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Delta morphology reveals timings of early ocean regression and hydrologic shift on ancient Mars



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Mars' ancient hydrologic history remains a subject of debate, with competing interpretations suggesting either a large ocean or scattered lacustrine environments. Here, we show that delta morphology on Mars records a shift between these hydrologic regimes. Through controlled tank experiments, we identify two distinct delta types: “lobe-extruding deltas” formed during water-level falls and “stepped fan-deltas” formed during rising water levels. The lobe-extruding deltas occur near proposed paleo-coastlines and are dated to ~3.8–3.2 Ga, consistent with the existence of a Late Noachian–Hesperian ocean and its subsequent regression in the Late Hesperian. In contrast, stepped fan-deltas are found at a wider range of elevations and exhibit significantly younger ages (~2.1–0.1 Ga), suggesting episodic, localized lake formation during the Amazonian. Our findings constrain the timing of the planetary-scale transition from a global hydrosphere to localized aqueous environments and refine the understanding of Mars' paleoclimate evolution and potential habitability.

Mars hosts extensive geomorphological evidence of past aqueous activity. Features such as outflow channels, valley networks, and deltaic landforms point to a time when liquid water was stable at and near the surface for extended geological periods^{1–10}. Two main hypotheses have been proposed to explain the nature of Mars' early hydrosphere. The ocean hypothesis posits a large, continuous water body that once filled the northern lowlands from the Late Noachian to the Early Hesperian, with the shoreline evidence supporting this hypothesis^{1,11–17}. In contrast, the multiple-lake scenario suggests that Martian aqueous activity was intermittent and geographically fragmented^{2,6,18–22}. In support of prolonged surface water, orbital spectroscopy has revealed widespread phyllosilicates, sulfates, and chloride-bearing deposits^{23,24}. In situ observations by rovers have further documented sedimentary structures associated with long-lived aqueous activity and water–rock interaction in standing bodies of water^{25–28}.

Although the global distribution of Martian deltas and alluvial fans is well documented, the potential of delta morphology to constrain past global-scale hydrology remains insufficiently explored. Deltas are commonly interpreted to have formed in association with a putative Late Noachian–Hesperian ocean^{1,3,7,29}, yet a study suggested that delta formation may have persisted into the Late Amazonian⁶. In contrast, multiple studies indicate that alluvial fans predominantly formed during the Hesperian–Amazonian period^{12,22,30–33}. Because deltas require sustained interaction between fluvial systems and broad standing bodies of water^{34–36},

while alluvial fans do not necessitate large or long-lived water bodies, distinguishing between these landforms and resolving their spatio-temporal distribution is essential for reconstructing the nature and longevity of aqueous activity on Mars.

Here, we hypothesize that Martian deltas retain diagnostic morphological signatures recording a transition from a globally connected ocean during the Late Noachian–Hesperian to increasingly short-lived and localized lacustrine environments during the Amazonian. To test this hypothesis, we integrate satellite image analysis with controlled laboratory tank experiments that are designed to simulate delta evolution under systematically varying water-level conditions. By explicitly incorporating both rising and falling water levels, our experiments reproduce key aspects of deltaic morphologies observed on Mars. While previous experimental studies have generated deltaic landforms^{37,38}, none have isolated the effect of water-level fluctuations, a critical control on delta architecture.

Our experiments further establish the formation conditions of landforms closely analogous to two distinct morphologies of Martian deltas. In this framework, we use “rising” and “falling” water levels to describe the experimental conditions, and “transgression” and “regression” to denote the corresponding stratigraphic and geomorphic expressions identified in Martian examples. This approach allows us to isolate morphological traits diagnostic of transgressive versus regressive delta development under sedimentary and hydrological regimes relevant to Mars^{39,40}. By integrating

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experimental results with remote sensing analyses, including crater-counting chronology, we provide new constraints on the timing, extent, and evolution of the Martian hydrosphere, with broader implications for understanding the planet's climatic evolution and its potential habitability.

Results

Delta morphology of water-level fall and rise experiments

We conducted a series of model experiments using the MARGI 5 tank facility at Nagasaki University^{35,36,39,40} to isolate and quantify the effects of water-level fall and rise on deltaic morphology (see Methods; Fig. S1; Supplementary Videos). In these experiments, a constant mixture of water and 0.1 mm quartz sand was supplied at the inlet and transported as bedload, while the basin water level was systematically lowered or raised.

Although the previous experiments^{37,38} and the present study share the fundamental concept that delta morphology is governed by the balance between sediment supply and water-level change at the shoreline, the key conceptual difference lies in how the morphological response to water-level fluctuations was evaluated. In the previous experiments, water and sediment were supplied concurrently, causing the water level to rise passively within a closed basin. The resulting delta morphology therefore reflected the coupled effects of variations in sediment flux and supply-driven water-level rise, making it difficult to isolate the morphological effects of water-level change alone. In contrast, our experiments imposed water-level fluctuations independently while maintaining constant water and sediment supply rates. This experimental design enabled us to isolate and characterize the morphological response of the delta to externally forced water-level fluctuations, thereby distinguishing the effects of base-level rise and fall from those associated with variations in sediment supply.

Figure 1 compares laboratory-generated deltas formed under falling water levels (Fig. 1a, c and Table 1) with morphologically similar Martian examples (Fig. 1b, d). Comparison with Martian delta topography is described in the next section. To understand how the delta topography changes with variations in the rate of water-level fall (R_{wlf}), we conducted the

following six experiments. First, we performed three experiments in which R_{wlf} was multiplied by two to four times (Run 1: 0.00373 → Run 2: 0.00767 → Run 3: 0.0141). Next, we reduced sediment supply rate (Q_s) and water supply rate (Q_w) by approximately half as follows (Run 3: Q_s : 0.739, Q_w : 9.93 → Run 4: Q_s : 0.368, Q_w : 4.80). We also conducted an experiment in which R_{wlf} was multiplied by six times in the middle of experiment [Run 5: 0.00226 (first set, 31 min) → 0.0133 (second set, 9 min)]. Run 6 is a continuation of the experiment from Run 5 after stopping the water level from falling.

The experimental results demonstrate that the delta platform is sensitive to the rate of water-level fall (R_{wlf}). Under slow fall conditions, the feeder channel migrated laterally across the topset, constructing a broad, fan-shaped delta plain composed of laterally amalgamated lobes (Fig. S2 and Table 1, Runs 1 and 2 under increasing R_{wlf}). In contrast, rapid water-level fall suppressed lateral migration and avulsion, resulting in a more confined channel that extended basinward without significant transverse displacement (Fig. S2; Run 3). In addition, an R_{wlf} value identical to Run 3, but with decreased rates of sediment and water supply (Q_s and Q_w) resulted in much narrower amalgamated lobes (Fig. 1c; Run 4).

When the fall rate was increased in the middle of the experiment, lateral channel migration decreased, and an increasing amount of sediment began to accumulate along the foreset. A protruding lobe then developed at the basinward edge of the previously wide, fan-shaped delta formed under slower-fall conditions (Fig. 1a; Supplementary Video Run 5). These results indicate that the delta lobe width responds directly to the local water-level fall rate. Narrow, elongated lobes formed consistently under rapid fall conditions when topographic gradients favored basinward progradation. We term this striking morphology a “lobe-extruding delta,” characterized by tongue-shaped lobes protruding from a previously formed delta surface (Fig. 1a, c and Fig. S2).

Furthermore, after the formation of the lobe-extruding delta (Fig. 1a and Table 1, Run 5), we continued sediment and water supply while maintaining a constant water level downstream (Fig. S2 and Table 1, Run 6).

