

TWO OCEANS ON MARS?: HISTORY, PROBLEMS AND PROSPECTS. James Head¹, Francois Forget², Robin Wordsworth³, Martin Turbet², James Cassanelli¹ and Ashley Palumbo¹. ¹Brown University, Providence, RI 02912 USA, (james_head@brown.edu), ²Lab. de Météorologie Dynamique du CNRS, Université Paris 6, Paris, France, ³Harvard University, Cambridge, MA 02138 USA.

Introduction and History: Geological data have been cited to support the presence of two separate oceans in the past history of Mars, one during the Late Noachian and a later one during the Late Hesperian [1]. The presence of oceans remains a critical question, as evidenced by one of the driving questions of the 2017 4th Early Mars Conference: “*Did early Mars have oceans, lakes, and seas? If so, how did they form? How long did they last? And what was their fate?*” We briefly review the history of these concepts and then use a series of questions to address the current state of understanding of the hypothesis of the two oceans, working backward in time.

Late Hesperian Ocean: Mariner 9 data first revealed evidence for extensive outflow channels (OC) emptying into the northern lowlands (NL) and the Hellas basin (see summary in [2]). After an early debate about the processes that carved them [3], water was quickly settled on as the medium, and the search for the fate of the water began. Early studies emphasized the possible presence of lakes at NL OC termini, but the complex geology of the NL precluded consensus on their size, fate of the water and sediment, and climatic effects of each event, particularly in the context of the current hyperarid, hypothermal Mars climate. At one end of the spectrum, many favored local NL lakes and little climate influence from the OC events [2], while at the other end, some favored an extensive ocean whose presence induced a warm climate [4] and was marked by several shorelines [5]. After extensive debate [2-3], a landmark paper [6] (Clifford, A Model for the Hydrologic and Climatic Behavior of Water on Mars) integrated a variety of data and perspectives and proposed that OCs formed in the circum-Tharsis region by cracking of a thick cryosphere, catastrophic release of groundwater under hydrostatic pressure, to flood the NL; recharge of the global aquifer was by basal melting of the south polar ice cap. Variations on this basic hypothesis [6] represent the current understanding and context for critical outstanding questions about the presence of an Hesperian ocean. **1. Where did the water come from?** Virtually all hypotheses call on cracking of a globally continuous cryosphere and derivation of water from the groundwater (GW) system, but details differ about the exact cryosphere-cracking mechanism [7]. **2. What was the climate at the time?** For the cracked cryosphere/pressurized groundwater release mechanism to work, there must have been a globally continuous cryosphere much like today [8]; supporting evidence comes from glacial-like features at Mangala Valles [9]. **3. How much water was there in each outflow event?** This is still highly debated [10]; early estimates [3,4] assumed bankfull flow and later analyses revealed serious difficul-

ties in sustaining very high flux estimates due to porosity, permeability, and overpressure factors [7]. These early very high estimates are likely to represent peak fluxes and thus lower overall total water volumes [11], with recent total OC volume estimated at 40 m GEL [10]. **4. Does the OC event change the climate to warm and wet? What happens to the OC/NL water during and between the OC events?** Recent climate models show that if the global MAT was similar to today, as required by the cryosphere-breach model, each outflow event would produce a severe regional weather disturbance, local snow precipitation, but no rainfall or any lasting effect on the global climate system [12]. If, for some reason, water did accumulate, a NL lake or ocean would rapidly freeze, sublime and go to cold traps [13]. There is no known mechanism to sustain an ocean in the intervening periods between OC events. **5. What was the period of time between outflow events?** There are numerous outflow channels ranging in age from Hesperian to late Amazonian [14], and the average recurrence is likely to be tens to hundreds of millions of years. There is no known plausible mechanism to preserve an ocean over the time period between OC events; even water in a debris-rich ice-covered salty ocean would rapidly sublime and migrate to cold traps [13]. **6. In the OC breached-cryosphere hypothesis, how does the groundwater (GW) aquifer get recharged between OC events?** MOLA data [15] showed that the Tharsis region cannot be recharged by the traditional south polar cap basal melting hypothesis [6]. Others have shown that top-down ice accumulation and basal melting are not plausible mechanisms for significant groundwater recharge [16] except at volcanic edifice heat pipes, which are volumetrically insufficient. A plausible mechanism for aquifer recharge is not currently available. **7. If the OC/GW breached-cryosphere hypothesis is correct, is there subsurface groundwater at other times in the Amazonian?** The 236 km Lyot crater is an early/mid Amazonian-aged drillhole into the GW system below the cryosphere in the northern lowlands. It does not appear to sample groundwater [17, 18]. This raises the question of the time at which the global ice-cemented cryosphere stabilized, and when the groundwater system might have been depleted due to a growing cryosphere [19]. **8. Is there evidence for the evaporative loss of ocean water in the northern lowlands?** It has been suggested that the Vastitas Borealis Formation (~100 m thick) which overlies km-thick Early Hesperian ridged plains in the NL [20], might be the sublimation residue of OC effluent [13,21]. **9. There is no ocean today: Is there evidence for northern lowlands ocean residual ice buried be-**

