An overfilled lacustrine system and progradational delta in Jezero crater, Mars: Implications for Noachian climate

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Abstract
The presence of valley networks and open-basin lakes in the late Noachian is cited as evidence for overland flow of liquid water and thus a climate on early Mars that might have supported precipitation and runoff. Outstanding questions center on the nature of such a climate, its duration and variability, and its cause. Open basin lakes, their interior morphology, and their associated channels provide evidence to address these questions. We synthesize the extensive knowledge of terrestrial open basin lakes, deltaic environments, and fluvial systems to assess these questions with evidence from Jezero crater, a 45 km diameter open basin lake and its 15,000 km² catchment area, ~645-km long drainage network, interior sedimentary facies, and ~50 km long outlet channel system. We document the presence of extensive scroll bars and epsilon cross-bedding, both indicative of meandering distributary channels that are not observed on alluvial fans but are typical of fluvial-deltaic depositional environments. A fluvial-deltaic environment is further supported by the post-formational erosion of the deltaic complex: the present-day "delta front" is actually an erosional escarpment truncating delta plain features with the clay-rich prodelta environment, predicted from facies models to make up the outer third of the complex, having been largely removed by eolian erosion. The extensive development via lateral accretion of scroll bars and epsilon cross-bedding, and the reconstructed sedimentary architecture suggest a stable baselevel, in contrast to an environment of constantly rising and falling baselevel related to variable input and evaporation that would favor incision during lowstands. The development of the outlet channel is interpreted to have provided baselevel control in the Jezero open-basin lake. The maturity of the outlet channel, in contrast to the catastrophically scoured landscapes typical of dam-breach channels, favors a consistent overfilled hydrology for the paleolacustrine environment. Sediment transport modeling studies of other valley network and related deposits on Mars have suggested durations in the decades to centuries range. We review meander migration rates in terrestrial fluvial environments to provide a comparison for considering the temporal stability implied by the evolution of scroll bars; values of 20–40 years are not uncommon for the structures and migration implied by observations in Jezero. Taking sediment accumulation rates from a variety of terrestrial fluvial-lacustrine environments in conjunction with our estimates of the sedimentary basin-fill thickness suggest timescales of the order of 10⁶–10⁷ years, far longer than implied by some sediment transport models, but still a short period of time geologically. The presence of significant residual accommodation space (space available for potential sediment accumulation) in Jezero indicates that sediment transport into the lake terminated before the basin was completely filled. Climate conditions sufficient for sustained overland flow of water in the valley networks are required to fill Jezero crater, to cause its breaching in a non-catastrophic manner, and to form the significant fluvial-deltaic environment of laterally migrating fluvial channels and scroll bars formed with an apparently stable baselevel. The lack of late-stage channel downcutting suggests that the conditions producing overland flow of water into the basin may have ended abruptly. Our estimates of the duration of fluvial activity (of order 10⁶–10⁷ years) suggest longer times than previously suggested (years to centuries) by sediment transport models, but generally relatively short durations from a geologic perspective.

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1. Introduction

Valley networks were first observed in Mariner 9 (Masursky, 1973) and Viking (e.g., Pieri, 1980; Carr and Clow, 1981; Carr, 1996, 2007) data of the 1970s. Interpreted as evidence of ancient fluviatile erosion, the degree to which these features are the result of precipitation (Cradock and Howard, 2002) or groundwater sapping (e.g., Laitvy and Malin, 1985) continues to be debated, with different minimum climatic requirements associated with each scenario. Evaluation of this paleoclimate question (e.g., Squyres and Kasting, 1994) – just how warm and wet, and for how long – has significant implications for Noachian hydrologic activity and potential habitability. Recent data suggest that periods of overland flow of liquid water occurred, evidenced by the aforementioned valley networks (e.g., Hynek and Phillips, 2001, 2003; Fassett and Head, 2008b; Barnhart et al., 2009; Hynek et al., 2010), lakes (e.g., Cabrol and Grin, 1999; Irwin et al., 2005; Fassett and Head, 2008a), and alteration mineralogies (e.g., Poulet et al., 2005). However, the cause, nature, and duration of the period(s) have remained uncertain.

Well-preserved fluvial and lacustrine sedimentary deposits on Mars have been recognized in a variety of locations on the martian surface in the last fifteen years (e.g., Ori et al., 2000; Malin and Edgett, 2000, 2003; Moore et al., 2003; Irwin et al., 2005; Fassett and Head, 2005; Weitz et al., 2006; Grant et al., 2008; Burr et al., 2009; Di Achille and Hynek, 2010). The depositional style and the nature of these deposits appear to range from alluvial fans to aggradational deltas, stepped-deltas, or progradational (Gilbert) deltas, and the depositional settings of particular deposits remain debated. The primary variable that differentiates these depositional styles is the stability and long-evity of the alluvial/fluvial–lacustrine system required for formation of the deposit. Much attention has focused on the Eberswalde crater deposit (formerly known as northeast Holden crater) (Malin and Edgett, 2003; Moore et al., 2003). Jerolmack et al. (2004) suggested that the deposit may not have a deltaic origin, but rather could have been formed by a riverine system without a standing body of water on a timescale of decades to centuries based on their modeling of alluvial-fan style development. In contrast, Bhattacharya et al. (2005) interpreted the deposit as resulting from a long-lived deltaic system based on evidence of multiple major channel avulsions and interpretation of a thick lacustrine section. Lewis and Abaronoff (2006) proposed that rapid aggradational deposition of topset beds is suggested by shallowly dipping layers that they interpret as inconsistent with foreset bedding. This scenario implies multiple episodes of rising baselevel and is not consistent with the progradational interpretation of Wood (2006), which was based on evidence of several progradational lobes, their cross-cutting relationships, and multiple sinuous distributary channels in comparison to terrestrial analogs. In contrast to Eberswalde, Jezero crater has a defined outlet channel that creates the opportunity for a detailed analysis of the sedimentary construction of a martian “fan deposit” in an open basin environment (Fassett and Head, 2005).

In summary, the presence of valley networks and open-basin lakes in the late Noachian is cited as evidence for overland flow of liquid water and thus a climate on early Mars that might have supported precipitation and runoff. Outstanding questions center on the nature of such a climate, its duration and variability, and its cause. Open basin lakes, their interior morphology, and their associated channels provide evidence to address these questions. Specifically, we summarize the terrestrial literature and address the following questions for the Jezero system: Were these deposits formed in an alluvial fan or deltaic environment? What was the nature of the lacustrine environment – was baselevel stable or did it fluctuate and perhaps cause the lake to undergo periodic desiccation? Was there a waning stage of activity during which lake level fell, the sedimentary deposits were incised, and the locus of deposition migrated basinward? What was the duration of overland flow, fluvial activity and deposition – could the deposits have formed on a decadal timescale, or was a longer period of time (> 10^5 years) required? What are the implications of the characteristics of the Jezero crater open-basin lake and fluvial system for Noachian climate?

