GROUNDWATER PROCESSES IN HEBES CHASMA, MARS. P. M. Grindrod[1,2] and M. R. Balme[3,4], [1]Department of Earth Sciences, UCL, Gower Street, London, UK, [2]Centre for Planetary Sciences, UCL, Gower Street, London, UK, [3]Department of Earth and Environmental Sciences, Open University, Walton Hall, Milton Keynes, UK, [4]Planetary Science Institute Tucson, 1700 E. Fort Lowell, Suite 106, Tucson, AZ, USA (p.grindrod@ucl.ac.uk).

Introduction: Although water is inferred to be a requirement for the formation of interior layered deposits (ILDs) on Mars, the exact nature of the water (e.g. atmospheric, standing, transient) during formation, and hence the timing in relation to the formation of Valles Marineris, is a matter of ongoing debate [e.g. 1-5]. Here we investigate the possible role of groundwater in the formation and evolution of ILDs in Hebes Chasma.

Hebes Chasma is a closed depression centered at 1°S, 284°E, located about 300 km to the north of the main Valles Marineris chasmata system. It has an elliptical outer boundary, with the major and minor axes approximately 315 and 125 km in W-E and N-S directions respectively, covering an area of 25,720 km^2. The total height difference between interior and exterior surfaces is ~9200 m, making Hebes Chasma one of the deepest canyon systems on Mars. Inside Hebes Chasma lies a distinctive layered central mound, Hebes Mensa, that mimics the elongation of the Chasma, measuring about 115 by 40 km with an area of ~4412 km^2.

Groundwater Processes:

Topographic pumping. Any groundwater present beneath the wider region around Hebes Chasma will naturally be driven by the surrounding topography towards the surface at the lowest point, in a process analogous to basin recharge on Earth. However, to investigate the pattern of any possible groundwater upwelling near Hebes Mensa, we look at the pressure-gradients set up by the topography of Hebes Chasma. We apply a topographic pumping method [6], in which it is assumed that a Darcy-style flow is driven by pressure-gradients set up in the solid matrix through which flow occurs. A simple sinusoidal topographic profile approximates a canyon without a central mound, and leads to a zone of upwelling ~75 km wide in the center of Hebes Chasma, as material flows down pressure gradients away from the walls and towards the central low region. By superposing several Fourier modes, we approximate the combined topography of Hebes Chasma with Hebes Mensa, which reduces the zone of upwelling to a central region ~37 km wide. It is likely that topographic pumping is not the only groundwater driving force, but other processes such as capillary action will probably be secondary in magnitude and operate only in the upper tens of meters of the subsurface [e.g. 7]. It is also possible that the groundwater would have risen to the greatest height in the center of the mound, where pressure gradients were greatest, but not necessarily reached the surface. In this case the actual height and influence of groundwater could be greater than that observed at the surface.

Crystallization effects. Any groundwater rising towards the surface would begin to evaporate as it encountered the martian atmosphere, leading to the crystallization of any dissolved species. The process of groundwater upwelling and evaporation will leave a distinctive pattern of crystallization that varies with depth and location in the central Hebes mound. At the surface, evaporation causes the groundwater to become supersaturated, and thus precipitation of primary salts occurs through efflorescence, a process common in building stones on Earth. The first salts to crystallize through efflorescence at the surface will be anhydrates, such as anhydrite ($CaSO_4$) or sodium chloride (NaCl), or low hydrates, such as monohydrates like kieserite ($MgSO_4{\bullet}H_2O$). As the evaporation front moves back into the interior of the mound, continued crystallization increases the concentration of salt in the remaining groundwater, causing salt to diffuse back towards the source [8]. The higher salt concentration in the groundwater that remains in the mound results in the crystallization of polyhydrated minerals such as epsomite ($MgSO_4{\bullet}7H_2O$) and mirabilite ($Na_2SO_4{\bullet}10H_2O$) through subflorescence (crystallization below the surface) [8]. Thus groundwater-driven crystallization will result in different zones of hydration: anhydrates and monohydrates at the surface through efflorescence, and polyhydrates in the interior through subflorescence.