Fig. 1 | Comparison between experimentally-generated lobe-extruding deltas formed under falling water levels and Martian examples that is morphologically similar. Lobe-extruding deltas produced in water-level fall runs (a, c) and found on Mars (b, d). The area surrounded by the red line is the formed delta in the experiments.

a Experimentally produced lobe-extruding deltas by changing rate of water level fall (R_{wlf} from 0.0023 cm/s to 0.013 cm/s; Table 1, Supplementary Video Run 5). The image is reversed left and right. **b** A comparable Martian lobe-extruding delta in Jezero crater (Table S1, ID 1–4; 77.30°E, 18.49°N). **c** Experimentally produced lobe-extruding deltas with a constant R_{wlf} of 0.01621 cm/s (Table 1, Run 4). Three vertical laser planes (horizontal spacing of 25.0 cm) and 23 horizontal laser planes (vertical spacing of ~7.5 mm intervals) are continuously projected onto the experimental area (Fig. S1). The image is reversed left and right. **d** A comparable Martian lobe-extruding delta in Hypanis Valles (Table S1, ID 1–3; 45.44°W, 11.29°N). For Fig. 1b, d, CTX⁸¹ images were used.

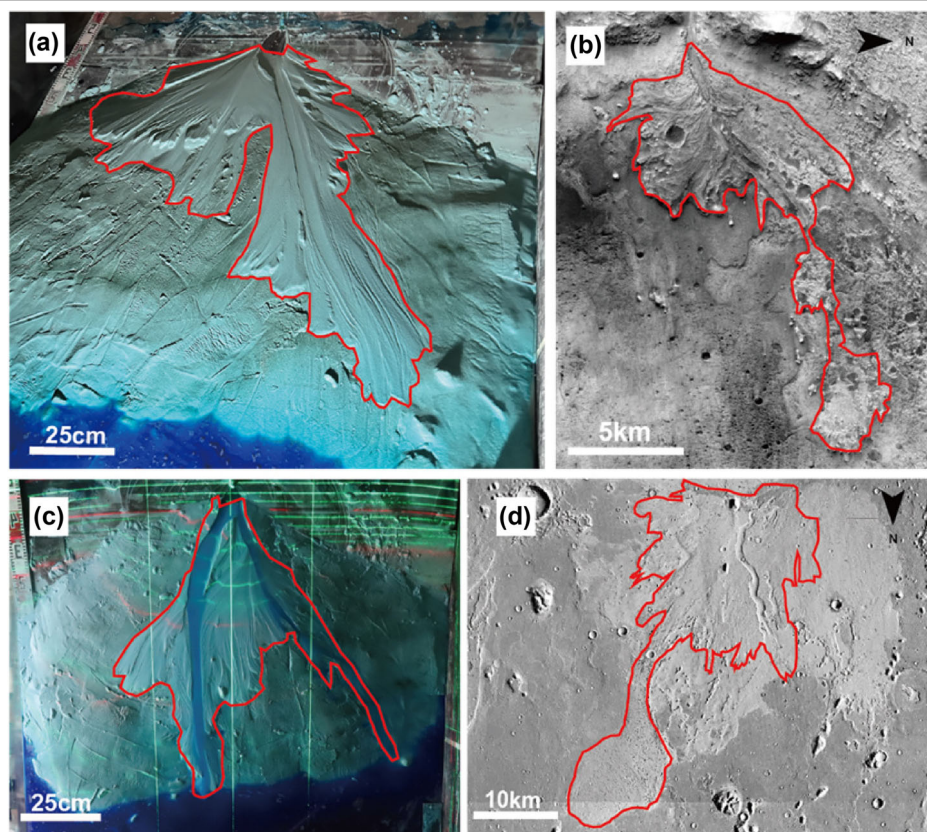


Table 1 | Conditions for the water level fall and rise experiments

Run no.	Rate of sediment supply [Q_s (cm^3/s)]	Rate of water supply [Q_w (cm^3/s)]	Water/Sediment ratio [Q_w/Q_s]	Rate of water level fall [R_{wlf} (cm/s)]	Rate of water level rise [R_{wlr} (cm/s)]	Run time [T (min)]	Area scale [Λ_{3D} (cm^2)]
Run 1	0.739	10.1	13.7	0.00373		62.5	198
Run 2	0.739	10.2	13.8	0.00767		29.0	96.3
Run 3	0.739	9.93	13.4	0.0141		15.8	52.4
Run 4	0.368	4.80	13.1	0.0162		15.3	22.7
Run 5*	0.368	4.80	13.1	0.00226 $\rightarrow$ 0.0133		31.0 $\rightarrow$ 9.0	163 $\rightarrow$ 27.6
Run 6	0.368	4.81	13.1	0		15.0	$+\infty$
Run 7	0.743	10.0	13.5		0.000628	300	1180
Run 8	0.739	9.88	13.4		0.00126	150	589
Run 9	0.700	9.94	14.2		0.000322	600	2170
Run 10	1.50	20.4	13.6		0.000653	300	2300
Run 11	0.361	4.68	13.0		0.000617	300	585
Run 12	0.361	4.68	13.0	0.00715		25.8	50.7

*Arrows in Run 5 means changes of setting in the middle of the experiment.

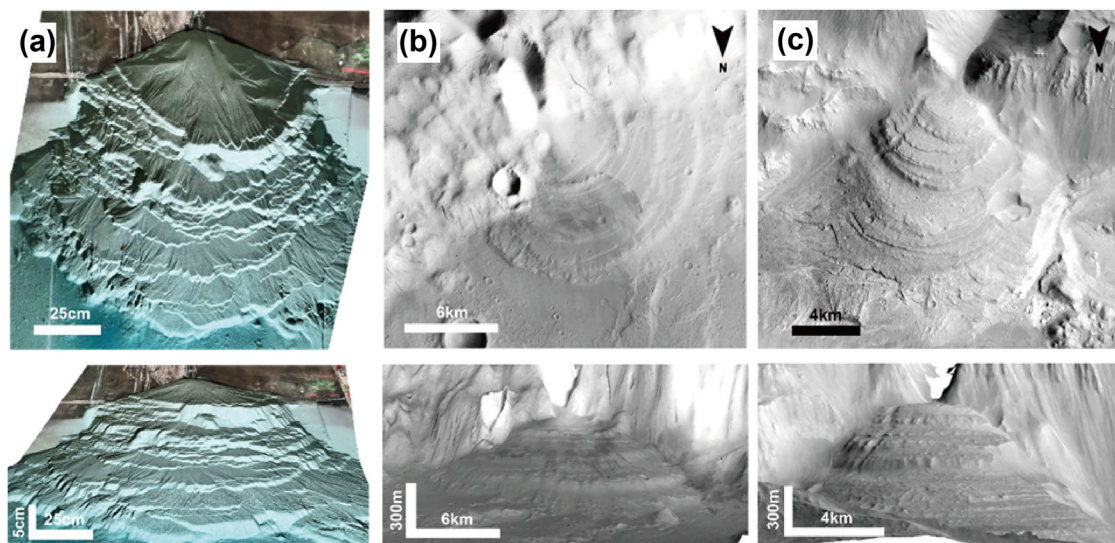


Fig. 2 | Comparison between experimentally-generated stepped fan-deltas formed under rising water levels and Martian examples that is morphologically similar. Stepped fan produced in water-level rise run (a) and found on Mars (b, c). The upper image shows a view from above, and the lower image shows a view from the front. **a** Experimentally produced stepped fan with a constant water level raise ($R_{wlr} = 0.000628 \text{ cm/s}$) (Table 1, Supplementary Video Run 7). The image was captured from a 3D image of the experimental result constructed using Agisoft

Metashape Professional version (Agisoft LLC, St. Petersburg, Russia). **b** A comparable Martian stepped fan, in Memnonia region (Table S2, ID 2–19; 159.26°W , 8.63°S). The lower image is vertically exaggerated by a factor of eight. **c** A comparable Martian stepped fan in Coprates Catena (Table S2, ID 2–30; 60.26°W , 15.02°S). The lower image is vertically exaggerated by a factor of three. For Fig. 2b, c, CTX⁸¹ images were used.