In this contribution we start by reviewing a facies-based classification scheme for terrestrial lakes and identifications of paleolakes on Mars. Then we consider the Jezero system including the watershed, topography, accommodation space, and outlet channel. In Section 5, we (1) explicitly address distinctions between alluvial fans and deltas, (2) evaluate the depositional history of the Jezero deposits, and (3) outline evidence of their extensive post-depositional erosion. Then we turn to the analysis of delta plain sedimentary structures including meanders and point bar sequences as well as tabular channel sand bodies. In our discussion, we propose a scenario for the development and evolution of the Jezero paleolacustrine system from initial breaching of the crater rim to termination of hydrologic activity, which occurred prior to exhaustion of available accommodation space. Using terrestrial sedimentation rates and meander migration rates, we discuss plausible temporal constraints on this scenario. We also compare our estimates of formation time with recent sediment transport modeling studies of other sedimentary deposits on Mars that report extremely brief formation times (0.01–10 years; Kleinhans et al., 2010) and identify input parameters for these models that may require further refinement for application to Jezero and similar deposits. Finally, we conclude with potential constraints on the climate regime at this time and implications for the selection of future landing sites for Mars Science Laboratory (MSL) types of missions.

2. Classification of lakes

Large terrestrial lakes are either of tectonic (e.g., East Africa rift lakes such as Tanganyika) or glacial (e.g., the Great Lakes of North America) origin (Johnson, 1984 and references therein). Tectonic lake assemblages, due to the relative paucity of ice ages, dominate the geologic record of lacustrine deposits. Terrestrial lake size parameters (depth, area, volume) do not correlate well with climate (precipitation/evaporation); in fact, a great diversity of lakes is found within particular climatic zones (Bohacs et al., 2003 and references therein). Latitude, altitude, and drainage basin area also are not closely linked to lake size parameters. Rather, Bohacs et al. (2003) showed that lake volume, area, and depth have power-law distributions, which Fassett and Head (2008a) also documented for Mars paleolakes. These size distribution trends point to lakes as scale-invariant phenomena at least for moderate sized lakes (Meybeck, 1995; Turcotte, 1997; Bohacs et al., 2003; Fassett and Head, 2008a; Seekell and Pace, 2011).

Modern lakes are intricate biogeochemical systems with complex feedback mechanisms that have confounded the development of simple process-oriented lithofacies models. In contrast, the lacustrine rock record is separable into three distinct end-member lithofacies associations that together characterize most lacustrine basin fills (Fig. 1). Such a tripartite division of lacustrine facies was first described by Bradley (1925) in characterizing the Green River Formation of the Uinta and Green River basins as composed of facies deposited in permanent freshwater lakes, in flooding and desiccating lakes, and lastly, under playa-like conditions. In extensive studies of Mesozoic-rift lacustrine strata of Newark Supergroup basins, Olsen (1990) identified and described a similar three-part division of lacustrine facies associations: “Richmond-type,” “Newark-type,” and “Fundy-type” (Olsen,
Richmond-type deposits are characterized by evidence of large depositional sequences; high relief sedimentary structures, such as prograding deltas, submarine channels, and turbidite fans; and no indications of interspersed subaerial exposure or desiccation. Newark-type deposits show evidence of numerous significant changes in lake level that prevented the development of large sequence boundaries or high-relief sedimentary structures; however, these deposits contain repeated Van Houten sequences that are climatically keyed to Milankovich orbital cycles (Olsen, 1986). Finally, Fundy-type deposits are characterized by thin beds that record shallow perennial lake and playa-like conditions, and exhibit desiccation features, evaporites, and eolian dunes. A similar tripartite division of lacustrine facies associations (fluvial–lacustrine, fluctuating profundal, and evaporative) has been introduced by Carroll and Bohacs (1999) for more general application (Fig. 1).

The Carroll and Bohacs (1999) nomenclature recognizes these associations as endmember lithofacies associations characterized from a very large suite of ancient and modern lacustrine systems (Bohacs et al., 2000, 2003). These endmembers are distinctive in their lithology, sedimentary structures, and biogeochemistry, but are relatively independent of age, water depth, and thickness (Bohacs et al., 2000, 2003). What, then, controls the occurrence of these lacustrine facies? Consideration of many lacustrine process–response relationships affecting sediment delivery and dispersal led to the development of a predictive classification scheme of lake basins as overfilled, balanced fill, or underfilled (e.g., Bradley, 1925; Olsen, 1990; Carroll and Bohacs, 1999). Two primary factors differentiate these lake types: accommodation space and the supply of water and sediment to the basin. This classification scheme provides a powerful framework for analyzing Mars paleolakes by integrating observations of basin structure (e.g., impact craters), outlet-controlled baselevel, and sedimentary deposits. After Carroll and Bohacs (1999).

Fig. 1. Lake classification system. The lacustrine geologic record is separable into three endmember lithofacies associations that correspond to three basin types: overfilled, balanced fill, and underfilled (e.g., Bradley, 1925; Olsen, 1990; Carroll and Bohacs, 1999). Two primary factors differentiate these lake types: accommodation space and the supply of water and sediment to the basin. This classification scheme provides a powerful framework for analyzing Mars paleolakes by integrating observations of basin structure (e.g., impact craters), outlet-controlled baselevel, and sedimentary deposits. After Carroll and Bohacs (1999).

Noachian-aged paleolakes were first identified with Viking imagery (Goldspiel and Squyres, 1991). Additional potential paleolakes were identified by De Hon (1992), Forsythe and Blackwelder (1998), Cabrol and Grin (1999, 2001), and Mangold and Ansan (2006), as well as Irwin et al. (2002, 2004) who described the very large Eridania basin associated with Ma‘adim Vallis. Because lake basins are identified based upon topographic relations (Hutchinson, 1957; Wetzel, 2001), the Mars Orbiter Laser Altimeter (Smith et al., 1999) and digital terrain models derived from the High Resolution Stereo Camera (Neukum et al., 2004) have provided additional crucial data for discerning potential paleolakes. Using these topographic datasets in conjunction with multi-mission visual images, Fassett and Head (2008a) cataloged 210 open-basins with distinct inflowing valley networks and outlets. The vast majority of these basins are impact crater related. Many intra-valley paleolakes are preserved than ~1 m, and therefore provide a predictive framework for the development of lacustrine basin fills (Fig. 1). The strong association of the endmember lithofacies with the lake classification scheme allows for prediction of lake type based upon limited outcrop data and sedimentary structures. Lake type and facies distribution predictions of this kind have proven to be a very effective framework for interpreting lacustrine basin fills (e.g., Johnson and Graham, 2004; Bohacs, 2004; Keighley, 2008). In the present study, we apply this framework to Mars and show that Jezero was an overfilled lake system. However, first we turn to the record of lakes on Mars and their identification to show that Jezero is not unique in its structure or watershed.

