^{-2}$  is the acceleration due to gravity. Table 1 shows values of  $U_f$  and  $H$  as a function of  $T$  for  $n_t = 1.3\%$ . The dependence on water temperature is neither strong nor negligible. Table 2 shows values of  $U_f$  and  $H_f$  as a function of  $n_t$  for a constant value of  $T = 30^{\circ}\text{C}$ . As expected, the dependence is much greater; however, only for aquifer water contents less than  $\sim 0.05 \text{ mass } \%$  does the fountain height decrease to values comparable to the  $[U^2/(2g)] = \sim 165 \text{ m}$  that would have been reached by the water even if it had contained no  $\text{CO}_2$ .

**Conclusion:** Unless martian magma  $\text{CO}_2$  contents were very low by terrestrial standards, many volcanically-triggered water release events should have been accompanied by km-high water droplet fountains.

**Table 1.** For  $n_t = 0.013$

$T/^{\circ}\text{C}$	$U_f/(\text{m s}^{-1})$	$H_f/\text{m}$
10	95.8	1233
20	97.2	1271
30	98.9	1314
40	100.7	1363
50	102.8	1420

**Table 2.** For  $T = 30^{\circ}\text{C}$

$n_t$	$U_f/(\text{m s}^{-1})$	$H_f/\text{m}$
0.013	98.9	1314
0.010	86.9	1015
0.007	73.6	728
0.004	58.4	458
0.001	40.5	220

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