As a result, channel migration resumed at the boundary with the water level, and the width of the lobe increased again. In all cases, our experiments demonstrate that elongated, narrow, protruding lobes form only during falling water levels. Lower R_{wlr} causes more widespread channel migration and multiple active distributaries, whereas a faster R_{wlr} causes flow to concentrate into a single channel: a pattern broadly consistent with regressive deltas on Earth (e.g., the Volga delta in the Caspian Sea⁴¹). While previous studies have suggested that the lateral spread and number of channels formed in deltas during water level lowering are caused by changes in discharge volume or grain size³⁷, our experimental results revealed that such morphological differences can arise solely from variations in the rate of water level fall (R_{wlf}).

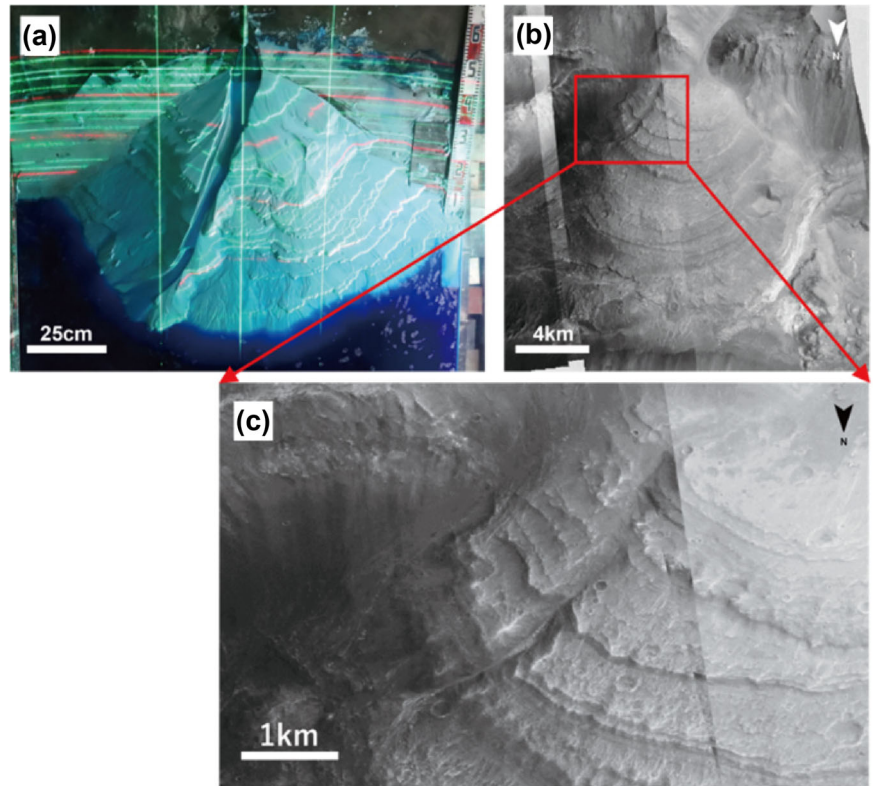
Figure 2 is experimentally generated fan-deltas with a multi-level stepped surface formed under a continuously rising water level (Fig. 2a and Fig. S3; Table 1; Supplementary Video Run 7). This landform does not

exhibit delta-front foresets or bottomsets. We therefore interpret these stepped morphologies as not being true deltas, but instead represent the preserved remnants of non-deltaic transgressive alluvial systems⁴⁰, herein termed “stepped fan-delta”.

In stepped fan-deltas, the lower surface corresponds to the older alluvial plains, whereas the stepped slopes form progressively in response to rising water level. Frequent avulsions and rapid lateral migration of distributary channels promote vertical stacking of lobes. The stepped morphology emerges when continuous aggradation is interrupted by avulsion^{35,40}. Consequently, the front edge of each step does not represent a delta-front foreset, but rather a cross-section through a laterally extensive accumulation of thin sand layers.

Across experiments, the ratio of step height to step area varies systematically (Figs. S3 and S4). Lower rates of water-level rise (smaller R_{wlr}) produce smaller step height/area ratios (Table 1, Run 8 $\rightarrow$ Run 7 $\rightarrow$ Run 9 in

Fig. 3 | Comparison between experimentally-generated channel incision into the stepped fan-delta and Martian example that is morphologically similar. **a** Experimental result of the fan morphology built in response to a water-level rise and subsequent fall (Table 1, Run 12). Three vertical laser planes (spaced at 25.0 cm intervals) and 23 horizontal laser planes (spaced at approximately 7.5 mm intervals) were continuously projected onto the experimental area (Fig. S1). Sediment supply continued throughout the entire run. **b, c** Martian stepped fan in the Coprates Catena subjected to channel entrenchment (Table S2, ID 2–30; 60.26°W, 15.02°S). For Fig. 3b, c, CTX⁸¹ images were used.



decreasing order of R_{wtr}). Similarly, smaller step height/area were formed with larger Q_s (Table 1, Run 11 → Run 7 → Run 10 in the increasing order of Q_s). Both reflect the larger length scale (Λ_{3D} ; Table 1), allowing sedimentation to prograde farther basinward (toward the ocean) (Fig. S3).

Previous experimental studies^{37,38} also attempted to reproduce step-like topography analogous to that observed on Mars, but only through episodic increases in sediment supply, which is fundamentally different from the processes examined in this study. In contrast, the stepped fan-deltas produced in our experiments exhibit strong structural similarity to stepped landforms observed in closed basins on Mars (Fig. 2b, c).

Our results provide a process-based explanation for these features: the stepped fan can form autogenically under constant sediment supply and a steady, continuous rise in water level. As autogenic shrinkage of the alluvial system proceeds, aggradation becomes increasingly focused upstream, generating a systematic increase in step height. Unlike previous interpretations that invoked episodic sediment supply^{37,38}, our experiments demonstrate that stepped fan-delta morphologies can emerge inevitably from steady water-level rise (R_{wtr}) alone⁴⁰.

To investigate how a fan evolves under conditions where regression follows transgression, we conducted an additional experiment following the formation of a stepped fan. After building a stepped fan, we lowered the water level with sustained Q_s and Q_w (Fig. 3a and Table 1, Run 12). This led to a distinct channel incision into the stepped fan-delta. The primary channel was entrenched into the stepped deposit, carving and deepening a valley and re-exposing the earlier step surfaces as internal terraces (Fig. 3a). By the end of the run, the channel had cut down through the stepped fan-delta sequence, forming a new prograding mouth lobe.

Comparison of experimental results and Martian delta morphology

A lobe-extruding delta is found on Mars, located in the Jezero crater (Fig. 1b and Table S1, ID 1–4)². Although the Jezero crater is connected to outgoing channels (Pliva Vallis) to the east, thus experienced a period of an open basin, the Jezero's delta is thought to have formed in a closed basin due to a water-level fall^{27,42,43}. It was formed by a river channel flowing from west to

east, creating a broad, fan-shaped delta in the west that transitions into an elongated lobe extending eastward. Our experimental delta morphologically resembles the Jezero crater delta on Mars, characterized by a similar fan-shaped form composed of overlapping depositional lobes²⁷.

The interpretation of the elongated lobes in the Jezero crater remains debated, with competing interpretations suggesting they represent either distal extensions of the western fan-shaped delta or remains of a separate northern fan sourced from the northern channel^{44,45}. However, CRISM analysis shows that the main delta and the northern part of the northern fan are composed of olivine- and carbonate-bearing deposits, whereas both the western fan-shaped delta and the elongated lobes exhibit similar low-calcium pyroxene signatures⁴⁶. On this basis, ref. 43 proposed that the elongated lobes formed during the late-stage progradation of the western delta that advanced south of the northern fan. Our results support this interpretation and further indicate that the development of elongated lobes was associated with a relative lowering of water level.