3. Lakes on Mars

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because of the relatively immature martian landscape (e.g., Stepinski et al., 2004; Gutierrez, 2005). How have subsequent geologic processes affected the paleolakes since their formation? Mars paleolakes are inferred to be Noachian in age (>3.55–3.75 Ga) based upon relations to the valley networks that sourced them (Carr, 1996, 2007; Fassett and Head, 2008b), but this does not reflect the full geologic history of these basins. Significant erosion and modification have occurred, such as continued infilling and resurfacing of the basin interiors. In their survey work, Fassett and Head (2008a) noted that 50% of the basins cataloged contained clear evidence of volcanic resurfacing. In addition to volcanic resurfacing – primarily by Hesperian ridged plains (e.g., Scott and Tanaka, 1986; Greeley and Guest, 1987; Head et al., 2006) – impact crater ejecta (e.g., Cohen, 2006), volcanic tephra (e.g., Wilson and Head, 2007), eolian sediments (e.g., Fenton et al., 2003), and glacial deposits (Goudge et al., 2011) can be important post-lacustrine basin fills. Therefore, while paleolakes are relatively common, and distributed throughout the southern highlands, preserved and observable sedimentary features associated with these basins are relatively rare due to post-lacustrine erosion, subsequent non-lacustrine basin fills, and resurfacing (Goudge et al., 2011). Well preserved basins with clear sedimentary deposits associated with valley networks are likely to number no more than 40 to 60 globally based upon recent surveys (Irwin et al., 2005; Fassett and Head, 2008a; Di Achille et al., 2008; Di Achille and Hynek, 2010). Consequently, while the basin and watershed themselves are not unique in their area and volume relationships (Fassett and Head, 2008a) the excellent sedimentary exposures in Jezero crater make this system particularly attractive for detailed investigation.

4. Jezero lacustrine system

Jezero crater (18.4°N, 77.7°E) is a 45-km diameter impact crater located in the Nili Fossae region of Mars. Fassett and Head (2005) mapped the associated valley networks, which drain a 15,000-km² watershed (Fig. 2), and identified two sedimentary fans in the basin that we interpret as a single sedimentary assemblage (Fig. 3). The watershed and surrounding Nili Fossae region are a mineralogically diverse Noachian terrane where many aqueous alteration products – such as phyllosilicate clays and carbonates – have been detected by visible/near-infrared spectroscopy (Bibring et al., 2006; Mangold et al., 2007; Ehlmann et al., 2008a; Mustard et al., 2008). In addition to the aqueous alteration minerals detected in the watershed, phyllosilicate and carbonate detections within Jezero crater sedimentary deposits suggest that these sediments were transported from the watershed rather than weathered in place (Ehlmann et al., 2009; Murchie et al., 2009).

The watershed ranges in elevation (relative to the Mars’ datum) from ~250 m along the northern drainage divide to ~2400 m, the elevation of the valley entrances and the outlet. The valley networks are composed of 645 km of mapped channels (Fig. 2). While the Strahler order (number of tributaries upstream) is low (third-order), the main valleys are quite mature. They are low slope (0.5° and 0.7° in their lower reaches) and have meanders that are incised hundreds of meters (Figs. 2 and 3). Low drainage densities (by terrestrial standards) are the norm for even the most well developed Noachian valley networks (Baker and Partridge, 1986; Carr and Chuang, 1997; Hynek and Phillips, 2003); the Jezero watershed is not unusual (0.043 km⁻¹). The lack of observable high-order tributaries on Mars leading to commensurately less mature landscapes has been explained by various mechanisms, including impact gardening which could remove rills and small tributaries (e.g., Hartmann et al., 2001), high infiltration rates which could minimize overland flow in tributaries (e.g., Carr and Malin, 2000), and a shorter period of hydrologic activity during which erosion in tributaries was modest (e.g., Stepinski et al., 2004; Stepinski and Stepinski, 2005).

Accommodation space (the space available for potential sediment accumulation) in the Jezero basin was created by the impact event during the Noachian that excavated a 45-km diameter crater. Complex crusters, such as Jezero, are characterized by broad, level floors, and often have terraces (circumferential rim failures), and central peak elements. Systematic crater depth–diameter ratio trends have been investigated by Garvin et al. (2003), and we use these to estimate original topographic profiles and the maximum accommodation space for water and sediments within Jezero (Fig. 4). A fresh crater of similar size is also used for comparison.

Using MOLA topography to characterize more than 6000 impact craters, Garvin et al. (2003) systematically investigated the depth–diameter relationship for Mars impact craters and developed a refined power-law relationship for complex craters: $d = 0.36D^{0.48}$ where $d$ is crater depth (km) and $D$ is diameter (km). The Garvin et al. (2003) data predict a depth $(d/D)$ of 2320 m (0.0516). Observed from MOLA profiles, the actual depth $(d/D)$ of
Jezero is 1080 m (0.0241). A comparable fresh crater (125.75°E, 8.25°N) selected from the crater catalog of Barlow (1988) has an actual depth of 1960 m (0.0435). The profoundly shallower profile for Jezero compared to statistical relations for complex craters (e.g., Garvin et al., 2003) and a similarly sized fresh crater (Fig. 4), show that Jezero has experienced substantial filling, ~1 km (see also, Ehlmann et al., 2008b). Models of ejecta thickness decay by Cohen (2006) suggest that at most 24 m of this fill is ejecta from subsequent impact craters.

The present basin interior is covered by a thin volcanic unit that is observed to embay the fan deposits (Fig. 5). Near the fan deposits we estimate this material is no more than 10–30 m in thickness based upon topographic relationships observed at eroded embayment contacts (Fig. 5). The crater size–frequency distribution (n=724) observed on 344-km² of this unit suggests an Early Amazonian age of 1.4 Ga using Hartmann (2005) isochrons (Fig. 6). While the volcanic unit is pervasive as a cap unit on the central basin floor, sedimentary “windows” are observed in relation to the fan deposits 10.5 km from the crater rim (e.g., Fig. 5). These windows occur where previously high-standing sedimentary material was embayed by the volcanic unit. Subsequently, the sedimentary material has further eroded, leaving the more resistant volcanic material as a raised rim around a depression of the sedimentary material (Fig. 5) with abundant dunes of reworked deltaic material. At these sedimentary windows, the known depth–diameter relationships described above enable us to estimate a thickness of ~750 m for the basin fill.