The pressure exerted by a crystal growing in a supersaturated solution within pore space will exert a pressure on the surrounding matrix. This crystallization pressure is greatest when a large crystal grows in a pore with small entries [8], and is often sufficient to cause tensile damage to the host rock. For example, in the sodium sulfate–water system, crystallization pressures are higher at lower temperatures, and at 0°C can be as high as 37 or 27 MPa in mirabilite or the metastable heptahydrate ($Na_2SO_4{\bullet}7H_2O$) respectively [9]. Although this pressure is exerted at the scale of the pores, if a large fraction of the crystals are in contact with their pore walls, and if the matrix is saturated with groundwater, then the crystallization pressures can be directly compared with the tensile strength of the rock matrix [9]. The tensile strength of rocks tends to be of the order of one-tenth of the uniaxial compressive strength [10], and so has an upper limit of up to about

30 MPa. The exact value of tensile strength for a particular rock can vary as a result of a number of factors, including composition, porosity, alteration, stress history, and micro-cracking [10]; for example, the tensile strength of intact basaltic rocks is about 15 MPa, whereas for jointed basaltic rocks the tensile strength is up to 2.5 MPa [e.g. 11]. Similarly, the tensile strength of sandstone can vary dramatically, ranging from less than 1 MPa up to 20 MPa [e.g. 12]. Regardless of the exact tensile strength of any particular rock mass that makes up Hebes Montes, it is clear that stress generated through the crystallization of salts under the right conditions is capable of causing rock fracture and subsequent collapse. In fact, as the higher crystallization pressures are generally the result of the precipitation of the highest hydrates, then it is possible that collapse in the polyhydrated subflorescence layers in Hebes Montes could be more important in the interior of the mound than at the surface.

Observational Evidence of Groundwater:

Zone of upwelling. The N-S distance across Hebes Mensa from the base of the ILDs is ~40 km, matching well with upwelling predicted by the the pressure gradients when a central mound is included. The base of the ILDs in the north and south of Hebes Mensa have elevations of roughly 0 and −1.5 km respectively, suggesting possible local variations in upwelling or increased burial in the north.

Collapse features. Hebes Mensa shows extensive evidence of collapse, with at least five large zones of collapse ranging from 6 to 23 km in width. Although not yet reported in the Hebes region, other ILDs show evidence of monohydrates outcropping on steep slopes and polyhydrates on shallower slopes [e.g. 13]. Polyhydrates have also been observed with a generally lower albedo than monohydrates in Capri/Eos Chasma [14]. These general observations match well with our Hebes Chasma groundwater upwelling and evaporation model, which predicts that crystallization-driven collapse would result in shallower slopes that have revealed the subflorescence zone (polyhydrates) where crystallization is not necessarily complete (giving a lower albedo).

Channel features. We identify three different types of channel feature, all of which are sourced from Hebes Mensa: (1) small-scale channels, (2) inverted channels, and (3) large-scale channels. The small-scale channels are numerous and have a wide range of dimensions, from ~100 to 1000 m wide, and from less than 1 km to over 13 km long. They generally originate from near the top of Hebes Mensa, where many small scalloped depressions join to form a single dominant channel. In some cases large alcoves are also present near the source region, the result of headward erosion of the mound material. Many areas have distinct truncated channels, evidence of several different channel flow directions, and possibly different periods of fluid flow. There are also several examples of sinuous channels, particularly at lower elevations, where the slope is reduced. The presence of inverted channels originating from Hebes Montes groundwater has been noted in a previous study [15]. These channels have a positive topography, are larger in size (up to 25 and 4 km in length and width respectively), and are less numerous than the spring-sapping channels. The inverted channels also usually show evidence of overlapping flows and have an almost deltaic appearance in some locations. The inverted channels also seem to be sourced from lower elevations than the spring sapping channels. The large-scale channels are the least numerous, but have the most well-defined erosional morphologies. The best example occurs to the east of Hebes Montes, is about 3 km wide, 500 m deep, and 26 km long, and has cut through Hebes Montes to create a 'mini-Mensa' [16].

Implications: A combined model of groundwater upwelling and evaporation-driven crystallization and collapse match well with features observed at Hebes Chasma and other ILDs on Mars. This model can also account for the observation of polyhydrates occurring above monohydrates [e.g. 13] (a situation opposite to that expected from an evaporating standing body of water) as the outer monohydrate layer is removed through erosion. Regardless of the chasmata formation method, groundwater processes could produce ILD interiors that are more water-rich than their surfaces, providing interesting targets for future study.

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