Recent rover observations from the Jezero crater provide additional support for this interpretation, documenting multiple stacked sediment units that record cyclic lake-level fluctuations and episodic deposition²⁷. Stratigraphic analysis of outcrops within the western fan-shaped region indicates lake-level falls at elevations comparable to those of the elongated lobes, consistent with lobe formation during a phase of water-level decline^{27,43}. At Jezero, the presence of stacked sediment layers points to repeated lake-level fluctuations, and one or more of these episodes may have involved a rapid drop in water level. The experimental and Jezero deltas together highlight analogous geomorphic and sedimentary responses to variable water levels, confirming that Jezero's delta likely formed under dynamic hydrological conditions consistent with those observed in controlled laboratory settings⁴⁷, where both gradual and abrupt changes shaped the delta architecture. However, the presence of buttes^{48,49} and eolian landforms⁵⁰ suggest that erosion has affected the Jezero delta. Therefore, there is a possibility that the extruding lobe differs from the topography at the time of deposition.

A second lobe-extruding delta is located in Hypanis Valles (Fig. 1d and Table S1, ID 1–3) on a broad, topographically open plain², which consists of

a wide, fan-shaped deposit near the source area, from which a long, narrow lobe extends toward the northeast. The distal tip of the lobe appears broad and rounded. Although no distributary channels are visible on the surface of the lobe itself, its morphological continuity with the fan-shaped section suggests that it was constructed by sediment transport through the same fluvial system. A narrow, northward-trending erosional channel incises the western fan margin and maintains a consistent elevation on either side. The lobe tip is slightly swollen but connects smoothly to the upstream deposits, indicating that it formed as part of basically the same series of depositional events.

The observed delta morphology in Hypanis Valles suggests a formation process controlled by water level fluctuations. Initially, under stationary or slowly falling water levels, the feeder flow could migrate laterally and lead to the formation of the fan-shaped delta. A subsequent rapid water-level fall reduced lateral migration, promoting downstream sedimentation and forming the elongated lobe. When the water level stabilized again, deposition resumed, thickening the lobe. Aggradation then allowed the delta to transition smoothly back toward lateral channel movement, widening the landform at its distal end.

The seamless connection between the fan and its lobe suggests that sediment supply was sustained during and after water-level changes. Previous studies^{37,51} attributed lateral differences in delta development to the basement topography or changes in grain size or discharge. Our results extend this interpretation by demonstrating that elongated lobes can form solely as a response to rapid water-level fall, even in the absence of pre-existing topographic undulations and under constant discharge and grain size. While another previous study⁵² has also examined the relationship between the genesis of this delta and water level fluctuations, they interpreted that there to be no clear correlation with water level variations. However, the present study supports the hypothesis that water-level decline played a dominant role in shaping the delta, complementing earlier topographic and stratigraphic interpretations⁵¹.

The stepped fan-deltas produced in our experiments, characterized by multiple backstepping lobes, closely resemble Martian landforms with stepped morphologies in closed basins^{2,37,38,53,54}. Figure 2b shows an example from the Memnonia region, within a closed basin lacking an outlet valley (Table S2, ID 2–19). The feeder channel flowed from southeast to northwest, depositing two prominent stacked sub-fans along with several smaller steps. These features closely mirror the geometry of the experimental stepped fan-deltas (Fig. 2a) and suggest formation during steady water-level rise.

A second Martian example is found in Coprates Catena (Fig. 2c and Table S2, ID 2–30), a trough southeast of Valles Marineris, where a fan was formed by a channel flowing from south to north^{2,53}. Like the Memnonia fan, this example shows vertically stacked lobes and stepped morphologies consistent with our experimental outcomes. Earlier interpretations proposed that such stepped forms on Mars resulted from episodic sediment supply^{37,38}. In contrast, our experiments suggest that stepped fan formation can occur under constant sediment supply, driven by progressive aggradation during steady water-level rise.

Both Martian fan-deltas show evidence of lateral channel migration and lobe development on the stepped surfaces, similar to patterns observed in previous work⁴⁰. Notably, the Memnonia fan-delta (Fig. 2b) is comparatively lower in relief and exhibits a smoother surface, whereas the Coprates Catena fan-delta (Fig. 2c) shows higher step relief, with reduced areas of non-depositional substrate. This steepening pattern is consistent with our experimental results (Fig. S3 and Table 1, Runs 7–11) and suggests lateral channel mobility combined with continued aggradation at uppermost fan-delta surfaces during rising water levels.

While previous studies proposed that Martian stepped landforms formed due to rapid changes in water level³, episodic flooding events^{55,56}, or a combination of both processes^{37,38}, our findings provide a simpler explanation. Our experiments demonstrate that stepped fan-deltas can develop under continuous sediment supply and a uniform rate of water-level rise, without invoking episodic flooding events, sudden slope breaks or special erosion processes. Furthermore, the absence of delta-specific slope changes

in some Martian stepped landforms is consistent with the results of our experiments, which show that stepped fan-deltas are formed by the accumulation of thin layers of sand⁵⁶. Although erosion-based terrace formation has also been proposed^{3,53,57}, the absence of corresponding terrace levels along basin walls argue against this hypothesis. In addition, the elevation of the front edge varies even within the same step, which also supports our interpretation that it formed due to lateral channel migration under rising water levels.

Taken together, the widespread occurrence of stepped fan-deltas on Mars (Fig. 4, Table S2, and Fig. S5) can be explained by gradual basin infilling during steady water-level rise and sustained sediment supply. These results remove the need to invoke intermittent sedimentation or rapid hydrological changes as essential conditions for stepped fan-delta formation.

Some Martian stepped fan-deltas are accompanied by channel incision (Fig. 3b, c and Table S2, ID 2–30). In the Coprates Catena, for example, the incised channel appears to originate on the distal margin of the latest step of the same valley system. However, unlike the experiment (Fig. 3a and Table 1, Run 12), it does not extend to the fan apex and instead terminates abruptly on the downstream surface. This suggests that the incised feeder flow was not sustained after the period of water-level rise (when the stepped fan-delta formed) and occurred in a different stage unrelated to the formation of stepped fan body¹. This supports the interpretation that fluvial input was limited to the phase of water-level rise and ceased before the onset of the fall.

Notably, except for a few of the stepped fan-deltas (e.g., Table S2, IDs 2–3, 2–10, 2–12, 2–30), most of the stepped fan-deltas do not have channel incision features. This implies that the water activity responsible for the stepped fan formation was relatively short-lived. Together with the observation that their feeder rivers are markedly shorter than those associated with lobe-extruding deltas (Tables S1 and S2), this indicates that the fluvial activity responsible for stepped fan formation was transient in nature.

Global distribution of Martian deltas

Martian deltas identified in our survey fall into two distinct morphological classes, each with different spatial distributions (Fig. 4a), suggesting that they formed under contrasting hydrological conditions. One class, which we term lobe-extruding deltas, is characterized by prominent depositional lobes extending into basin floors (Fig. S5). These deltas are clustered within the proposed paleo-shoreline elevation range (Table S1). There are two estimated paleo-shorelines, Arabia Level (Contact 1, -2090 ± 1400 m⁵⁸) and Deuteronilus Level (Contact 2, -3790 ± 240 m^{11,13}), which correspond to hypothesized sea-level highstand and lowstand, respectively. Across the Arabia Level map traces compiled by ref. 58, the calculated average elevation ranges from -1560 m to -3560 m. Furthermore, the average elevation of the deltaic fronts is clustered around -2540 ± 177 m, suggesting that a stable ocean existed at this level around 3.5 Ga¹. Five lobe-extruding deltas occur on unconfined plains at elevations ranging from approximately -2080 to -3120 m, and two are situated in closed basins at -1720 and -2330 m. All lie within the proposed paleo-coastline elevation range of the higher Arabia Level (-1560 m)^{11–13,21,59,60} and average deltaic front elevation (-2540 m)¹. Considering the effects of post-deformation on the paleo-shoreline topography^{60,61}, the extent of the observed variations in elevation is consistent.

