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TITLE PAGE

Title: SEQUENCE STRATIGRAPHY ON AN EARLY WET MARS

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ABSTRACT

The evolution of Mars as a water-bearing body is of considerable interest for the understanding of its early history and evolution. The principles of terrestrial sequence stratigraphy provide a useful conceptual framework to hypothesize about the stratigraphic history of the planets northern plains. We present a model based on the hypothesized presence of an early ocean and the accumulation of lowland sediments eroded from highland terrain during the time of the valley networks and later outflow channels. Ancient, global environmental changes, induced by a progressively cooling climate would have led to a protracted loss of surface and near surface water from low-latitudes and eventual cold-trapping at higher latitudes -- resulting in a unique and prolonged, perpetual forced regression within basins and lowland depositional environments. The Messinian Salinity Crisis (MSC) serves as a potential terrestrial analogue of the depositional and environmental consequences relating to the progressive removal of large standing bodies of water. We suggest that the evolution of similar conditions on Mars would have led to the emplacement of diagnostic sequences of deposits and regional scale unconformities, consistent with intermittent resurfacing of the northern plains and the progressive loss of an early ocean by the end of the Hesperian era.

INTRODUCTION

Here we examine the geologic consequences of assuming that Mars possessed an ancient northern ocean, subject to declining surface temperatures and atmospheric pressures through the end of the Hesperian. The result is a redistribution of surface and near surface water to the colder regions of the planet, and a progressive draw-down of surface water levels. Mars' northern lowlands are bordered by the global dichotomy (Figure 1), whose greater than three kilometer rise in elevation is assumed to predate the formation of any long-standing primordial northern ocean (i.e., within the first few 100 Myr following accretion; Wilhelms and Squyres, 1984; Smith et al., 1999; Frey, 2006; Watters and McGovern, 2006; Nimmo at al., 2008; Andrews-Hanna, et al., 2008). It is this topography that provided the needed relief for the fluvial transport of weathered and eroded sediments from their southern highland source towards the northern lowlands (i.e., a proxy passive-margin basin). Mars exhibits ubiquitous evidence of an early period of fluvial erosion and deposition (e.g., Carr, 1995; Baker, 2001; Craddock and Howard, 2002; Bhattacharya et al., 2005; Howard et al., 2005; Jerolmack, 2013), the nature, extent and timing of which, may be pragmatically revealed and extrapolated through the proposed use of sequence stratigraphic principles and techniques.

In the terrestrial field of sequence stratigraphy, a sequence is defined as a relatively conformable genetically related succession of strata bounded by unconformities and their correlative conformities (typically surfaces of erosion or non-deposition), which are hypothesized to form in response to cyclic changes in relative base-level, i.e., the lowest level to which fluvial systems flow (Posamentier and Allen, 1999). These sequences are enveloped by sequence boundaries (SB). These unconformities are postulated primarily to be caused by fluvial incision and correlative marine erosion, and are created during falls in sea-level (Posamentier et al., 1988). The stratigraphic point at the beginning of undisturbed subaqueous sequential strata, the correlative conformity, occurs where the sequence boundary meets the paleo-ocean floor at the onset of sea-level fall. The intervening depositional layering produced during falling sea-level is defined by the concept of a forced regression (Posamentier et al., 1992; Nummedal et al., 1995; Plint and Nummedal, 2000; Catuneanu, 2002), and in combination with stratigraphic evolution based primarily on stratal stacking patterns, sequence position and bounding surfaces, as espoused by Van Wagoner et al. (1990), provides an analytical starting point for examining ancient depositional environments on Mars in light of a disappearing ocean. To date, Pondrelli et al. (2008) have used sequence stratigraphic concepts on Mars to examine the temporal development of localized deltaic deposits within Eberswalde Crater.

Understanding the history and evolution of water on Mars is advancing through the introduction of new spacecraft and technologies delivered to Mars over the years. Currently, volcanic and aeolian deposits mantle much of the planet, making the direct and unambiguous detection of allocthonous fluvial and lacustrine sedimentary deposits, structures and mineralogy difficult. Yet, through the use of multiple techniques, such as orbital photogrammetry, spectroscopy, ground penetrating radar (GPR), Gamma Ray Spectrometer (GRS) and limited surface based reconnaissance, highly detailed observations begin to illuminate the planet's ancient and complex climate, volatile, depositional and stratigraphic history. The Mars Explorer Rovers (MER) Opportunity and Sprit and the Mars Science Laboratory (MSL) Curiosity rover show complex and expansive stratigraphically and geochemically layered outcrops and deposits indicative of aeolian, volcanic, fluvial or lacustrine depositional and evaporative processes (Tosca and McLennan, 2006; Hurowitz et al., 2017). Some units exhibit cyclical bundling, differential weathering, stair-stepped morphologies and cover areas over several hundred or thousands of square kilometers and attain thicknesses of several hundreds of meters (Arvidson et al., 2005; Hynek and Phillips, 2008; Lewis et al., 2008). Bedforms, sequences and facies associations, both aeolian and fluvial, are expansive and proposed to indicate regional scale significance (Grotzinger et al., 2005). Mineralogical assessments from orbiting spectrometers also show distinct stratigraphic associations such as phyllosilicate–bearing outcrops; examples include Meridiani Planum (Flahaut et al., 2014), Mawrth Vallis and Endeavour Crater (Wray et al., 2008, Wray et al., 2009; Loizeau et al., 2012). Gale Crater is an example where water born sedimentation provides insight into the history of regionally emplaced sedimentary deposits and highlights the associated dynamics of their accumulation including divisions between subaqueous and subaerial stacking histories (Milliken et. al., 2010). Additionally, changes in bedding orientation, topography, as well as albedo have been observed in Gale Crater (Milliken et al., 2010), and the importance regarding interactions between hydrology and surface topography have been noted by Howard et al. (2007).

In order to determine the depositional and paleohydrologic history of Mars, beyond the upper most strata and thus most recent periods in history, techniques and tools other than imagery, photogrammetry or spectral imagery must be employed. In the fall of 2005, the first subsurface radar observations of Mars were acquired, revealing the details of the stratigraphy, structure, and basal topography of the polar layered deposits (PLD) (Plaut et al., 2007; Phillips et al., 2008), non-polar ice deposits (Holt et al., 2008; Mouginot et al., 2012), and buried channels (Morgan et al., 2013), providing new and direct investigations of the planets subsurface environment. Both the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) and the Shallow Subsurface Radar (SHARAD) continue to collect subsurface data (Picardi et. al., 2005, Seu et al., 2007). An example of an aerially-extensive subsurface reflector, observed by both SHARAD and MARSIS, underlies the Medusae Fossae Formation (MFF; Watters et al., 2007; Carter et al., 2009). Amazonis Planitia, represents one of the largest and smoothest regions within the northern lowlands of Mars, containing expansive volcanic deposits, wide spread evidence of pariglacial landforms, and has been shown by SHARAD to be underlain by at least one regional horizontal subsurface radar-reflective interface (Campbell et al., 2008). Bramson et al. (2015) correlated terrace depth observations with SHARAD reflector data to show that Arcadia Planitia contains upwards of 10^4 km^3 of near surface water ice. Stuurman et al. (2016) recently found

SHARAD reflective regions underlying western Utopia Planitia, and espouse widespread near-surface deposits, 80-170 meter thick, with a significant water ice fraction. Recent theories propose that at least some observed ice deposits are a result of obliquity and climate variations well into the Amazonian era (Head et al., 2005; Madeleine et al., 2009; Rodríguez et al., 2014), which could either mask or interact with an older burred cryosphere. Currently, evidence of deep water fine-scale internal layering or water-table interfaces have yet to be discovered beneath the northern lowlands (Farrell et al., 2009), though potential aeolian layering seems plausible (Séjourné et al., 2012). Therefore, increasingly comprehensive radar investigations of subsurface structures and stratigraphy, combined with increasingly detailed orbital imagery observations and opportunities to test theoretical depositional and structural models, such as the application of the concepts of sequence stratigraphy to regionally emplaced sediments on Mars, are needed in order to delineate the chronological history of northern lowland sedimentary deposits.