Baselevel within the paleolake was controlled by the outlet channel on the east side of the crater. Development of the outlet channel originated from initial overtopping of the crater rim and subsequent erosion of the rim breach (250–300 m) to the present condition where the breach and fan deposits share a topographic contour within a few tens of meters (see line on Fig. 4). The watershed/basin area ratio of ~10:1 implies, for example, runoff production from the watershed of ~10 cm/year (equivalent to an arid terrestrial environment, Köppen classification BW) and a discharge of 50 m³/s to balance 1 m/year of evaporation from the lake. While Noachian evaporation rates are uncertain (Irwin et al., 2007), this scenario illustrates a plausible minimum level of activity (e.g.,
Andrews-Hanna and Lewis, 2011) that development of the outlet channel indicates was exceeded. Inflow to Jezero in excess of evaporation could have occurred and been lost by infiltration to a regional groundwater system, or discharged from the basin via the outlet channel, or both. Loss to regional aquifers, if any, is speculative and difficult to constrain from remote data. The outlet channel is mapped for \( \sim 53 \) km before it is obscured by overlying geologic units (Fig. 2). Incision of the breach and the maturity of the channel (Fig. 7) indicate that an overflowing hydrology developed. Along its course, the outlet channel meanders and fluvial sedimentary deposits are preserved (Fig. 7). Planar bedding within light-toned material is common on the inside of meander bends and along reaches of the channel (Fig. 7). The channel itself must have eroded the sediment for these features because the 40 km distance across the basin from the inflowing valley networks would have effectively trapped all sediment from the watershed. The development of this mature, low slope (0.6\(^\circ\)) outlet channel requires that Jezero was a stable overfilled paleolake (Fig. 1). The stable baselevel near \(-2400\) m controlled by the outlet (Fig. 4) would be an ideal lacustrine environment for the development of a progradational delta (Fig. 1).

### 5. Deltaic deposits

The continued ambiguity regarding the depositional history of fan deposits on Mars has led to a complex collection of terms used in reference to these sedimentary features, including “fans,” “alluvial fans,” “delta fans,” “alluvial deltas,” “distributary fans,” and “deltas.” This issue of uncertain depositional conditions was raised directly by Malin and Edgett (2003) and has not been adequately resolved (see discussion in Moore and Howard, 2005). However, new sub-meter resolution data from the HiRISE camera on the Mars Reconnaissance Orbiter (McEwen et al., 2007) enable a detailed assessment of these sedimentary deposits. In conjunction with a comparison to terrestrial sediment transport and deposition processes, this allows for firm discrimination between

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**Fig. 5.** Lava flooding of the Jezero crater floor in areas of eroded deltaic deposits. Directly basinward of the continuous sedimentary deposits in Jezero (Fig. 3), embayment relationships indicate that the delta was larger in the past. In this scene, light-toned sedimentary material (with dunes) has been embayed by an early Amazonian (Fig. 6) unit interpreted as volcanic. Craters that impacted on the boundary between the competent volcanic material and the weak sedimentary deposit (marked with white arrows) have experienced differential preservation. The previously high-standing deltaic material eroded to approximately its present configuration prior to formation of the volcanic unit. Portion of HiRISE: PSP_002743_1985.
an alluvial fan origin and deltaic origin for the sedimentary assemblage in Jezero. We present evidence of meandering distributaries on the Jezero delta fan deposit that indicate these deposits are of fluvial-deltaic origin and contrast their distinguishing features with the defining attributes of alluvial fans as well as sediment deposited under unstable lacustrine conditions. There are several very fundamental differences in the formation of alluvial fan deposits compared to deltaic deposits. Alluvial fans are entirely subaerial, semicircular deposits that radiate from sharp breaks in slope, most commonly along mountain fronts. They are deposited primarily in stream floods, sheet floods, and debris flows, resulting from vigorous but episodic precipitation events. Alluvial fan streams are braided and modestly entrenched; channel cuts and fills are common in alluvial fan stratigraphy and sorting is typically poor because transport distances are short (Blissenbach, 1954; Bull, 1977; Harvey et al., 2005).

In contrast, deltas are partially subaerial sediment masses that are deposited where a low gradient channel debouches into a standing body of water. Changes in baselevel (i.e., local sea level or lake level) exert an important control on delta morphology by shifting depositional trends (see discussions in Payton, 1977; Catuneanu, 2006; and references therein). However, primary delta morphology is controlled by the rate of sediment input relative to reworking or removal by energy sources within the basin (Galloway, 1975). This characteristic has led to a ternary classification scheme for delta morphologies, which contrasts the relative influences of sediment supply, wave energy, and tidal variations (Fig. 8).

The demarcation of alluvial fans and deltas, based upon extensive terrestrial field studies (e.g., Bull, 1977), illustrates distinct contrasts in gross morphology that are applicable to martian and remote sensing studies of deltas (e.g., Pondrelli et al., 2005, 2008; Hauber et al., 2009; Farris, 2009) and alluvial fans (e.g., Moore and Howard, 2005; Kraal et al., 2008a; Williams and Malin, 2008; Hardgrove et al., 2009, 2010). Alluvial fans are semi-conical in shape, restricted in radial length, convex in cross-profile, and have high values of radial slope. In contrast, deltas have generally lobate planforms and have low radial and cross-profile slopes (Blair and McPherson, 1994). Deltas are well-sorted fine-grained deposits, compared to the coarser, poorly sorted, sediments that construct alluvial fans. Alluvial fan sediments are sourced from smaller drainage basins on bold topography and transported shorter distances by high-competence streams or debris flows (Blair, 1999). In contrast, deltaic sediments are typically suspended load and bedload of extended river systems. The higher slope of alluvial fans (> 1.5°) leads to flows that are often supercritical (e.g., sheetfloods), while flows in low-slope delta environments are subcritical. The conical form of alluvial fans leads to rapid expansion and attenuation of flow, which therefore reduces the competence and capacity of the stream, leading to rapid sedimentation near the fan apex (Blair and McPherson, 1994). In contrast, deltas commonly have leveed channels, meandering distributaries, overbank deposits, splays, and abundant associated channel and mouth bars (e.g., Coleman, 1981).

Deltas are divided into three environments of deposition (Rich, 1951): the delta plain, the delta front, and the prodelta. The delta plain is comprised of alluvial sediments and includes meandering distributaries’ floodplains, marshes, and beach environments. The more inclined (< 5–7°) delta front is the primary locus of deposition, while the distal prodelta receives the finest sediment fraction. These environments are associated with topset (delta plain), foreset (delta front), and bottomset (prodelta) beds of large-scale prograding clinoforms in seismic reflection data. Generally, depositional angles are quite low even in foreset beds (Mitchum et al., 1977), which effectively prevent the recognition of such large depositional packages in martian remote sensing studies. At present, the front of the Jezero fan is a steep (≥ 10–30°) erosional escarpment, not a primary depositional feature.