The feeder channels of the lobe-extruding deltas consistently trend northeastward to eastward, transporting sediment toward the northern lowlands (Fig. 4a). Their spatial clustering along the dichotomy boundary and the basinward geometry of the lobes suggest that these deltas formed at the retreating margin of a once-extensive ocean. The observed morphology reflects delta construction during a period of falling water level, or forced regression, where rivers extended their mouth lobes into the regressive shoreline. The long channel lengths (Table S1) associated with these deltas indicate sustained fluvial activity, likely under Late Noachian to Late Hesperian climatic conditions when surface liquid water was more stable and widespread^{11,62}. Similar to terrestrial analogs of forced-regressive deltas, these Martian examples show elongated lobes and persistent channel

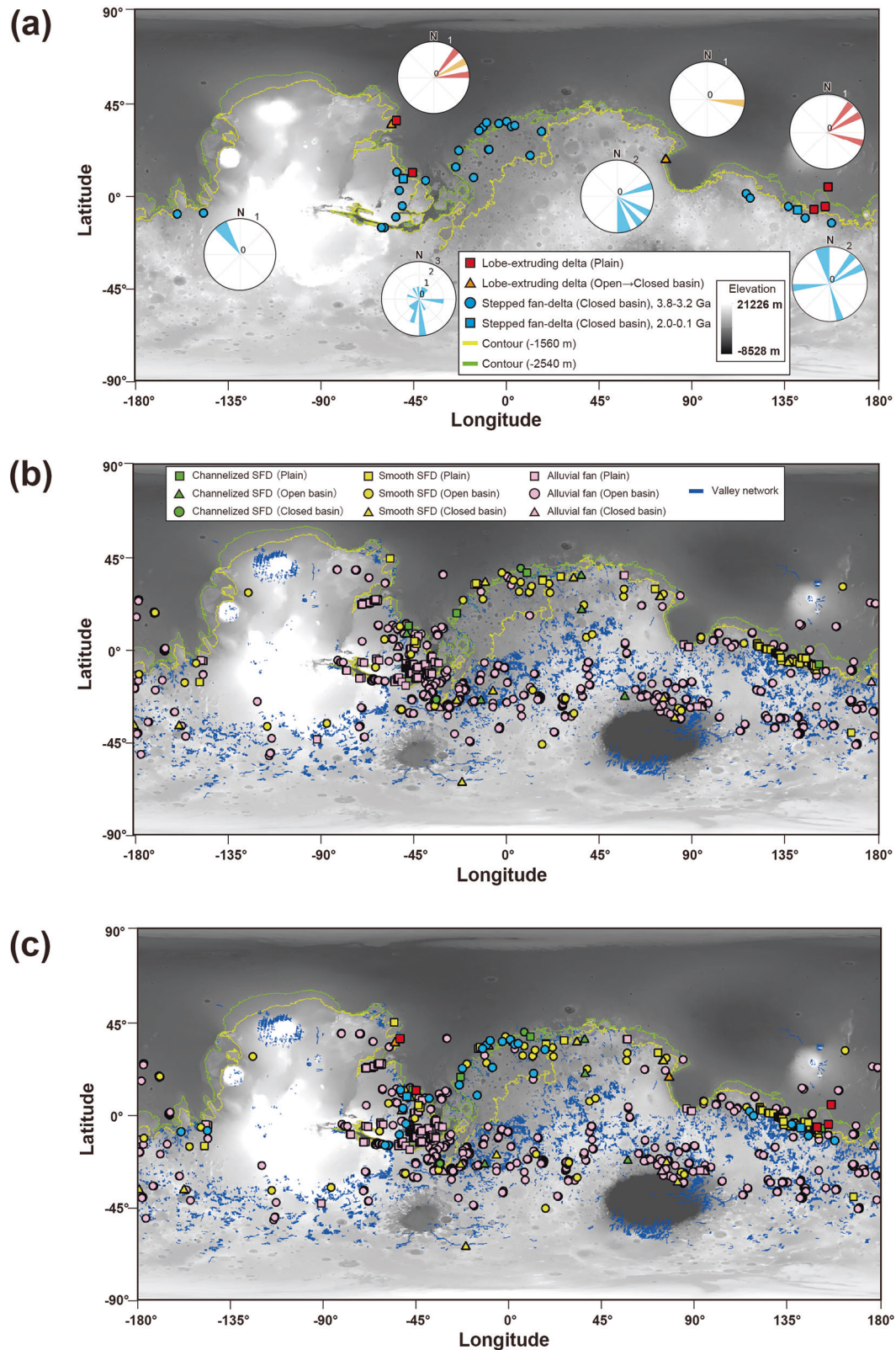


Fig. 4 | Global distribution of the target deltas and comparisons with other landforms. Data from this study, with rose diagrams indicating river inflow directions (a), previous study (b), and combined data of both this study and previous study (c). Channelized SFD, Smooth SFD, and Alluvial fan data are from ref. 2, while Valley networks data are from ref. 69. The yellow and green lines are the elevation

contours of two proposed paleo-coastlines [−1560 m (highest elevation of Arabia level); −2540 m (delta clustered elevation¹)], respectively. The map was prepared by the authors using ArcMap Academic Pack medium version (Esri, Redlands, California, USA).

networks that prograded seaward as water levels declined. The Hypanis Valles delta (Figs. 1d, S5 and Table S1, ID 1–3) exemplifies this morphology and has previously been interpreted as a regressive deposit marking the final stage of a northern ocean⁵¹.

In contrast, stepped fan-deltas were found at 30 locations, predominantly within interior closed basins such as craters and valley systems (Fig. S7 and Table S2). None of them are located on the open northern lowland plains. These stepped fan-deltas span a broad elevation range, from about –4670 to +1950 m, and are typically situated far south and well above the putative ocean coastlines. Their distributary channels are oriented in multiple directions, often directed southward or toward basin interiors, reflecting locally confined watersheds (Fig. 4a).

The morphology and basin settings of these stepped fan-deltas indicate that they formed during episodes of local transgression within isolated basins. As lake levels rose by increased inflow, deltaic lobes backstepped, with frequent lateral channel migration and minor avulsion events. The lengths of feeder channels for the stepped fan-deltas (Table S2) are markedly shorter than those associated with the lobe-extruding type (Table S1), suggesting that water and sediment inputs were relatively short-lived or episodic. These conditions point to stepped fan-delta formation driven by localized hydrological events, such as pulses of glacial meltwater or discharge from groundwater springs. In many cases, flow appears to have ceased before mature fluvial systems could develop. The geographic clustering of stepped fan-deltas in the lower latitudes of the southern highlands (not found in the mid- to high-latitudes of the southern hemisphere) supports the interpretation that mountain snow/ice melt was a key source of transient lacustrine activity in these regions (Fig. 4a).

While post-depositional erosion has likely modified some Martian deltas^{63–68}, the preservation of consistent stepped and lobe-extruding morphologies across multiple sites suggests that erosion has not completely overprinted the primary depositional architecture. If erosion were the dominant control, a greater diversity of morphologies would be expected rather than the systematic patterns observed in this study.

We also compared our findings with the distributions of other landforms, including channelized scarp-fronted fan deposits (SFDs), smooth SFDs, alluvial fans², and valley networks⁶⁹ (Fig. 4b, c). SFDs are landforms characterized by distinct breaks in slope, and are referred to as “delta” in this study. Channelized SFDs are characterized by channels developed on their surfaces and by lobes extruding from fan-shaped platforms. In contrast, smooth SFDs have relatively featureless surfaces, with no visible traces of channels or lobes.