In order to further understand the depositional evolution, we apply established concepts of sequence stratigraphy to describe the potential evolution of Martian stratigraphy and propose a general model for categorizing and explaining sedimentary deposits across the northern lowlands of Mars. Our model accounts for unidirectional global climate change through the Noachian and into the Hesperian, where any early northern ocean would have experienced a progressive and protracted decline and lowering of base-level as a result of evaporation, freezing, sublimation, and a redistribution of water to the polar ice caps and cold-trapping in an expanding cryosphere. The timeframe spanning the unidirectional loss of the purported paleo-ocean is regarded in terms of a "perpetual" forced regression. Therefore, near the dichotomy, the primary sequence stratigraphic systems tract or depositional unit in the northern lowlands is hypothesized to be forced regressive in nature, followed by any potential post-ocean deposits. In order to set the stage for the proposed model we first review the current understanding regarding the presumed Martian paleo ocean and propose that the period of sustained desiccation during the Messinian Salinity Crisis (MSC) may serve as a terrestrial analogue to our Martian forced regression resulting from the progressive desiccation of the planet's ancient northern ocean.

1.0 A MARTIAN OCEAN: THE THEORY AND PREREQUISITE ASSUMPTIONS

To date, the Mars Odyssey GRS instrument provides one of the best observations of global near-surface water inventories based on hydrogen abundance (Boynton et al., 2002; Feldman, 2004), and its distribution reflects the process of cold-trapping of subsurface ice at high latitudes; yet, its origins are still questioned. If Mars did possess an ocean, then it seems probable that it formed early in the planet's history (e.g., within 0.1 Myr of the end of a magma ocean phase according to modeling by Lebrun et al., 2013), and similar to the first appearance of Earth's oceans, which where are believed to have formed as far back as 4.404 Gya, just following the Moon forming collision (~4.4 Gya;, Peck et al., 2001; Wilde et al., 2001; Lunine, 2006).

The evidence for climatic conditions vastly different from today (e.g., a warmer and wetter Mars, Carr (1996)), and the presence of an ancient northern ocean minimally includes the identification of potential shorelines (Parker et al., 1986), impact generated tsunami deposits (Mahaney et al., 2010; Rodriguez et al., 2016; Costard et al., 2017), fluvial drainage systems and deposits (Lucchitta et al., 1986; Carr, 1996; Hynek et al., 2010) and a distribution of ice-related landforms along the planetary dichotomy and throughout the northern plains (Séjourné et al., 2011; Davis et al., 2016). In Figure 1 the northern lowlands are shown, including a rough delineation of the planetary dichotomy separating the southern highlands and the northern lowland basin (dark brown contour line), primary water impingement routes (blue arrows) and the low lying areas likely inundated by a paleo-ocean (most likely ferruginous, and possibly green colored, as proposed for certain episodes of Earth's Archean-Hadean ocean predating the Great Oxygenation Event (GOE); Scott et al., 2011). Coincident evidence for a wetter climate and potentially denser atmosphere is widespread and includes valley networks (Luo et al., 2017), rainfall indications and erosion requirements (Craddock and Lorenz, 2017), large, low elevation, long-lived standing bodies of water and their associated sedimentary deposits, or sequences (e.g., lake deposits, channel belts and fluvial-deltaic systems: Cabrol and Grin, 2001; Bhattacharya et. al., 2005; Dromart et al., 2007; crater lakes: Cabrol and Grin, 1999; clay mineral formation: Milliken et al, 2010). Yet, the largest and probably longest lived standing body of water to have existed on Mars would have been an early northern ocean, and its presence is based on expanding lines of evidence (Parker et al., 1986, 1989; Carr, 1996; Clifford and Parker, 2001; Frey et al., 2002; Perron et al., 2007; Luo and Stepinski, 2009; Gaetano and Hynek, 2010; Hynek et al., 2010; Davis et al., 2016), which we continue to briefly explore below.

Sediments covering the northern plains would have been deposited in conjunction with the decline of an early ocean as the planet's climate evolved into something more closely resembling that of today. Many observations support the ocean theory including the distribution of crater excavated hydrated minerals across the northern lowlands (Pan et al., 2017), which imply an ancient underlying hydrated basement. Di Achille and Hynek (2010) further provide a global map showing the distribution of deltas and small valleys, whose morphology is consistent with an origin by rainfall (Craddock and Lorenz, 2017) and distribution within the southern highlands delineates two candidate equipotential sea–level surfaces roughly paralleling the dichotomy boundary at -1680 and -3760 meters respectively. Mounting evidence supporting the ocean hypothesis further includes observations of hydrologically weathered surfaces and materials, the extreme smoothness of the northern plains (Head et al., 1998), and the existence of putative

Martian paleoshorelines (see Figure 1 and 2a) whose elevations appear to approximate an equipotential surface (Parker et al., 1986, 1989, 1993; Head et al., 1998, 1999; Clifford and Parker, 2001, Webb, 2004). Some, possibly expected, discrepancies between the elevation of the purported shorelines and an equipotential surface may be explained when the effects of true polar wander (Perron et al., 2007) and crustal deformation due to the isostatic rebound (Ruiz, 2003; Ruiz, et al., 2004; Leverington and Ghent, 2004) or the growth of Tharsis (Dohm et al., 2009) are taken into account. Debates, regarding the existence of an ocean based on geomorphic evidence of marginal features (i.e., shorelines and wave-cut erosion features) or interior cold-climate features (which are thought to be related to the presence of subsurface ice), continue (Smith et al., 1999; Malin and Edgett, 1999, Car and Head, 2003, Ghatan and Zimpleman, 2006). For example, it has been suggested that the layered terrain of the Vastitas Borealis Formation (VBF), a geomorphic assemblage purported to be related to outflow channel formation, may provide stronger evidence of the ponding of ancient waters and redistribution of sediments within the northern plains than evidence associated with the proposed shorelines (Kreslavsky and Head, 2002; Carr and Head, 2003).

Additional significant evidence supporting the ocean hypothesis results from the estimation that Mars amassed large quantities of volatiles, including an inventory of water sufficient to cover the surface to a depth of between 500 - 1000 meters (i.e., global equivalent layer (GEL)), through the accretion of asteroids and comets and the subsequent outgassing of the interior (Carr, 1996; Lunine et al., 2003). The estimates of historical water inventories are supported by the geomorphic identification of fluvially-cut valley networks (Luo et al., 2017) of Noachian age and outflow channels, apparently carved by the catastrophic discharge of groundwater, whose occurrence appears to have spanned a majority of Martian geologic history but which appear to have peaked during the Late Hesperian (Craddock and Howard, 2002; Tanaka et al., 2003; Kreslavsky and Head, 2002; Rodriguez et al., 2006). Luo et al. (2017) further calculated that a minimum of 6.86 x 10^{17} m^3 or approximately 5 km GEL of water was needed to cut the Martian valley networks. Other geomorphological features along the dichotomy boundary have been identified, including lobate debris deposits, which are consistent with the occurrence of vast impact-generated tsunamis originating from within the northern plains (Rodriguez et al., 2016; Costard et al., 2017); and potential terrestrial sedimentary and geomorphological analogues including the Alamo and Chicxulub impact events (Warme et al., 2002; Claeys et al., 2002; Mahaney et al., 2010).