The resurfacing history of the basin provides significant evidence that the Jezero delta was substantially larger and has experienced significant erosion prior to the most recent resurfacing of the present basin floor. The most recent resurfacing event has been dated to the Early Amazonian (best fit: 1.4 Ga) based upon the size–frequency distribution of superposed craters (Fig. 6). The erodibility of the deltaic deposits and the relative strength of the embaying volcanic unit are shown in Fig. 5, where the resurfacing event can be seen surrounding what is now an eroded depression. This sedimentary window was a positive topographic feature when the embaying unit was emplaced, but has since eroded somewhat further. Dunes of the eroded sediment are present along the contact. Differential crater preservation on the contact between these units occurs where a portion of a crater is well preserved on the embaying unit, but the remainder of the crater that would have been impinging the sedimentary material has been removed by erosion, further demonstrating the post-depositional erosional retreat of the deltaic deposits. Isolated distal remnants of sedimentary material, located ~3 km from the continuous deposit, rise ~150 m above the basin floor and also serve as indicators of the larger previous extent of the delta (Fig. 9). These isolated kipuka-like remnants are entirely eroded by the resurfacing unit and, with peaks approximately 50 m below the height of the present escarpment, represent a minimum previous extent of the delta nearly twice as large as the continuous fan deposit of today (Fig. 9).

Post-lacustrine erosion of the delta and resurfacing of the basin floor obscure the prodelta region from current observation (prodelta would be basinward and at lower elevation than the most distal sedimentary deposits that are observable). The present “delta front” is an erosional feature – an escarpment – resulting from post-depositional erosion of the deposits and is not related to primary deposition. Rather, sedimentary structures characteristic of a delta plain environment are truncated by the scarp (Fig. 10). Therefore, the delta plain environment, particularly the western portion, remains as the most well-preserved.
Fig. 7. Outlet channel morphology. The outlet channel has a sinuous planform (A) that can be traced for ~53 km eastward from Jezero into a terrane with superposing units (Fig. 2). Bar deposits and terraces indicate that this channel did not form from a singular catastrophic breech of Jezero. The 40-km distance across the basin from the input of the valley networks to the outlet (Fig. 2) would have effectively trapped sediment. Therefore, in our interpretation most of the development of sedimentary bedforms in the channel (B–D) is attributable to erosion and deposition by through flow after the initial breaching of the outlet, as shown by arrows. (B) Planar bedding and terraces; (C) Point bar and inner channel; (D) Inner channel and planar bedding exposed by a ~1-km crater; (E) inner channel and massive deposits. Portions of CTX: P15_007068_1971_XN_17N281W and P02_001965_1988_XN_18N281W.
and depositionally-representative, portion of the Jezero delta complex (Fig. 10) and is the focus of the next section.

6. Delta plain sedimentary features

Meanders and point bar sequences are well-studied features of both the Quaternary and older geologic record because of their importance to petroleum systems (e.g., Smith 1988; Bridge and Tye, 2000), navigation (e.g., Fisk, 1947), and natural hazard management (e.g., Johnson, 2005). In alluvial stream systems, the active channel morphology is controlled by the interaction of flow on boundary materials that have been deposited by the stream and can be eroded and transported by the stream. In this environment, meanders form naturally as a result of secondary spiral currents that enhance flow velocity and channel depth along the outer margin of a bend (Leopold and Wolman, 1960; Ikeda et al., 1981; Blondeaux and Seminara, 1985; Parker and Andrews, 1986; Ikeda and Parker, 1989; Stølum, 1996; Seminara, 2006; Howard, 2009). The evolution of meanders was studied on numerous alluvial streams by Brice (1974), who devised a canonical classification scheme for meander loops based on their degree of symmetry and geometric complexity. The natural tendency of meanders is to increase the sinuosity of the channel system by eroding their outer banks and depositing sediment along their inner banks where point bars develop. They also translate downstream. Variations in streamflow, sediment load, and relative proportions of washload and bedload influence meander development and behavior (e.g., Schumm, 1963).

Point bars (e.g., Nanson, 1980) are prograding, diachronous, time-transgressive, laterally continuous, fining upward sequences that form at the inner bank of meanders (Fig. 11). The growth of point bars produces distinctive lateral accretion topography (Fig. 11) characterized by scroll bars and intervening swales (e.g., Puigdefabregas, 1973; Hickin, 1974; Hickin and Nanson, 1975; Nami, 1976; Schumm, 1985). The planimetric signature of lateral accretion topography is easily recognized in remote sensing data due to the distinctiveness of the scroll bar pattern (Fig. 12). First studied in detail by Fisk (1947) on the lower reaches of the Mississippi River, point bars form in meandering systems of all scales (Smith, 1998) and are well studied sedimentologically (e.g., Allen, 1965). Recently, so-called counter-point bars have also been described (Smith et al., 2009). These deposits develop downstream from point bars at the point of meander inflection and thicken distally from the upstream point bar. While point bars are sand-dominated, counter point bars (also called concave bank-bench deposits) are predominately composed of silt (Smith et al., 2009). On the Jezero delta plain, it is possible that erosion products from such counterpoint bar deposits could contribute to the detections of clay minerals (Ehlmann et al., 2008b), but counterpoint bar deposits are not observed directly.

In addition to the distinctive topographic signature of point bars (scroll bars, Fig. 12), prograding point bars also develop inclined accretion surfaces, termed epsilon cross-bedding (Allen, 1963), that are visible in cross-section (e.g., Nami and Leeder, 1978; Stewart, 1983; Smith, 1987). The paleocurrent direction is parallel to the strike of the inclined accretion surfaces. The inclined lateral accretion surfaces dip in the direction of channel migration (arrows in Fig. 13). A 1-km diameter crater superposed on the western portion of the delta plain provides the necessary
The fan deposits (Fig. 2) indicate that the sedimentary assemblage coincident elevation of the outlet channel notch and the surface of Jezero system contains well-exposed sedimentary deposits. The faced (e.g., Fassett and Head, 2008a; Goudge et al., 2011), the scour the substrate and do not develop similar bars (e.g., Baker stable discharge. In contrast, singular dam-breach-flood events with associated bar deposits (Fig. 7) that indicate formation under length of time. The outlet channel has a meandering planform indicates that this basin had an overflowing hydrology for some from Jezero crater (Fig. 7), similar to many open-basin paleolakes, and source the fan deposits are consistent with precipitation (e.g.,

The somewhat dendritic valley networks that drain the watershed, away from the escarpment). This orientation requires a more extensive delta in the past. Portion of HiRISE: PSP_002387_1985.

exposed and reveals epsilon cross-bedding in its walls (Fig. 13). The inclined lateral accretion surfaces indicate that sediment was extensively reworked at this location as a succession of point bars prograded in multiple directions (Fig. 13).