Among the channelized SFDs identified by ref. 2, six were classified as “lobe-extruding deltas” in this study because they exhibit narrow lobes extending from the margins of fan-shaped delta bodies, similar to the morphologies produced in our experiments (Figs. 4a, S5 and Table S1, ID 1–2 to 1–7). The remaining 11 SFDs were retained in the channelized SFD category (Fig. 4b). The results of our tank experiments suggest that channelized SFDs may form under either constant or falling water level conditions. In contrast, smooth SFDs² are morphologically distinct from both the lobe-extruding deltas and channelized SFDs examined in this study because they lack channels and lobes on their surface. This morphology suggests that the possibility of erosional modification cannot be excluded. Furthermore, because smooth SFDs are substantially smaller than lobe-extruding deltas and channelized SFDs, their age estimates are subject to greater uncertainty. We therefore show only their spatial distribution in Fig. 4b and exclude them from the age analysis.

Four channelized SFDs are located in the plains near the dichotomy boundary (Fig. S9 and Table S3), with elevations ranging from –2090 to –2970 m (Fig. 4b), similar to those of a lobe-extruding delta (Fig. 4a). Five channelized SFDs are located in the open basins on the landward side of the dichotomy boundary with elevations ranging from +60 to –1670 m. Two channelized SFDs are located in closed basins; one is located at a higher elevation area at –1310 m, while the other is located in the northern lowlands, at an elevation of –3070 m.

There are 43 smooth SFDs in the plains, and most of them are located along the dichotomy boundary (elevations ranging from –780 to –3860 m), except for two located inland at elevations of +480 and +1020 m. However, some of these smooth SFDs located along the proposed coastline are suggested to have been formed in lakes rather than the ocean⁷⁰.

About 288 alluvial fans are found in the plains, predominantly distributed at low latitudes². Their elevation range is +2420 to –3690 m. Nine alluvial fans are located in open basins, distributed relatively inland within an elevation range of +480 to –3920 m. There are 941 alluvial fans in closed basins, distributed globally from northern lowlands to mid-latitudes in the southern hemisphere. Their elevation range is +3190 m to –5200 m (Fig. 4b).

Valley networks are clustered from low latitudes in the northern hemisphere to mid-latitudes in the southern hemisphere, differing from the distribution patterns of lobe-extruding deltas and stepped fan-deltas.

Chronology of Martian deltas

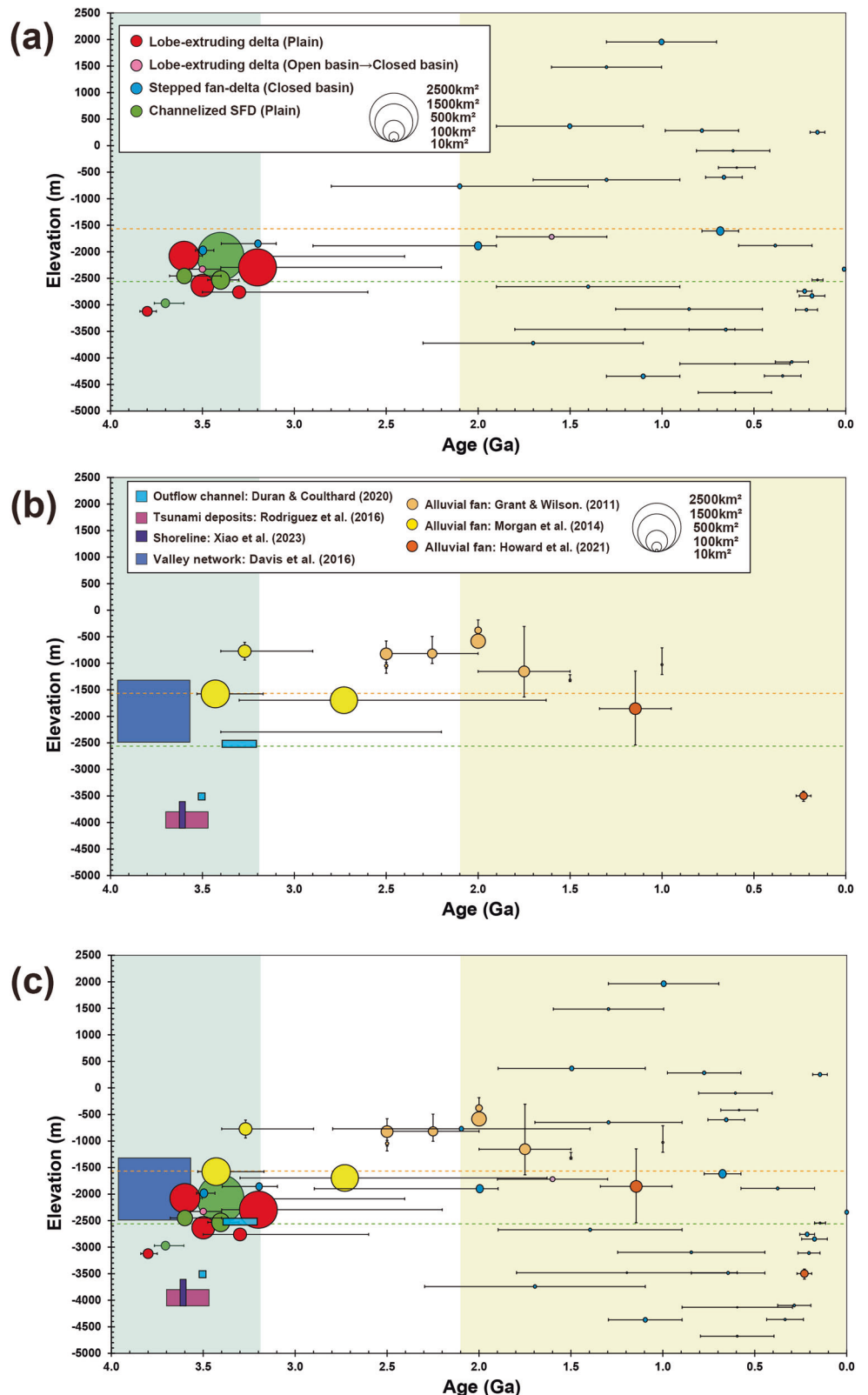
To assess the timing of delta formation relative to these environments, we estimated crater-retention ages for delta surfaces and examined their age–elevation distribution (Figs. 5a, S6, S8, S10 and Tables S1–S3). Crater size–frequency distribution (CSFD)⁷¹ measurements yield model ages indicating that the lobe-extruding deltas and channelized SFDs are among the oldest deltaic deposits, while the stepped fan-deltas tend to be much younger (Fig. 5).

Lobe-extruding deltas and channelized SFDs in the plains along the Martian dichotomy boundary are clustered in the Late Noachian to Late Hesperian period (~3.8–3.2 Ga), indicating the presence of an ocean with a shoreline elevation between –2080 and –3120 m during this interval, followed by progressive sea-level lowering (Figs. 5a, S6, S10, and Tables S1 and S3). Although limited numbers of lobe-extruding deltas must be considered carefully, channelized SFDs also show similar age (~3.8–3.2 Ga) and consistent elevation with a proposed paleo-shoreline range. These ages are also consistent with previous studies suggesting multi-phase sea-level fluctuations^{16,28,51} (Fig. 5b, c). However, the shoreline elevation inferred by tsunami deposits¹⁶ and outcrop surveys of the shoreline landform by the *Zhurong* rover²⁸ suggest a substantial regression to –3600 m to –4100 m, which is significantly lower than the regression indicated by the lobe-extruding delta. This inconsistency can be explained by invoking multi-phase sea-level fluctuations, with the major regression event at ~3.6 Ga (Fig. 5b). Independent support for sea-level rise and fall during ~3.5–3.2 Ga is provoked by knickpoint elevations within outflow channels⁵. Interestingly, a major environmental transition also occurred at ~3.5 Ga, from one dominated by valley networks to one dominated by outflow channels^{8,72}. The occurrence of multiple lobe-extruding deltas and channelized SFDs spanning a relatively large elevation range of ~1000 m and distributed over a broad age interval further implies that Mars’ Ocean experienced repeated episodes of significant sea-level falls.