For Mars, an ongoing debate between the “warm-wet” and “cold-icy” scenarios remain active. As such, any early ocean was subject to unique constraints, including the size of the planet, the formation of the global dichotomy, frequency of large impacts, and the evolution of the planet’s magnetic field, atmosphere and climate (Terada et al., 2009; Tian et al., 2009). Constraints to ocean hypothesis regarding reduced early solar luminosity (i.e., estimated to be 25-30% less than today; Rosing et al., 2010) have been implicated as a potential barrier to early ocean development on Earth and Mars, and climate models favoring the cold early Mars have been similarly forwarded (Forget et al., 2012; Wordsworth et al., 2015). However, Rosing et al. (2010) suggests that, on Earth, low early global albedo (i.e., reduced continental surface area) and the lack of biogenetic cloud nucleation would be sufficient to maintain environmental conditions above the triple point of water, independent of presumed greenhouse-gas concentrations, thus favoring Earth’s first oceans. Such conditions may or may not serve the Martian equivalent argument, yet highlight the some of the complexities regarding planetary atmospheres and ocean development.

We move forward by assuming the former presence of an early northern hemisphere encompassing ocean or multiple large liquid or ice covered ocean sized bodies on Mars. Under this assumption, one would expect to find evidence of periodic or sustained sediment deposition associated with the erosion and runoff that created the valley networks and the earliest catastrophic floods during the planet's first two billion years of geologic history (Carr, 1996). Regions with the most probable occurrence of buried ocean related depositional structures and strata include the oldest and lowest lying basins on the northern lowland boarder, where the major runoff or fluvial access routes cross Chryse, Arcadia and Utopia (Hynek et al., 2010), as shown in Figure 1. Therefore, the theoretical model presented below accounts for ongoing observations that correlate to an ancient ocean and may encourage classification of potential genetic sources of fluvial-detrital and evaporitic sediments, as well as interbedded volcanic, impact and eolian deposits, across the northern lowlands. The structural profiles provided in the model are derived with the hypothetical transect A-A´ in Figure 1 in mind. The regional geology should contain widespread sequences of stacked sedimentary deposits that can therefore be interpreted by applying the precepts of sequence stratigraphy.

2.0 POTENTIAL TERRESTIAL ANALOGUE AND CONSIDERATIONS

On Earth, an event called the Messinian Salinity Crisis (MSC) occurred within the Mediterranean basin at the end of the Miocene 5.96 Mya ago (Krijgsman et al., 1999). The desiccation history resulting from this event provides, potentially, the best example of the removal of very large amounts of sea water creating regional stratigraphic structures and evaporitic deposits across and multiple basins (Clauzon et al., 1996, Krijgsman et al., 1999, Roveri and Manzi, 2006, Gargani et al., 2008). Figure 3a & b shows the distribution of evaporite deposits across the Mediterranean, and a representative seismic profile from the Gulf of Lions

(Bertoni and Cartwright, 2015; Bache et al., 2015). Extensive seismic profiling has shown that this Mediterranean-wide event is characterized by falling sea-levels (a minimum of 1300 m according to Urgeles et al., 2010), detrital fan deposits (Lofi et al., 2005), tectonic isolation and uplift (Duggen et al., 2003; 2004; 2005), and very large-scale canyon incision, isostasy and erosion of the basin margins (e.g., the Nile and Rhone rivers; Gargani , 2004; Loget and Driessche, 2006; Gargani et al., 2010). Estimates for a mean rate of regressive erosion resulting from isostatic rebound alone is a much as -2.5 m/yr on the River Nile (Gargani et al., 2010). The MSC is also uniquely identified as an event that transformed as much as 6% of the Earth's ocean salt into giant regressive evaporitic deposits (>1500 m thick) created by relatively rapid sea-level drop and high evaporation rates (estimated around 1.75 $m^3/m^2/yr$, by Bache et al., 2015), and which diachronously drape the Mediterranean sea floor (Hsü et al., 1973; Clauzon et al., 1996; Clauzon, et al., 2005). Estimates show that at least 8 times the volume of the present-day Mediterranean would need to have evaporated in order to create the evaporite deposits we see today (Gargani et al., 2008). Variations in river profiles, erosional surfaces and evaporitic unit production are explained by intermittent water level fluctuations or infilling (from 0.75 mm/yr to 0.3 mm/yr) prior to the point of near or complete desiccation (Gargani et al., 2007). Regulation of seasonal evaporite cycles is also believed to be a result of variations in orbital obliquity and precession during the time the Mediterranean was tectonically isolated from major refilling (Krijgsman et al., 1999; Gargani and Rigollet, 2007). At the height of the event, it is believed a near complete isolation and desiccation of the Mediterranean Sea occurred, with similar effects within adjacent shallower basins. The MSC, as abruptly as it started, seems to have ended 5.33 My ago across the entire Mediterranean basin (Krijgsman et al., 1999). Sometimes termed the "Zanclean Deluge," it marks the breaching across the Gibraltar Strait and the refilling of the basin from the Atlantic Ocean (Blanc, 2002). Though its precise origin, timing and duration are still debated (Butler et al., 1995; McKenzie, 1999; Hardie et al., 2004), we believe that the overall trend of the event represents a potential analogue for Mars with respect to the evolution and emplacement of evaporite deposits and associated erosional morphologies during a long and protracted loss of an ocean or other large bodies of surface water.

The draping of evaporite ocean salts on the floor of the Mediterranean, as the tell-tale sign of the MSC, may be mirrored on Mars by the ubiquitous clay, evaporite and sulfate deposits (Arvidson, 2005; Johnson et al., 2008; Flahaut et al., 2015) measured in Martian bedrock outcrops, duricrust and aeolian sediments across the planet. The early deposition of such Martian sulfates are thought to coincide with a dense and possibly warm atmosphere, large surface water reservoirs and periodic volcanic outgassing through the Noachian and Early Hesperian (Johnson et al., 2008), and serve as an indicator of globally changing environment and hydrologic systems in response to the redistribution of surface water and declining sea-levels (including increasingly acidic waters (Chevrier and Mathe, 2007) and the mineral phases Jarosite and gypsum (Madden and Rimstidt, 2004)). The MSC was not an entirely unique event, except in scale, and therefore it is important to examine as many potential analogues as possible to better understand the disappearance of oceans and standing bodies of water on early Mars. Examples of extinct or desiccated seas and pluvial or endorheic lakes that should be considered for their relevance to the loss of large bodies of water on early Mars include: the Panonian sea, Aral sea, Lake Manly, Lake Lahontan, Lisan Lake, Lake Nam Co, Lake Eyre, Lake Agazzis (Steininger and Wessely, 1999; Rögl, 1999; Grotzinger et al., 2005; Cabrol and Grin, 2010), and many more. Lake Bonneville, for example, has already been examined from the analogue perspective (Figure 2a & b, Chan et al., 2016). From the onset of isolation and growing regional drying, the MSC resembles a forced regression resulting from sea-level decline to the point of inconsiderable inflow or complete desiccation. This provides the impetus for our model, which examines the loss of an ancient northern ocean on Mars.

3.0 A MARTIAN SEQUENCE STRATIGRAPHY: OLD CONSTRUCT, NEW PLANET

From the oldest to the most recent periods (i.e., the Noachian to the Amazonian), short term variations aside, Mars appears to exhibit a progressive unidirectional change in its environment and loss of the presumed primordial ocean -- a change that would induce a forced regression across increasingly desiccated water-bearing basins on a global scale. Given the active nature of the planets early history (i.e., substantially greater geothermal heat flux, volcanism and impact rates), it is assumed that any depositional expression as a result of possible climate or mechanical driven eustatic ocean-level cycles would not be retained in the sedimentary record during an active oceanic period, therefore diminishing any associated transgressive expression within the sedimentary record. Changes in obliquity and insolation, chaotic over time scales greater than about 20 Myr (Laskar et al, 2004), may involve cyclic climate changes. However, should such cycles have occurred and contributed to ocean level increases then the potential exists for the expression of a more complex transgressive stratigraphy during short, environmentally stable periods of relatively constant ocean level. Such cycles would account for relatively short duration changes within the environment, on the order of a few 10 to 100 Myr, spanning periods of stable ocean-baring conditions which may include quasi-periodic (Lewis et al., 2008) or local transgressive units, and any associated patterns should be completely bound by the sediments deposited during the time where maximum standing water process were possible. Examples where local conditions might counter the overall proposed global trend and result in a more complex stratigraphic structure have been proposed (Pondrelli et al., 2008), but such deposits remain to be stratigraphically correlated on a regional scales in relation to any proposed paleo-ocean. The additional complexity added by such transgressions is not further explored in this work.