neath later deposits? It has been proposed that significant buried residual ice from an Hesperian ocean lies buried beneath the NL surface [22], but the suggested thicknesses are not consistent with the documented stratigraphy [23] and cannot be readily distinguished from later obliquity-induced mid-high latitude phases of glaciation [e.g., 24]. **10. Are there alternative scenarios for OC/GW formation for OCs?** No comprehensive model comparable to [6] has yet been proposed, but volcano-ice contact and deferred melting may provide potential meltwater generation and aquifer recharge mechanisms [25,26]. **Remaining Unexplained:** Several investigators have proposed that unusual features near the dichotomy boundary represent tsunami deposits from impacts into a northern lowland ocean [27-29]. Alternative explanations have not been proposed. Several previously proposed shorelines [5,8] have been shown to vary significantly from predictions for an equipotential surface [30], but not all (e.g., Utopia) have been explained by alternate mechanisms. **Synthesis:** Clearly, the OCs provided water to the NL periodically, but the total volumes, residence times and cumulative effects all still remain unclear. The issues and questions discussed above must be resolved before the presence of an Hesperian ocean can be confidently confirmed.

Late Noachian Ocean: Evidence exists for a “warm and wet” Mars (valley networks, enhanced weathering rates and crater degradation) [31] in the Noachian before the cryosphere had become globally continuous. These features suggest the presence of rainfall and overland flow. **1. Where did the oceanic water come from?** The “warm and wet” interpretation [8] implies global MAT >273K and a vertically integrated hydrologic system; these surface conditions further imply direct connections between the surface and the groundwater system and the presence of a NL ocean [8]. **2. How much water was there?** Noachian shorelines suggest at least a 10% greater area covered than the Late Hesperian Contact 2 (estimated at 100 m GEL) [29], but these contacts are not well defined [30] and alternative estimates for the inventory at this time are much lower [10]. **3. Do the proposed Noachian shorelines define an equipotential surface expected of an ocean?** Proposed Noachian shorelines [8] (e.g., Contact 1) are not well defined and deviate significantly from an equipotential surface [30]. **4. Was the Noachian ocean episodic (as in the OC input to the Hesperian ocean)?** The Noachian ocean is predicted to persist as long as MAT exceeded 273K and the hydrologic system was vertically integrated. Eventual transition to a global cryosphere would have caused freezing of an ocean and growth of polar ice caps. **5. What climate and MAT are needed to sustain a Noachian northern lowland liquid ocean?** To maintain a vertically integrated hydrologic cycle and a groundwater-fed ocean, MAT must exceed 273K. An MAT >273 climate [32-33] predicts some rainfall, but not in places

consistent with the distribution of valley networks [32], and requires a robust and continuous warming mechanism of undetermined character. **6. Where did Noachian oceanic water go?** As the climate transitioned to the nominal Hesperian-Amazonian climate, the ocean froze, sublimated and migrated to cold traps, the ice-cemented cryosphere became globally continuous and sealed off the groundwater system from the surface [8]. **7. What are the implications of the loss of the Noachian ocean for the surface/near-surface water budget?** The estimated volume of the Noachian global ocean (>> 100 m GEL) is added to the polar/surface/near surface ice budget. There is a discrepancy between the surface-near surface water budget and these values [10], which is not readily accounted for solely by the freezing of GW to form the cryosphere [22]. **8. Is there evidence for Noachian northern lowlands ocean residual ice buried beneath later deposits?** Any such deposits [22] would lie beneath ~1-2 km of Early Hesperian volcanic ridged plains [23]; at this lava thickness, buried ice would undergo either top down heating and melting during emplacement, and/or deferred melting and loss to the groundwater system [25-26]. **9. Are there alternative scenarios to the presence of a Noachian ocean to explain the observations?** Recent Late Noachian climate models [34-35] predict global MAT ~225K, a globally continuous cryosphere and no rainfall or surface melting under a wide range of conditions. Punctuated heating events [36], however, are required to cause top-down melting of snow and ice to form the observed fluvial features. **Synthesis:** Multiple subsequent events in the NL have obscured direct evidence for a Noachian ocean; its presence requires sustained global MAT >273K, in conflict with recent climate models. Establishing the presence of a Noachian ocean requires reconciliation of these issues.

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