7. Discussion

The facies distinctions and lake classification scheme developed by Bradley (1925), Olsen (1990), Carroll and Bohacs (1999), and Bohacs et al. (2000) provide a powerful interpretative framework (Fig. 1) for understanding the development of lacustrine basin fills. On Mars, the accommodation space dimension of this framework is simplified because most paleolakes, including Jezero, occur in impact craters. Because impact cratering is a well-understood process (e.g., Melosh, 1989; Barlow, 2009, and references therein), estimates can be made of the basin fill (Fig. 4). The somewhat dendritic valley networks that drain the watershed and source the fan deposits are consistent with precipitation (e.g., Fassett and Head, 2008a,b). The existence of an outlet channel from Jezero crater (Fig. 7), similar to many open-basin paleolakes, indicates that this basin had an overflowing hydrology for some length of time. The outlet channel has a meandering planform associated with bar deposits (Fig. 7) that indicate formation under stable discharge. In contrast, singular dam-break-flood events scour the substrate and do not develop similar bars (e.g., Baker and Milton, 1974; Rydlund, 2006; Lamb et al., 2008).

While most Noachian paleolakes have been extensively resurfaced e.g., Fassett and Head, 2008a; Goudge et al., 2011), the Jezero system contains well-exposed sedimentary deposits. The coincident elevation of the outlet channel trench and the surface of the fan deposits (Fig. 2) indicate that the sedimentary assemblage (Fig. 3) developed via deltaic progradation rather than as a deepwater submarine fan (e.g., Bouma et al., 1985), or as an alluvial fan in a playa like environment (e.g., Blair, 1999; Hardgrove et al., 2010). Extensive erosion of the fan deposits occurred prior to the most recent resurfacing of the basin interior (Figs. 9 and 10), dated to the Early Amazonian (~1.4 Ga), and subsequent erosion has continued to alter the deposits (Fig. 5). While the sharp erosional relief of the delta front scarp is the most obvious manifestation of the erosional history, impacts and eolian erosion have also altered the local topography of the delta plain and improved exposure of some depositional sedimentary structures. Therefore, the delta plain environment provides the most extensive geological evidence of sedimentary structures that are useful for constraining depositional processes and interpreting the lacustrine system.

7.1. An overfilled lacustrine system:

The Jezero fan deposits (i.e. delta plain) are very low slope (~0.5°) and approximately of the same contour (~2400 m) as the outlet channel that controlled base level. Detections of phyllosilicates (Ehlmann et al. 2008b) occur in areas of swale-and-ridge topography that we interpret as scroll bars (Fig. 12). Scroll bars are evidence of lateral accretion and point bar sequences deposited by meandering channels (Fig. 11). The sediment cohesion required to form these features (e.g., Peakall et al., 2007) is interpreted to be provided by the clays that have been detected from orbit (Ehlmann et al., 2008b). Spectral identification of clays may also be attributable to the co-development of silt-rich counterpoint bars (e.g., Smith et al., 2009) in association with the sand-dominated point bars responsible for the scroll bars.

Truncations within these scroll bar patterns suggest extensive reworking of alluvial sediment by meandering channels (Fig. 12). A large (~1 km-diameter) crater that postdates the depositional epoch provides cross-sectional views of the deposits. Multiple generations of point bar sequences deposited by meandering channels are required to account for the multiple sets of epsilon cross bedding (Allen, 1962) observed within the crater walls (Fig. 13). Elongate sediment bodies observed on the delta plain surface are interpreted as channel sands (green lines on Fig. 14). These topographically and stratigraphically higher (Fig. 15) channel systems fed more distal depocenters of the delta complex that have subsequently been eroded. Finer grained overbank and splay deposits from these channels are likely to represent a majority of the material eroded from the fan surface between these distinct channel sand bodies (Figs. 14 and 15B). Cross-cutting relationships between the channel sand bodies (Fig. 14) suggest that some of these deposits were emplaced in a series of sequential depositional episodes (e.g., lobe/channel-switching). What we interpret as channel sand bodies (Fig. 14) are more resistant to erosion and as would be expected compositionally, phyllosilicic detections are not associated with these features (Ehlmann et al., 2008b). Channel sand bodies are common in terrestrial deltaic systems in a variety of physiographic settings (Busch, 1971; LeBlanc, 1972; Busch and Link, 1985). Similar high standing channel sand bodies have been documented in fluvial sandstone formations of the Colorado Plateau (e.g., Stokes, 1961). These channel sands (Fig. 14) are consistent with our interpretation of a previously more extensive delta (e.g., Fig. 10).

Utilizing the facies and basin classification framework (Fig. 1), we interpret Jezero as an overfilled basin. Initial accommodation space is the result of the formation of a Noachian-aged fresh impact crater. Crater degradation processes and precipitation-fed valley networks breached the crater rim and initiated filling of the basin. Crater breaching by valley networks is common on Mars (Fassett and Head, 2008a; Enns et al., 2010) and may be aided by infiltration through impact-related faults (e.g., Kumar and Kring, 2008; Kumar et al., 2010) akin to infiltration and piping.
induced dam failures (Bedmar and Araguas, 2002; Richards and Reddy, 2007), or by topographic ponding and subsequent overtopping and down-cutting of the crater rim. Once these valley networks flooded the crater basin, formation of the outlet channel began.

Sediments transported by the inflowing valley networks constitute the fluvial–lacustrine facies association that in our interpretation is a majority of the basin fill (e.g., Fig. 4). Episodic filling and desiccation of the basin (e.g., as might be indicated by fluctuating-profundal facies) is inconsistent with the large high-relief deposits (Fig. 3) and the mature outlet channel (Fig. 7). If Jezero was a dominantly balanced-fill lake, the outlet channel would be absent or very immature. Any outlet would be relatively short and dominated by scour rather than exhibit the bar deposits that are observed (Fig. 7). In a dominantly balanced-fill lake, the locus of sediment deposition would have experienced major shifts shoreward (highstand systems tract) and basinward (lowstand systems tract) with the fluctuating lake level. Transgressive surfaces would be dominant features and lateral accretion deposits (Figs. 12 and 13) would not have developed. Desiccating lowstands would lead to channel incision (e.g., Weitz et al., 2006, their Figure 4c) and possibly even alluvial fan deposition.