Figures 4 through 8 depict the cross-sectional evolution of the proposed Mars sequence stratigraphy. Since landforms are locally dependent, the graphic is suggestive and not to scale. Figure 4 shows an early Mars with the hypothesized northern ocean residing at its highest level beginning in the Early Noachian; a period of evolving surface conditions, including heightened impact rates, volatile redistribution, surface precipitation and standing bodies of water. Figures 5 and 6 depict the subsequent evolution of this environment through the end of the Noachian, when climate begins to change to conditions resembling those of today, most likely resulting from the extinction of the planet's magnetic dynamo, progressive freezing, sublimation, and cold-trapping of water in an evolving cryosphere and at higher latitudes (Clifford et al., 2010), as well as loss to space of volatiles through impact and solar wind erosion (Jakosky, 1990; Chassefiere et al., 2006; Stanley et al., 2008; Tian et al., 2009). The result of these combined processes was a global decline in ocean levels at the end of the Noachian and into the Hesperian, when environmental conditions suitable to maintain surface water ceased to exist. This long-term progressive loss of water constitutes a perpetual Martian forced regression.

The first depositional system that has been applied within this model records the highest sea-level and is called Highstand Systems Tract (HST). As in terrestrial deposits, prograding clinoforms (distal movement of sloping sedimentary packages: Fongngern et al., 2016) would form a defining regional stratigraphic record as long as runoff brings sediment into a standing ocean. Additionally, as long as the climate sustains standing bodies of water, the physical structure of any Martian fluvial and subaqueous deposits are expected to produce stratigraphic columns that substantially parallel those exhibited in terrestrial columns even in light of a diminished gravity field. The HST would have been emplaced during the time of stable maximum ocean level and associated fluvial impingement. Further, it seems unlikely that any transgressions or regressions, as used in terrestrial sequence stratigraphy, would impinge the Martian HST to any significant extent; including effects of eustatic cycles, obliquity changes and solar or moon induced tidal influences (Grotzinger et al., 2005). Additionally, any tsunami emplaced strata (i.e., uprush deposits) high on the dichotomy may confusingly resemble transgressive deposits and backwash debris flows and turbidity currents would drape existing offshore slopes and together may mask the HST boundary. Continued water and volatile loss from the early ocean and atmosphere throughout the Hesperian resulted from several ongoing and interacting mechanisms (e.g., sublimation, atmospheric loss to space (Jakosky and Jones, 1997) and freezing/cold trapping within the cryosphere and at high latitudes; Clifford and Parker, 2001). Ultimately the cessation of surface precipitation represents the largest driver for progressive ocean level decline (Hodges, 2002). The drawdown of ocean levels would leave highstand deposits (i.e., detrital and evaporite deposits) perched along the dichotomy boundary and possibly delineated by declining equipotential surface layers inscribed by the declining ocean shoreface.

On Mars, environmental changes occurred that would progressively cause the loss of any paleo-ocean (e.g., sublimation, atmospheric loss to space and freezing/cold trapping within the cryosphere and at high latitudes, Carr, 1996, Hodges et al., 2002; Terada et al., 2009), and hasten the decline in ocean levels marking the beginning of the forced regression (Posamentier et. al., 1992; Posamentier and Morris, 2000). The time of maximum ocean fall occurs at the point in which the ocean is completely lost, ice covered or sequestered into the cryosphere. Forced regressions, by definition, may occur independently of variations in sediment flux (Posamentier et. al., 1992), or alternatively, are defined based on the supply and deposition of sediment at the shoreline during sea-level fall (called either a non-accretionary (little to no sediment) or accretionary forced regressions; Helland-Hansen and Gjelberg, 1994)). Detrital fluvial sediments transported onto the northern plains along the margins of the planetary dichotomy, after the onset of the forced regression, would have been deposited in progressively seaward prograding clinoforms as sea-levels fell. Terms for these depositional units historically include the Forced Regressive Wedge Systems Tract (FRWST; Hunt and Tucker, 1992), the Early Lowstand Systems Tract (ELST; Posamentier and Allen, 1999) and the Falling Stage Systems Tract (FSST; Plint and Nummedal, 2000; Plint et. al., 2001). It is the concept of FSST that has been adopted for use in this model, because, as sea-level falls, it is characterized by prograding offlapping clinoforms (i.e., a basinward shift in facies), and erosive-based shore-face successions lying above the HST as long as the forced regression is active. Therefore, this paradigm implies that the FSST should contain all Martian depositional units associated with periods of active precipitation and surface runoff and the erosional histories associated with the valley networks as ocean levels dropped. Observations indicating basin-ward transitioning strandlines, already identified by Clifford and Parker (2001) and expanded on by others (Webb, 2004; Kraal et al., 2006) should correlate with FSST surfaces. Relatedly, paleo-lake strandlines have been observed in Shalbatana Vallis (Di Achille et al., 2009). Additional markers include subaerial erosion on shoreface sandbodies above the HST as well as downward stepping (offlaping) prograding clinoforms, higher-order sequence stacking, and distal mass flow deposits. Ultimately, as water is removed from the environment, the shoreline trajectory is forced basinward due to the fall in ocean level resulting in an ocean-ward transition of facies that may be expressed below the proposed shoreline levels identified by Parker et al. (1989). Therefore on Mars, we assume a perpetual forced regression would have continued throughout periods where standing bodies of liquid or ice covered water were present and yet diminishing in the environment.

The main stratigraphic surface adopted in this model is the sequence boundary (SB). It is defined at the time when ocean levels first begin to drop and occurs between the HST (Posamentier and Morris, 2000) and the FSST. Though still a debated indicator as Plint and Nummedal (2000) suggest pragmatically placing it on top of the FSST as that surface experiences subaerial exposure throughout any period of relative sea-level fall. The Martian SB (see Figure 4) would be expressed (i.e., through radar sounding or drilling) throughout the northern plains as the contact immediately below the lowest and most widely distributed ice deposits, depending on how rapidly the atmosphere thinned. Fluvial activity during the waning stages of the valley networks has been shown to result in the incision of between 50 and 350 meters into previously emplaced Noachian deposits (Howard et al., 2005), thus providing reference points for the start of the SB unconformity as proposed in our model.

4.0 A UNIQUE MARTIAN SEQUENCE STRATIGRAPIC ADDENDUM

The cross-sections depicted in Figures 6 and 7 represent a Hesperian-era dust and ice covered northern ocean and the beginnings of a phase of regional episodic, flood-incurred stratigraphic deposition. Regional scale unconformities may be emplaced as a consequence of the erosion caused by massive catastrophic floods called outflow channels (Carr, 1996). These massive flooding events appear to have occurred from the Late Noachian through geologically recent (i.e., Late Amazonian) times (Rodríguez et al., 2014; Vijayan and Sinha, 2017). Such large discharges over surfaces with sufficient topographic relief would have resulted in a number of deep incisions, similar to those created by the valley networks, that cut and erode previously emplaced deposits, forming important stratigraphic discontinuities and temporary ponding of relatively large bodies of water. Evidence for erosional surfaces and deeply incised channels formed by these catastrophic floods include Tiu Vallis, Ravi Vallis and Ares Vallis (Warner et al., 2009). Water entrained sediments embayed on the lowland plains from outflow events would also cause localized, down-slope fluvial scouring, incision and erosion resulting in an unconformity cutting into underlying, younger, sequences of dust, volcanic, tsunami, impact and ice deposits; and potentially submerge regional scale topographic lows still containing liquid or ice covered bodies. Basinward, this erosion would potentially demarcate a depositional boundary for detritus emplaced above previous ice covered bodies or depositional units; and based on estimates of atmospheric loss to space (Jakosky et al., 2017) it would seem unlikely that liquid water could exist in equilibrium within the surface environment inferred to exist at this time (McKay and Davis, 1991; Carr and Head, 2009). The steady addition of fine grained air-fall dust and volcanic materials serve to impede (for billions of years, Clifford and Hillel, 1983) water and ice loss to the atmosphere for each additional flooding event. Each local scouring surface may demark additional sequence boundaries during periods of active outflow channel erosion and deposition over desiccated or frozen remnants of the northern lowland paleo-ocean. The scoured channels, now buried by subsequent infilling, could potentially leave unique signatures, observable in either drill cores or radar soundings, which may prove similar to the valley features associated with terrestrial examples, including the deep incisions and infilling of the Mediterranean Rif coast associated with the Messinian Salinity Crisis..