Among the lobe-extruding deltas and channelized SFDs in the plains, only one exception is located in a closed basin at a relatively high elevation (–1720 m) and exhibits a significantly younger age (~1.6 Ga) than others (Table S1, ID 1–7). Given its significantly smaller size and positioned in the higher elevation compared with the other lobe-extruding deltas and channelized SFDs in the plains, it likely formed in a separate, localized lake system rather than being linked to the northern ocean. One possibility is that this relatively high-elevation, small-scale lobe-extruding delta may have formed by temporary fluvial activity during the Middle Amazonian. Alternatively, there may be issues with the accuracy of the crater age due to the delta’s small size. Excluding this, the rest of the lobe-extruding deltas and channelized SFDs are in both age (~3.8–3.2 Ga) and elevation near the putative coastlines, strongly supporting their formation during the early ocean phase on Mars (Fig. 6).

It should be noted that the preserved lobe-extruding deltas likely represent only a subset of the original delta population associated with the northern lowlands. Although long-term erosion rates on Mars are generally

Fig. 5 | Plot showing ages versus elevations of Martian deltas and comparisons with other landforms. Data from this study (a), previous study (b), and the combined data of both this study and the previous study (c). Circle size is proportional to delta, SFD and alluvial fan surface area, providing a cue for depositional scale. Each point represents the mean age and average elevation of deltas within a morphologic class. Error bars reflect the range of age errors and elevations within each group, spanning the highest and lowest values. The yellow and green dotted lines are the elevation of proposed paleo-shorelines (−1560 m, −2540 m), respectively.



low, these deposits have been exposed to surface modification processes for more than three billion years. Consequently, erosion, and resurfacing may have removed or altered some ancient deltaic deposits and introduced additional uncertainty into crater-retention age estimates. Nevertheless, the fact that numerous deltas, not only those with lobe-extruding deltas but also channelized SFDs, are clustered near the proposed paleo-shoreline

elevations (Fig. 4a, b) and that the ages of these large-sized deltas are concentrated in the Late Noachian–Hesperian periods (Fig. 5a), support their formation during a period when a large standing body of water occupied the northern lowlands.

In contrast to the lobe-extruding deltas and channelized SFDs, the stepped fan-deltas span a broad range of ages, mostly in the Amazonian

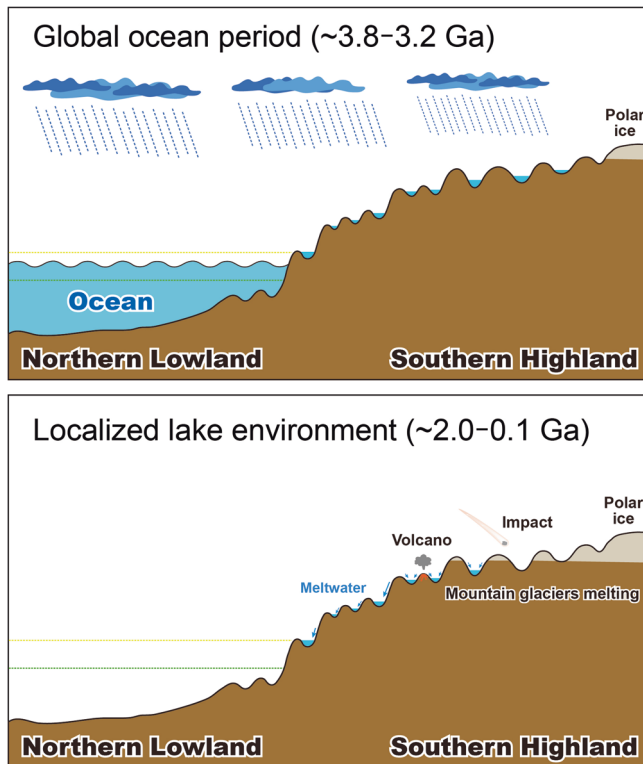


Fig. 6 | A conceptual schematic of the transition from the early ocean period (upper) to a localized lacustrine environment (lower). The yellow and green lines are the elevation of proposed paleo-shorelines (–1560 m, –2540 m), respectively.

(Figs. 5a, S8 and Table S2). Crater counts derived age indicates that stepped fan-deltas in closed basins formed between ~3.5 and ~0.1 Ga, with a prominent clustering in the mid- to late Amazonian (~2.1–0.1 Ga). This concentration suggests a spike in localized hydrologic activity relatively late in Mars' history, long after the disappearance of large standing oceans (Fig. 6). Their occurrence primarily in closed basins, together with morphological evidence, indicates that these landforms likely formed in response to widespread but localized lacustrine environments with episodic lake-level rise possibly triggered by localized events such as volcanism or impact-induced, glacial melting or groundwater release^{6,22,73}. The spread of ages, however, also implies multiple episodes of crater lake formation over time rather than a single synchronous event. There are two stepped fan-deltas (Table S2, ID 2–17 and ID 2–20) showing 3.5–3.2 Ga at similar elevations to lobe-extruding deltas and channelized SFDs (Fig. 5a).

We note that no stepped fan-deltas are observed between 3.2–2.1 Ga, despite the continued presence of alluvial fans^{2,30,31,33} (Fig. 5). Alluvial fans form through subaerial deposition, whereas stepped fan-deltas require sustained rises in lake-levels. Their absence therefore implies that, although runoff was sufficient to construct alluvial fans during this interval, water volumes were inadequate to produce persistent crater lakes. Alternatively, warm episodes associated with volcanically driven meltwater may have been short-lived, with rapid reversion to cold and dry conditions that precluded long-term water storage and the development of stepped fan-deltas. Together, these observations indicate that fluvial activity capable of building deltas declined sharply after ~3.2 Ga and did not resume until ~2.1 Ga. Mars therefore experienced a prolonged hydrological hiatus between the late Hesperian and early Amazonian, during which lake deltas were largely absent. This interpretation is consistent with a transition to a colder and drier climate after the late Hesperian, coincident with the cessation of outflow channel formation^{4,7,72,74}, and the sequestration of remaining water as ice. The markedly smaller areal extent of stepped fan-delta deposits compared to the larger Noachian–Hesperian lobe-extruding deltas and

channelized SFDs (Fig. 5) also reflects this dramatic decline in surface water availability.

Discussion

The spatial and temporal patterns of delta formation on Mars reveal a profound transition in the planet's hydrologic regime, from an early ocean system to a later stage dominated by localized lacustrine environments (Fig. 6). The model of Mars' climatic and hydrogeological evolution presented in this study is essentially consistent with existing conceptual models^{62,72,75}. The originality of this study lies in precisely constraining the timing of the disappearance of Mars's ocean and its hydrological transition based on process-based interpretation through delta formation experiments, and detailed crater-counting chronological analyses.

During the late Noachian to late Hesperian (~3.8–3.2 Ga), Mars likely harbored a substantial northern ocean. This interpretation is supported by the exclusive concentration of lobe-extruding deltas and channelized SFDs in the plains along the mean elevation contours of paleo-coastlines (between –1560 and –2540 m), and the consistent northeastward-directed paleo-flow of their feeder rivers (Fig. 4), indicating sediment delivery into a large, low-lying oceanic basin. The presence of laterally extensive, elongated lobes and long distributary channels (Fig. S5 and Table S1) is consistent with sustained fluvial activity and shoreline progradation during an ocean highstand under warm hydrosphere conditions, followed by regression.