Similarly, a high-discharge cataclysmic filling of the basin, breaching of the rim, and near-immediate decline of the inflowing channels is not consistent with the observed deposits in our interpretation. Such a high discharge, short period, scenario would not result in the stable baselevel required to form the lateral accretion deposits that are observed. Depositional features within the outlet channel require a sustained discharge for sediment erosion, transport, and deposition (Fig. 7). Because the basin would be an excellent sediment trap, sediment in the outlet channel must be eroded by the outlet channel – a singular catastrophic outflow would only scour a path (e.g., Rydlund, 2006); the outlet channel morphology requires a stable overfilled lacustrine hydrology.

7.2. Sedimentation rates

Measurements of sediment package thickness, in conjunction with terrestrial experience with sedimentation rates, allow us to
estimate minimum durations of stable activity in the Jezero system. Comparing the topographic profile of the present Jezero crater with a fresh crater of the same diameter and depth-diameter relationships (Garvin et al., 2003) suggests a lacustrine basin fill of \( \sim 750 \) m. Even the most conservative estimate of sediment thickness, taken by differencing the elevation between the most basinward and most proximal present-day sedimentary exposures, would suggest a thickness of \( \sim 300 \) m. Terrestrially, impact crater basin analogs are rare due to the Earth’s much more vigorous geologic history. Lake El’gygytgyn in the Russian arctic (67.5° N, 172° E) is an open basin lake system formed in a 12-km diameter Pliocene-age crater. Studies of shallow sediment cores and seismic imaging of the sediment fill suggest deposition rates of 3–12 cm/Kyr (Melles et al., 2005).

However, sediment accumulation rates have been observed or measured extensively in a variety of other terrestrial basin environments. Therefore, conservative assumptions derived from a very large dataset enable estimates of the minimum timescale for deposition. In a seminal study, Sadler (1981) compiled nearly 25,000 measures of sediment accumulation rates and showed conclusively that such rates are inversely related to the time span of the measurement. For lacustrine environments, the Sadler (1981) rates span four orders of magnitude (\( \sim 0.01–100 \) m/Kyr) depending on the time span of the measurement (10–10^8 years).

Fig. 12. Scroll bars. Numerous scroll bars (lateral accretion topography, Fig. 11) are observed adjacent to the 1-km crater on the delta plain (Fig. 13) and stratigraphically below erosionally-resistant materials interpreted as channel sands (Fig. 14). These features (A–H) result from the development of point bars at the inside of distributary channel meander bends (Fig. 11). Arrows indicate the direction of channel migration. Unconformities in the scroll bar patterns are common and suggest successive channel migrations. Portions of HiRISE: PSP_002387_1985.
However, sediment accumulation is not uniform in a basin. In particular, a progradational delta system has localized depocenters and sediment deposition is concentrated along the delta front (e.g., Corbett et al., 2006). Assuming that a delta front sediment accumulation rate of cm per annum (Hori and Saito, 2008) prevailed for the entire depositional history of Jezero suggests a lifetime on the order of $10^4$ (Earth) years for the system, while median paleolacustrine sediment accumulation rates of Stadler (1981) indicate a potential lifetime of $10^6$–$10^7$ years.

An important consideration in such calculations is the availability of sediment supply in the watershed. In terrestrial settings, biota is an important component of chemical and physical weathering processes, but biota can also retard erosion (Dietrich and Perron, 2006); the net effect of the absence of these counteracting influences on martian sediment generation and transport is unknown. Impact gardening is likely to be a dominant sediment-forming process on Mars today (e.g., Hartmann et al., 2001), but rates of impact gardening during the Noachian are poorly known. The higher impact flux in the Noachian would suggest more rapid impact gardening than at present, but an early thick atmosphere could have shielded the surface from small impacts, reducing the efficiency of gardening (e.g., Hartmann and Engel, 1994).

Measurements of the clearly identifiable scroll bars (Fig. 12), in conjunction with terrestrial experience with meander migration rates, can also suggest minimum durations of depositional activity in the Jezero system. Scroll bars here (Fig. 12), elsewhere on Mars (e.g., Eberswalde; Wood, 2006), and terrrestrially (e.g., Hickin

Fig. 12. Deltaic deposit cross-sections. (A) A 1-km diameter crater provides a cross-sectional view of the deltaic sedimentary materials. The crater is oriented in this view such that north is to the left and basinward toward the top. In the walls of this crater, epsilon cross-bedding (Allen, 1963) is observed. Epsilon cross-bedding results from lateral accretion surfaces within point bars (Figs. 11 and 12). Portion of HiRISE: PSP_002387_1985. (B) Within the 1-km diameter crater, three clear examples of epsilon cross-bedding are observed (A,B,C). In these outcrops lateral accretion is observed in both the basinward direction (A, C) as well as laterally (B), consistent with our interpretations of meandering distributaries of a subaerial delta plain environment. Lateral accretion surfaces dip in the direction of channel migration (indicated by arrows). The paleocurrent direction is parallel to the strike of the lateral accretion surfaces. Portion of HiRISE: PSP_002387_1985.
and Nanson, 1975; Schumm, 1985) commonly exhibit numerous cutoffs and unconformities formed by erosion and redeposition of previously laterally accreted sediments by an active channel. Cutoff events have an important dynamical influence on the continued evolution of other meanders (Camporeale et al., 2008; Constantine and Dunne, 2008). Therefore, lateral measurements of continuous point bar deposits are very conservative estimates for the overall lifetime of the system. In Jezero these individual features are commonly tens to hundreds of meters in width (Fig. 12).

Fig. 14. Channel deposits. (A) Stratigraphically above the scroll bars (Fig. 12) and epsilon cross-bedding (Fig. 13) are elongate erosional resistant materials that we interpret as channel sands. Consistent with our interpretation of a more extensive delta in the past (e.g., Fig. 10), these channel sands would have been deposits in distributary channels sourcing more distal depocenters. In our interpretation these channel sand deposits are high-standing because they are more erosional resistant than overbank deposits. (B) Channels sands are mapped in green, scroll bars in blue, and craters in purple. Portion of CTX: P04_002743_1987_ XL_18N282W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The development of meander loops (Rich, 1914) and their evolution and migration through time has long been an empirical inquiry of geologists. As products of the fluvial environment, the formation and evolution of meanders and their geological preservation in point bars are affected by the major factors controlling alluvial stream channel form. Landmark field studies by Brice (1974); Leopold et al. (1964); Schumm (1985), and others have suggested relations between stream parameters (e.g., radius of curvature) and meander bend migration rates.

Fig. 15. (A) Topographic map with 100 m contours from HRSC. (B) Topographic profiles across the delta reveal the stratigraphic position of the channel sands (Fig. 14) above the scroll bars (Fig. 12) and epsilon cross-bedding (Fig. 13). Portion of CTX: P04_002743_1987_ XL_18N282W. MOLA Orbits: 15454 and 15127.
We utilize a large dataset of stream bank meanders that was originally compiled for the Transportation Research Board (TRB) of the National Academies for purposes of civil engineering (Lagasse et al., 2004). This dataset encompasses 89 rivers in the continental United States, and includes data from 1503 unique meander bends at 141 field sites. These study sites were re-occupied multiple times allowing for comparison of the meanders over years and decades. Some meanders were cutoff, while at other locations, new meanders were observed to form along previously straight reaches.