Through the end of the Hesperian, waning-flood deposits covering any basin would leave fluvial deposits lying directly above the erosional flooding surface and would be composed of a mixture of volcano-sedimentary successions, fluvial sediments and scour-detritus from each outflow channel incision. Such deposits could result from a single outflow channel event, localized updip, and might resemble prograding wedges or lobate-like deposits intersecting steeper slopes with the more level ice covered plains (See Figure 7). Another unique layer could result from temperature changes on a basin floor due to standing water that may partially melt and intermix layers at the lowest surfaces of the deposit. Throughout this period there may have been numerous episodes of catastrophic flooding followed by stabilization, each with incision surfaces overlain by waning flood deposits and buried by subsequent volcanic, impact ejecta, dust and ice mantling deposits. In regions where these events occurred in close proximity they could create overlapping or cyclic, depositional bed forms.

Finally, Figure 8 depicts the present state of the northern plains. Post-outflow surfaces, at various locations, associated with or emplaced above the last materials deposited basinward of a given outflow event consist of fluvial sediments, lava flows, impact breccia, volcanic ash and aeolian dust deposits. Obscuration of older strata and production of additional layering is possible especially if atmospheric ice and dust deposition occurs during periods of high obliquity (Madeleine et al., 2009). Such a relatively young stratigraphy and geology retains signatures of obliquity-induced changes in the distribution and preservation of ice, lag or loess deposits. Fine grained air-fall-mantling deposits could, over time, effectively trap and retard the vertical movement of remaining water and the sublimation of near surface ice (Clifford and Hillel 1983), even through the lower obliquity phases (22º-26º) of the past 300 ka (Head et al., 2003; Grimm et al., 2017). Buried and pressurized deposits could further geochemically and morphologically interact with sublimating water or migrate, and thus add yet additional layering (e.g., clay, Sun and Milliken, 2015) or complexity to the stratigraphic column as shown from MSC observations (Bertoni and Cartwright, 2015). Today water continues to play an important physically and morphologically perplexing role on Mars (Ojha et al., 2015; Massé er al., 2016). The youngest strata blanketing Mars, adds to the stratigraphic profile and masking deeper features, demonstrates a plethora of periglacial surface morphologies (e.g., scalloped depressions and stratified layering resulting from the thaw of ice-rich permafrost (Séjourné et al., 2012), and lobate debris aprons (LDAs, Plaut et al., 2009). Competing interpretations for the youngest features, especially at lower latitudes, include the mobilization or redistribution of younger or extant water or ice sources (Travis et al., 2013; Rodríguez et al., 2014) due to environmental changes. Across the northern lowlands, low surface permittivity ranges as determined by ground penetrating radar, hint at the extent of subsurface ice, which may be remnants from the last time Mars had water flowing on its surface.

DISCUSSION

The model presented herein examines the consequences of the existence of large standing bodies of water or oceans and an environment clement enough to sustain rainfall long enough to permit surface erosion. The Mars ocean hypothesis has been gaining momentum for many years and has been bolstered by ever increasing observations regarding water based erosion across the planet, especially around the Noachian-Hesperian boundary (Hynek et al., 2010). Ultimately, to truly understand the role of liquid water and ice below the northern lowlands, anticipated loss must be quantified through higher resolution techniques, including surface investigations. Our model hypothesizes that Mars experienced a perpetual forced regression as ocean levels dropped following the onset of declining atmospheric pressure, temperature, and active surface runoff. Both throughout and following this transition in climatic conditions, the declining formation of valley networks and the occurrence of episodic short-lived catastrophic outflow events caused canyon-scale incisions as water flowed across grade changes creating extensive subaqueous and subaerial depositional packages, including deltaic deposits, erosional knick-points, and unconformities. Lastly, with the cessation of outflow channel activity, a final unique succession of regionally emplaced deposits draping the frozen remnants of outflow channels and the early northern ocean (Clifford and Parker, 2001) should show a relatively conformable stacking pattern of thinning ice interspersed with layers of wind-blown dust, fluvial deposits, impact ejecta, lavas, and volcanic ash. Enhanced orbital spectral analysis and eventual ground observations of the layered sulfate and evaporite deposits (Wray et al., 2009; Flahaut et al., 2015) provide a tantalizing analogy to the Mediterranean sea-floor evaporites from the time of the MSC. In the stacking order, it is the layered mantling of these deposits which provides the thermal and diffusive insulation that insures the preservation of (either ancient or modern) near-surface ice layers. Finally, the progressive loss of liquid water from the Martian near-surface inventory has resulted in the relatively cold and dry planet we see today. The potential for local variations in sedimentary sequence morphology, including possible resubmersion due to basin flooding cycles has not been addressed. As geochemical and stratigraphic investigations of ancient lacustrine (e.g., Gale crater, Frydenvang et al., 2017; Hurowitz et al., 2017) and fluvial environments continue (Rodriguez et al., 2015), a better understanding of erosional and depositional evolution, diagenesis, and the timing and longevity of surface and near-surface water or ice bodies will be developed. Future missions to Mars are likely to employ instruments that are capable of investigating to progressively greater depths beneath the surface. Arvidson (2016) provides a good historical instrumentation overview regarding the history of water on Mars. Yet, improving our understanding of the Martian subsurface specifically will require much more including a combination of GPR, seismic profiling, drilling, and other in-situ techniques. Combining observed data with a robust and workable sequence stratigraphic framework will prove useful in further defining and understanding the geological record and climatic history of the planet. Future work in assessing radar and image data for potential depositional sequences proximal to the proposed shorelines will more conclusively address current unanswered questions.

CONCLUSION

Identifying and delineating differences in sedimentary deposits is key to reconstructing the history of water on mars. We introduce regional scale sequence stratigraphic concepts within a model that provides the framework for understanding ongoing geomorphological and geochemical observations and potentially explain the geological evolution of the extensive and planar northern lowlands of Mars. This model, evidentially supported, assumes a sufficiently dense atmosphere, an ancient active hydrologic cycle sustaining standing bodies of water, including an early northern ocean demarked by shorelines that are roughly bounded by the hemispherical dichotomy. Further, geomorphologies indicative of active precipitation and surface runoff, the emplacement of subaqueous strata and buried and entrapped subsurface ice are suitable for sequence stratigraphic interpretation. Redistribution within an active albeit diminished water cycle would continue to sequester ice at polar locations and permeability constricted regolith traps. Should future high definition GPR, drilling or field investigations find subaerial erosion on identifiable shoreface deposits above an HST or perhaps downward stepping (offlaping) prograding clinoforms or distal mass flow deposits (all parts of the FSST), then this interpretation may prove useful in understanding such observations. Ongoing observations of banded evaporite deposits may correlate with down-stepping segments, as near-surface water was lost from sediments around each shoreline interval.

We also recommend the Messinian Salinity Crisis as a potential terrestrial analogue to large scale, unidirectional, losses of water from a variety of planetary basins regarding resulting geomorphology and mineralogy. Comparisons to potentially similar terrestrial depositional environments and environmental changes, ancient and present, such as those that developed during the Messinian drawdown, provide reasonable analogues and should be further explored. Ultimately, the development of a working understanding of the stratigraphy of the northern plains may assist in the search for ancient signs of life and the distribution of viable water resources that could support future human exploration in a manner similar to how such constructs have aided in the search for petroleum resources on Earth.

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List of Figures:

Figure 1. Northern Hemisphere of Mars highlighting the approximate boundary of the planetary dichotomy, primary fluvial impingement routes, the model's hypothetical transect (A-B), and portions of the putative Duteronilas paleoshorelines (yellow; Parker et al., 1989).

Figure 2. Comparative morphologies indicating proposed Mars and extant terrestrial shorelines, a) Cydonia Mensae and b) Lake Bonniville (Images courtesy of T. Parker, Cptr. 9, Cabrol and Grin, 2010).

Figure 3. a) Messinian evaporite distribution (Bertoni and Cartwright, 2015), and b) Gulf of Lions seismic profile showing transition from Miocene shelf to evaporitic layers and overlying onlap terminations (Bache et al., 2015).

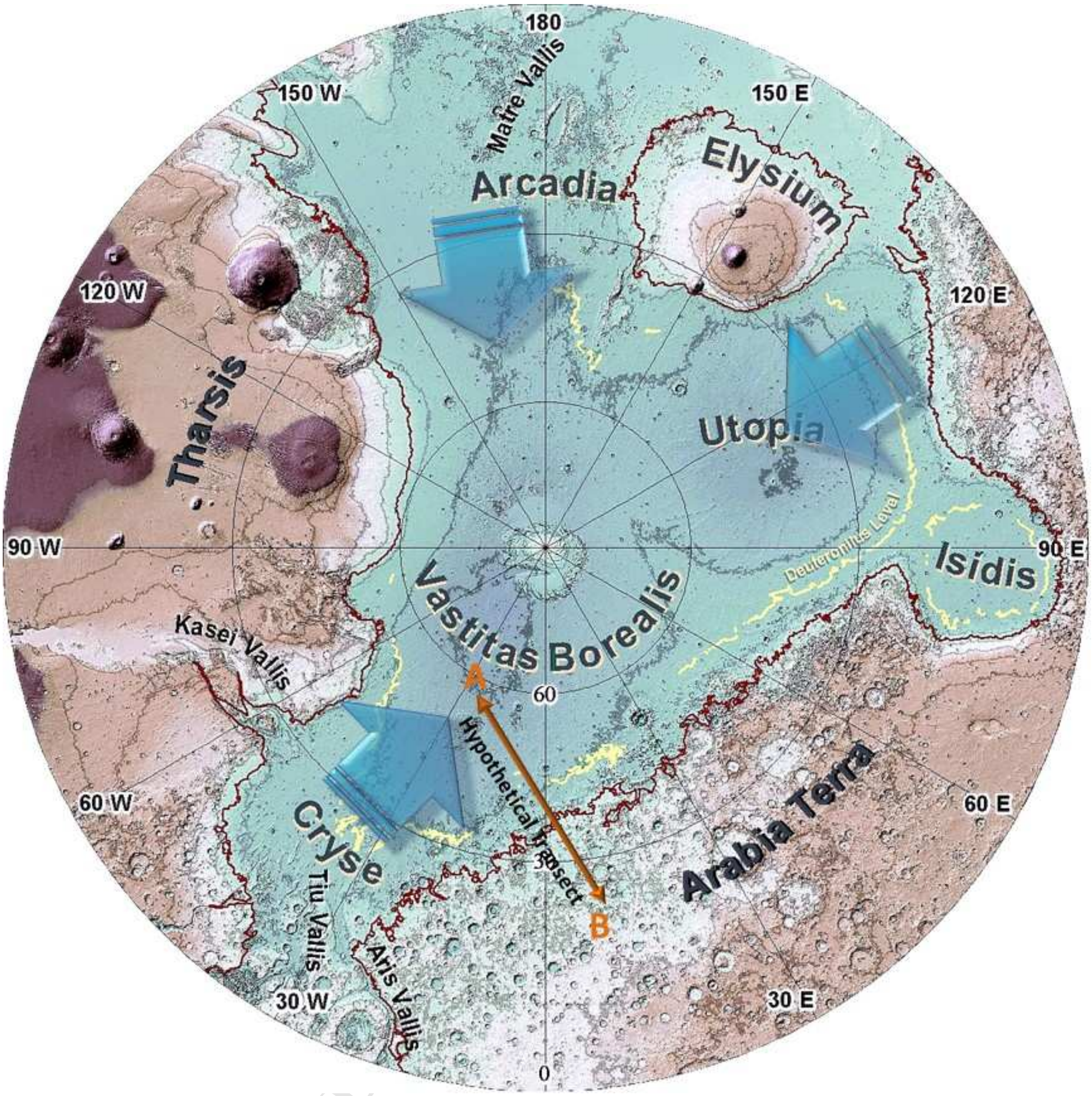
Figure 4. Early Noachian: prograding basin deposition through active precipitation and runoff; coeval falling sea/surface level (S.L) as water is removed from the ocean through heightened impact rates and thermally driven volatile redistribution. Depositional sequences include Highstand Systems Tract (HST), Falling Stage Systems Tract (FSST) and Sequence Boundary (SB).

Figure 5. Middle and Late Noachian: incipient environmental changes including atmospheric thinning, declining precipitation, cryosphere development, initial ocean surface freezing and beginning of over-ocean deposition.

Figure 6. Early Hesperian: waning fluvial processes, volcanic, dust and ejecta blanket a subsiding ice covered ocean, furthering the development and stratification of lowland layered deposits.

Figure 7. Middle and Late Hesperian: outflow channels episodically deluge basin filling water bodies that become ice covered and continue to subside while being mantled with regolith, detritus and dust layers.

Figure 8. Amazonian: fully developed cold Mars with paraglacial landforms delineating near surface ice, transient water volatilization and cycling; surface weathering and aeolian mantling continue. Labels A and B delineate a first order depositional stacking pattern.