We employed a variety of historical imagery for reconnaissance of each meander bend and excluded all field sites impacted by artificial revetments (e.g., riprap and other bank stabilizations) or channel modification (e.g., sand and gravel mining). Excluding meander cut-offs, 1009 measurements of meander migration were calculated with a minimum (0.03 m/year), mean (3.76 m/year), median (2.52 m/year), and maximum (30.00 m/year) rate of meander migration (Schon et al., in preparation). These rates suggest that plausible timescales for the formation of the individual scroll bar sets (Fig. 12) are likely on the order of decades (~20–40 years) assuming average terrestrial migration rates.

7.3. Comparison to modeling results:

Our estimates of the duration of lacustrine activity in Jezero (~10^9–10^7 years) are substantially longer than the short minimum timescales of formation (0.01–10 years) calculated for some Mars fan deposits using sediment transport models (Kleinhans, 2005; Kleinhans et al., 2010). Neither Kleinhans (2005) nor Kleinhans et al. (2010) considers the Jezero system specifically. But, for example, modeled minimum timescales for the sedimentary fan deposits of Ma'adim, Nanedi, Sabrina, and Hypanis valles are all less than a decade. While the sediment transport mechanics employed by Kleinhans (2005) and Kleinhans et al. (2010) are well-validated and internally consistent with their starting assumptions, multiple geologic features of the Jezero system and different assumptions explain our divergent conclusions about the length of inferred activity: (1) while discharge is difficult to constrain with certainty, we suggest that bank-full discharge is not a good approximation for a long-lived fluvial system such as Jezero; (2) the valley networks may have been detachment-, or supply-limited, akin to a bedrock river; and (3) the Jezero delta plain morphology requires a cohesive component (clay: Ehlmann et al., 2008b) and sand, which are inconsistent with Kleinhans et al. (2010) assumptions regarding the size-distribution of transported clasts (“a median grain size of 0.1 m and a 90th percentile size of 0.6 m diameter”). Meandering systems transporting primarily gravel and larger sediment are unknown; these materials give rise to braided channel patterns terrestrially (Harms et al., 1975).

Kraal et al. (2008b) suggest that so-called “stepped deltas” formed quickly (years to decades) due to enormous discharges and fast-rising lake levels. In contrast, the deltaic architecture at Jezero suggests a stable baselevel and a longer time-scale for formation. While Jezero has a large watershed drained by established valley networks, the Kraal et al. (2008b) example has an extremely short channel (~20 km) that is implied to have had a discharge comparable to the Rhine or Mississippi Rivers in their analysis. Kraal et al. (2008b) favor a large release of groundwater rather than a precipitation-fed origin for the discharge. Therefore, these “stepped delta” deposits (see also, Weitz et al., 2006) are indicative of local or regional groundwater releases (Kraal et al., 2008b) in contrast to progradational deltaic deposits such as Jezero or Eberswalde (e.g., Bhattacharya, 2005; Wood, 2006; Pondrelli et al., 2008; Dietrich, 2010) that due to their large catchments are more representative of general climatic conditions during their deposition (e.g., Di Achille and Hynek, 2010).

Lastly, in a landform evolution model-based evaluation of the time needed to generate the late Noachian or early Hesperian Parana Basin Valley network, Barnhart et al. (2009) concluded that a period of 10^5–10^6 years best fit the quantitative morphology of the valley network – concordant with our analysis of fluvial–lacustrine activity in Jezero.

8. Conclusions

The Jezero crater open-basin paleolake contains eroded deltaic deposits (Fig. 3). While the apparent modern delta front is actually an erosional scarp (Fig. 10), the delta plain is well exposed with an extensive pattern of scroll bars (Fig. 12) that formed via lateral accretion from meandering distributary channels (Fig. 13) coincident with phyllosilicate detections (Ehlmann et al., 2008b). The presence of a stable subaerial delta plain environment with meandering distributaries indicates that the delta prograded during an extended period of baselevel stability in an overfilled lake system (e.g., Fig. 1). Isolated remnants of the delta (Fig. 9), embayment and erosion relationships (Fig. 5), and stratigraphically higher elongate channel sand bodies (Figs. 14 and 15) point to the larger previous extent of the delta. The larger previous extent of the delta is evidence of extensive post-depositional erosion predominantly prior to Early Amazonian volcanic resurfacing of the basin floor (Fig. 5). Sedimentary bars in the outlet channel (Fig. 7) provide independent evidence of the stable overfilled lacustrine system. Topographic comparison with fresh craters and impact crater scaling relationships (Fig. 4) require a significant basin-fill in Jezero consistent with the delta and lacustrine sedimentation.

Our interpretations of the depositional characteristics and plausible sedimentation rates suggest that formation of the Jezero delta required a period of ~10^6–10^7 years to form. This suggests a minimum persistence of climatic conditions sufficient for valley network formation and open basin hydrology during a portion of the Noachian. Our analysis has not revealed any evidence of waning-stage channel incision or forced progradation, indicating that the end of the Noachian climate period during which these deposits formed was likely to have been rapid. The accommodation space that remains (~200–300 m) indicates that while our interpretation implies that these environmental conditions persisted in the Noachian for longer than required by some models (e.g., Kleinhans, 2005; Kraal et al., 2008b), sediment transport and deposition in the Jezero paleolacustrine system was fundamentally limited by a secular shift in climate.

The Jezero delta is an attractive target for in situ exploration by missions following MSL that will seek to characterize the stability and longevity of Noachian habitable environments (e.g., Grotzinger, 2009; Golombek et al., 2011; Grant et al., 2011). Based on analysis of Jezero during the MSL landing site selection process, this would likely require improvements in precision landing capabilities (reduction in landing ellipse size) over the MSL architecture. Observations from the crater floor of the deltaic escarpment would reveal the finest-scale details of the bedding, while the traversable terrain of the delta plain contains sedimentary structures and mineralogical diversity deserving further investigation (e.g., Fassett et al., 2007; Ehlmann et al., 2008b). Finally, the sedimentary basin fill within Jezero presents a compelling target for future subsurface exploration with capabilities being developed by NASA’s Mars Technology Program (Miller et al., 2004). Terrestrial overfilled lacustrine systems contain numerous organic-rich units with the potential for excellent biomarker preservation. If drilled, the Jezero sedimentary record could elucidate the history of Mars’ climate and surface weathering environment in dramatically higher resolution than possible by remote analysis of the planetary surface.


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