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Vastitas Borealis
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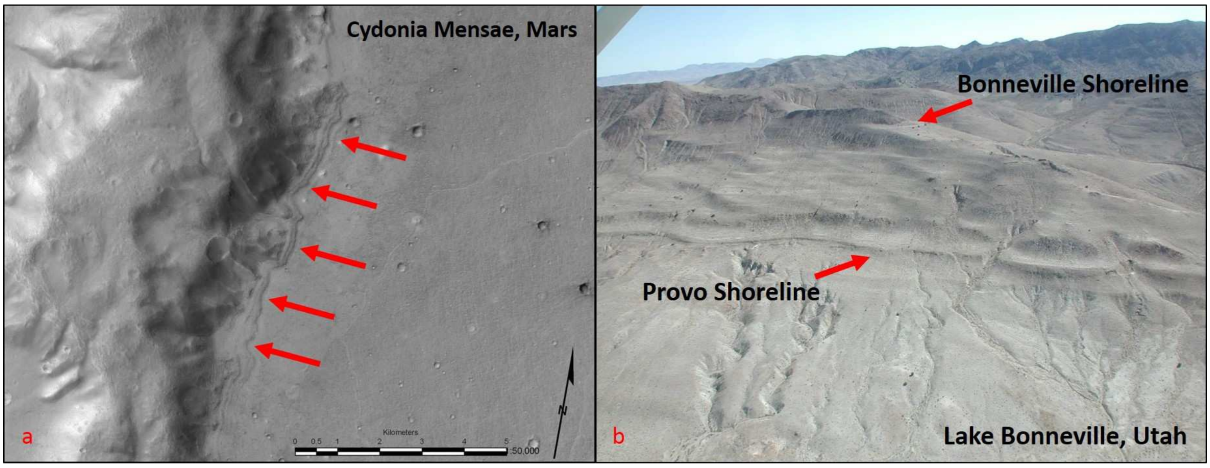
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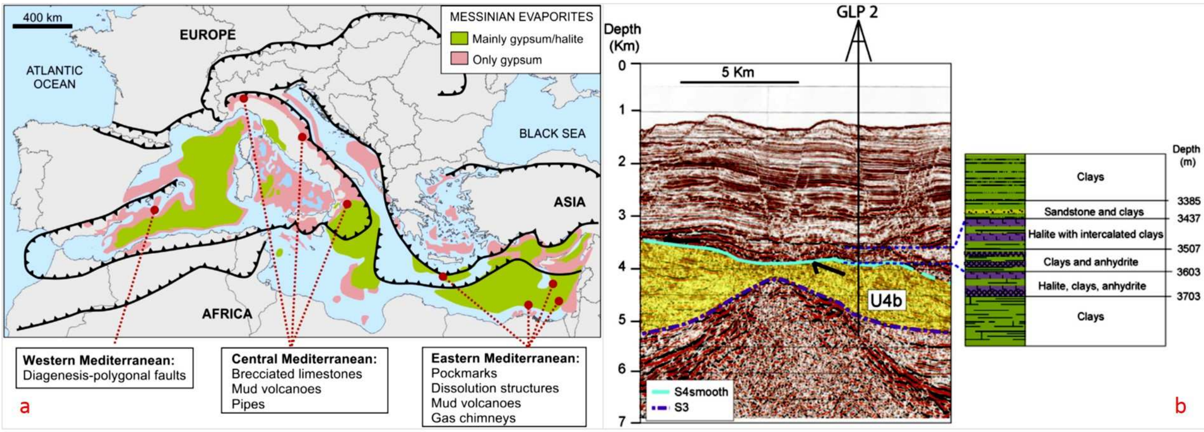
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EUROPE
ATLANTIC OCEAN
MESSINIAN EVAPORITES
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Only gypsum
BLACK SEA
ASIA
AFRICA
Western Mediterranean:
Diagenesis-polygonal faults
Central Mediterranean:
Brecciated limestones
Mud volcanoes
Pipes
Eastern Mediterranean:
Pockmarks
Dissolution structures
Mud volcanoes
Gas chimneys
a
GLP 2
Depth (Km)
5 Km
U4b
S4smooth
S3
Clays
Sandstone and clays
Halite with intercalated clays
Clays and anhydrite
Halite, clays, anhydrite
Clays
Depth (m)
3385
3437
3507
3603
3703
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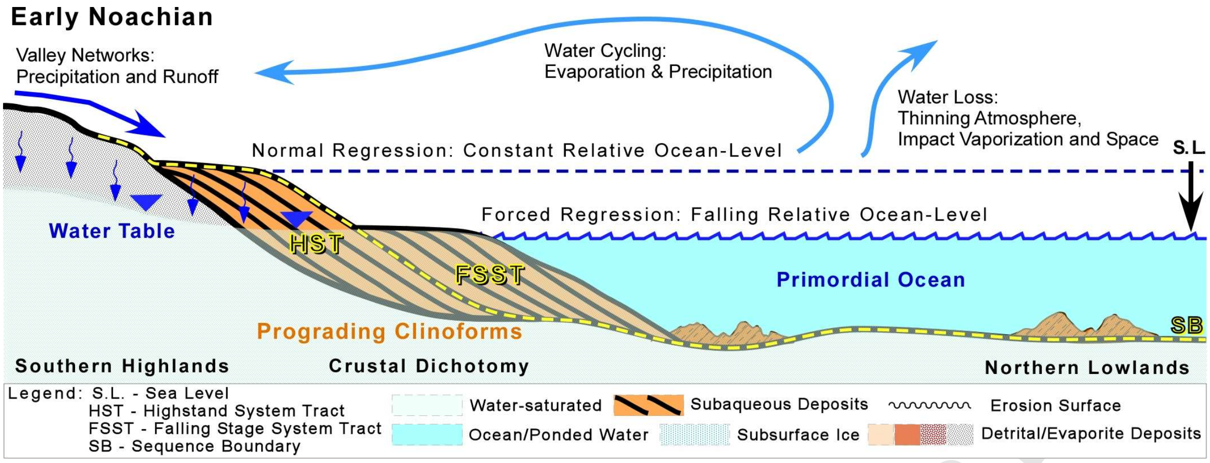
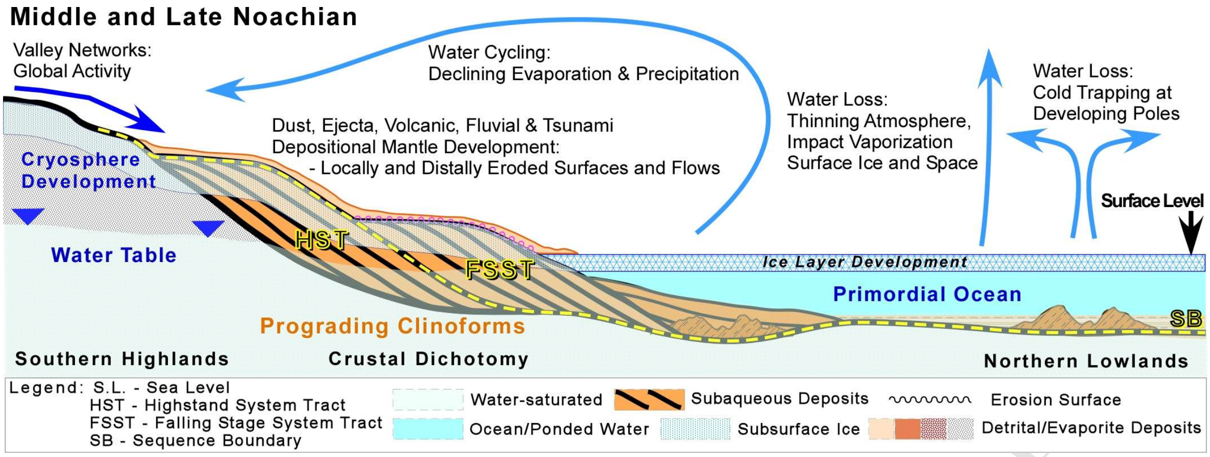
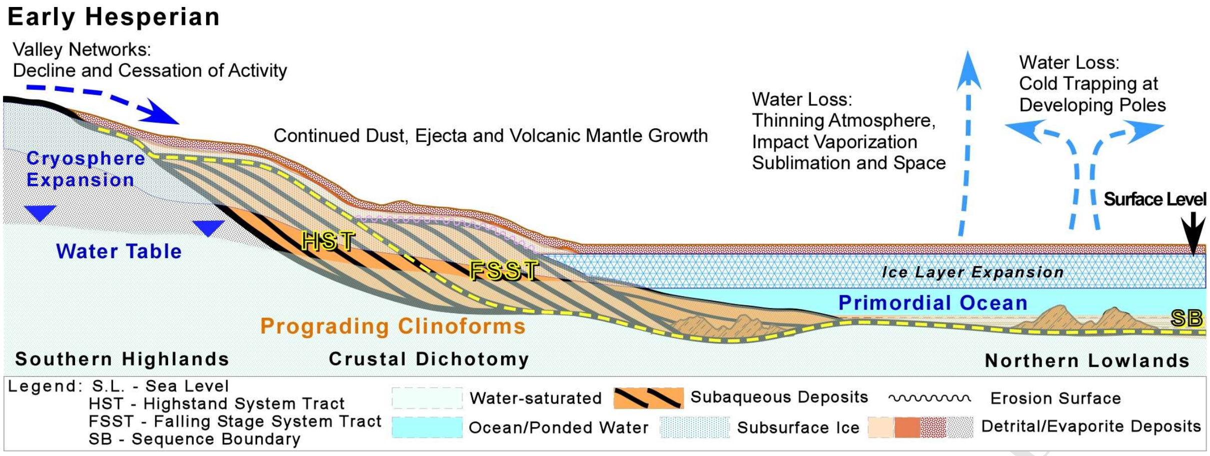
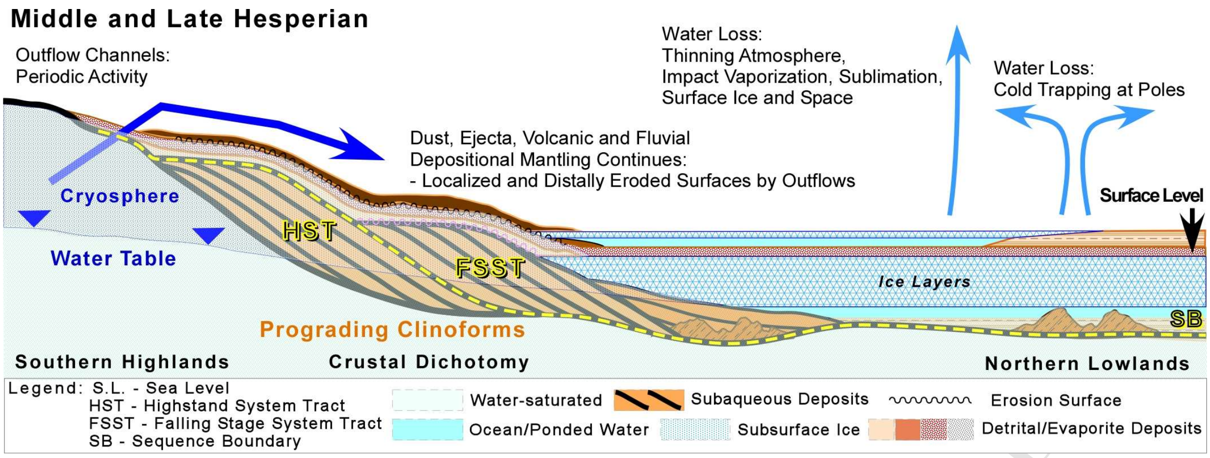
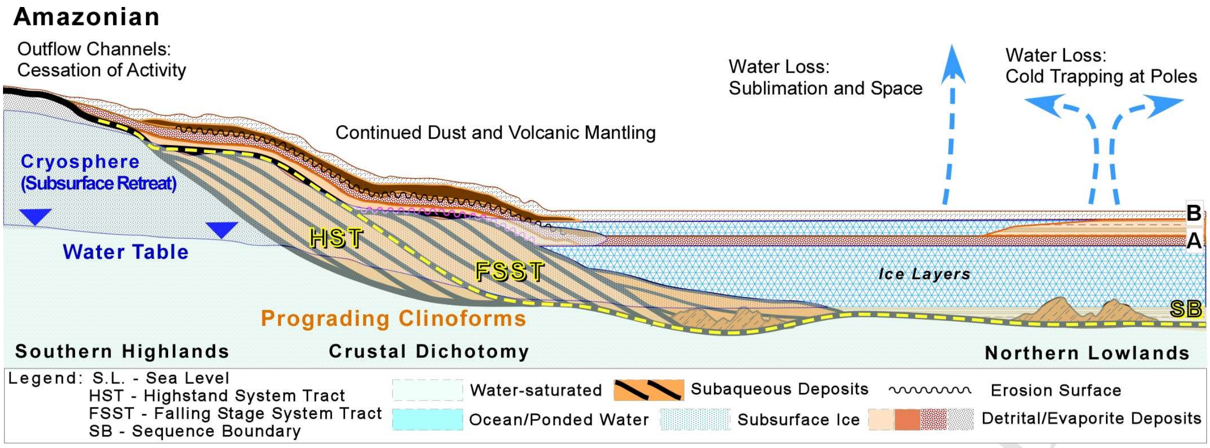

Early Noachian
Valley Networks:
Precipitation and Runoff
Water Cycling:
Evaporation & Precipitation
Water Loss:
Thinning Atmosphere,
Impact Vaporization and Space
Normal Regression: Constant Relative Ocean-Level
S.L
Forced Regression: Falling Relative Ocean-Level
Water Table
HST
FSST
Primordial Ocean
Prograding Clinoforms
SB
Southern Highlands
Crustal Dichotomy
Northern Lowlands
Legend: S.L. - Sea Level
HST - Highstand System Tract
FSST - Falling Stage System Tract
SB - Sequence Boundary
Water-saturated
Subaqueous Deposits
Erosion Surface
Ocean/Ponded Water
Subsurface Ice
Detrital/Evaporite Deposits


Middle and Late Noachian
Valley Networks: Global Activity
Water Cycling: Declining Evaporation & Precipitation
Dust, Ejecta, Volcanic, Fluvial & Tsunami Depositional Mantle Development: - Locally and Distally Eroded Surfaces and Flows
Water Loss: Thinning Atmosphere, Impact Vaporization Surface Ice and Space
Water Loss: Cold Trapping at Developing Poles
Surface Level
Cryosphere Development
Water Table
HST
FSST
Ice Layer Development
Primordial Ocean
SB
Prograding Clinoforms
Southern Highlands
Crustal Dichotomy
Northern Lowlands
Legend: S.L. - Sea Level
HST - Highstand System Tract
FSST - Falling Stage System Tract
SB - Sequence Boundary
Water-saturated
Subaqueous Deposits
Erosion Surface
Ocean/Ponded Water
Subsurface Ice
Detrital/Evaporite Deposits


Early Hesperian
Valley Networks:
Decline and Cessation of Activity
Continued Dust, Ejecta and Volcanic Mantle Growth
Water Loss:
Thinning Atmosphere,
Impact Vaporization
Sublimation and Space
Water Loss:
Cold Trapping at
Developing Poles
Surface Level
Cryosphere
Expansion
Water Table
HST
FSST
Ice Layer Expansion
Primordial Ocean
SB
Prograding Clinoforms
Southern Highlands
Crustal Dichotomy
Northern Lowlands
Legend: S.L. - Sea Level
HST - Highstand System Tract
FSST - Falling Stage System Tract
SB - Sequence Boundary
Water-saturated
Ocean/Ponded Water
Subaqueous Deposits
Subsurface Ice
Erosion Surface
Detrital/Evaporite Deposits


Middle and Late Hesperian
Outflow Channels:
Periodic Activity
Water Loss:
Thinning Atmosphere,
Impact Vaporization, Sublimation,
Surface Ice and Space
Water Loss:
Cold Trapping at Poles
Dust, Ejecta, Volcanic and Fluvial
Depositional Mantling Continues:
- Localized and Distally Eroded Surfaces by Outflows
Cryosphere
Surface Level
Water Table
HST
FSST
Ice Layers
SB
Prograding Clinoforms
Southern Highlands
Crustal Dichotomy
Northern Lowlands
Legend: S.L. - Sea Level
HST - Highstand System Tract
FSST - Falling Stage System Tract
SB - Sequence Boundary
Water-saturated
Subaqueous Deposits
Erosion Surface
Ocean/Ponded Water
Subsurface Ice
Detrital/Evaporite Deposits


Amazonian
Outflow Channels:
Cessation of Activity
Water Loss:
Sublimation and Space
Water Loss:
Cold Trapping at Poles
Continued Dust and Volcanic Mantling
Cryosphere
(Subsurface Retreat)
Water Table
HST
FSST
Ice Layers
B
A
SB
Prograding Clinoforms
Southern Highlands
Crustal Dichotomy
Northern Lowlands
Legend: S.L. - Sea Level
HST - Highstand System Tract
FSST - Falling Stage System Tract
SB - Sequence Boundary
Water-saturated
Subaqueous Deposits
Erosion Surface
Ocean/Ponded Water
Subsurface Ice
Detrital/Evaporite Deposits

Highlights

A sequence stratigraphy model for an early wet Mars is proposed.

The model relies on an active water cycle including precipitation and runoff.

Global environmental change and loss of ocean induces protracted forced regression.

The Messinian Salinity Crisis is proposed as a terrestrial analogue for early Mars.