By the late Hesperian (~3.2 Ga), the formation of large-scale lobe-extruding deltas and channelized SFDs ceased, marking the end of Mars' ocean phase. The lack of deltaic activity points to a prolonged hydrological hiatus (~3.2–2.1 Ga) during which Mars transitioned into a much drier and colder climate. This interpretation is consistent with the decline of volcanism and fluvial erosion, global cooling, and the inferred collapse of Mars' early atmosphere, which would have limited the persistence of surface water^{76–78}.

The mid to late Amazonian period (~2.1–0.1 Ga), however, shows a renewed but spatially restricted hydrologic activity, evidenced by the formation of stepped fan-deltas in closed basins across diverse elevations (Figs. 5, 6). These stepped fan-deltas formed under local transgressive conditions, as rising lake levels produced backstepping steps in crater interiors. The morphologies and settings of these deltas indicate that they were not associated with a global hydrologic network but rather resulted from episodic water releases, possibly glacial melt induced by localized volcanism and impact heating, or groundwater upwelling⁷³. Several lines of evidence support this interpretation^{6,22,29,70}. Many stepped fan-deltas occur in regions close to the Amazonian volcanism, and their formation ages coincide with known episodes of fluvial channel activity attributed to glacial or subglacial melting⁷⁹. Notably, their occurrence at elevations far above any proposed paleo-coastline (Fig. 5) suggests they formed from locally sourced water induced by mountain glacier melting. The scarcity of incised channels on stepped fan-deltas (Fig. 3) also implies that water input was rapidly curtailed after lake levels peaked. This autogenic retreat behavior suggests that stepped fan formation was limited to the rising stage of lake level and did not extend into prolonged stable or falling lake level phases.

In summary, by combining controlled tank experiments with orbital geomorphic analysis, we show that delta architecture can be used to reconstruct the evolution of surface hydrology across the planet. The two delta morphologies identified in this study, lobe-extruding and stepped types, serve as geomorphic markers of these transitions and provide critical constraints on the timing, scale, and climatic drivers of Martian water history. Our results point to a two-stage hydrologic evolution on Mars: an early ocean-dominated period with globally integrated drainage networks from ~3.8–3.2 Ga, followed by a later phase ~2.1–0.1 Ga, when surface water flow became episodic and confined to isolated basins. Nevertheless, the absence of identified stepped fan-deltas between ~3.2 and ~2.1 Ga does not necessarily imply an absence of aqueous activity. Instead, it may reflect a combination of preservation bias and environmental conditions that were

generally unfavorable for the development or preservation of long-lived closed-basin lakes capable of producing stepped fan-deltas.

From a planetary evolution perspective, the presence of these Amazonian stepped fan-deltas provides additional implications for the persistence of hydrologically active microenvironments on arid Mars. These transient lakes may have represented the last refugia for habitability, offering episodic access to liquid water and nutrient transport even during the Amazonian. However, the scarcity of incised channels in stepped fan-deltas suggests short-lived lake environments with rapid reduction of water input. Such short-term phenomena preclude the persistency of habitable environment required for life, sufficient to support chemical equilibration via water–rock interaction, as well as nutrient cycling for biological activity that possibly existed prior to 3.2 Ga. Nevertheless, our findings highlight the development of short-lived surface aqueous environments even during the middle–late Amazonian, and future landing explorations are expected to verify whether biosignatures linked to sustained surface habitability have been preserved in those regions.

Methods

Tank experiments

We performed a series of controlled tank experiments using the MARGI 5 tank facility at Nagasaki University to investigate how different water-level changes influence delta morphology (Fig. S1). The setup and procedures follow the methods of previous studies^{35,36,39,40}. A non-erodible base consisting of a sloping hinterland part ($\Phi = 28^\circ$) and a horizontal basin floor part was placed as a basement in the tank (length 2.8 m, width 1.4 m, depth 65 cm). In all experiments, a mixture of sediment (0.1 mm quartz sand) and water was used, fed through a hose in the sloping hinterland to simulate an input stream. The proximal end of this system overlies a gently sloping basement plane. The water level in the tank was controlled by pumping water in and out using a PC-controlled electromagnetic flow meter. Before each run, sand and water were supplied from the upstream section by hose for approximately 30 min with the water level maintained at a constant baseline height to create the preliminary alluvial-deltaic system. Blue dye has been added to the water to make changes in the water level easier to see. As a result, the quartz sand also becomes a bluish tint.

We conducted two types of experiments (Table 1; Supplementary Video). The first experiment was conducted to lower the water level (Fig. S2), while the second experiment was conducted to raise the water level (Fig. S3). The supply rate of water and sand (Q_w , Q_s) was adjusted by feeders. In both experiments, the preliminary alluvial-deltaic system was created at a constant water level (water depth 2.0 cm), and then the water level was lowered/raised while sand and water were constantly supplied through the hose. During each experiment, overhead photographs were taken at regular time intervals (15 s). Three vertical laser planes (spaced at 25.0 cm intervals) and 23 horizontal laser planes (spaced ~ 7.5 mm apart, with a reference plane set 2 cm above the bottom of the experimental tank) were continuously projected onto the experimental area. The landform formed by the experiment was captured from multiple angles and constructed in the 3D model using the software Metashape. The height and area of each step of stepped fan-deltas were measured from the created 3D model and overhead photographs (Figs. S3 and S4). The area was calculated by considering the steps as fan-shaped.

A total of six water-level fall experiments were conducted (Runs 1–6). In Runs 1–3, the water level was lowered at a constant rate (Table 1, R_{wlr} : 0.00373, 0.00767, and 0.0141 cm/s). As the rate of water-level fall increased from Run 1 to Run 3, the channels and lobes less frequently migrated laterally, did more rarely avulse, and instead simply extended basinward. As a result, narrower lobes were formed among the three runs (Fig. S2, Runs 1–3). In Run 4, the rate of water level fall was the same as that in Run 3, and the rates of water and sand supply were half of those in Runs 1–3 (Table 1). As a result, two narrow branched channels were initially formed, then the two channels merged and became a single channel. Finally, an elongated, narrow lobe was formed (Fig. 1c). In Run 5, the rate of water level fall increased during the middle of the experiment (Table 1). During the

beginning of the experiment, R_{wlr} was slow (0.00226 cm/s), and the channel frequently migrated laterally, forming a wide fan-shaped delta. Then, after increasing the R_{wlr} (0.01333 cm/s), the lateral channel migration decreased, and the elongated lobes extended downstream (Fig. 1a). After the formation of the lobe-extruding delta of Run 5, we continued sediment and water supply while maintaining a stationary water level in Run 6 (Table 1, $R_{wlr} = 0$ cm/s). As a result, channel migration resumed along the shoreline, and the width of the lobe increased again (Fig. S2, Run 6).

A total of five water-level rise experiments were conducted (Runs 7–11). In Runs 7–9, the rate of water level rise was varied (Table 1, $R_{wlr} = 0.000628, 0.0126, 0.000322$ cm/s), while in Runs 7, 10, 11, the rate of sand and water supply were varied (Table 1, $Q_s = 0.743, 1.50, 0.361$ cm³/s). The ratio of water to sand (Q_w/Q_s) is nearly the same in all experiments. In all of the water level rise experiments, many distributary channels developed and repeated lateral migration while deposition (Supplementary Video Run 7). The sedimentation area retreated landward due to rising water levels. The channel became shorter, and the area of the channel within the sedimentation area increased. As a result, deltas with several layers of stepped surface overlapping upward were formed, which we termed stepped fan-deltas (Figs. 2a, S3). The formation mechanism of the stepped fan-delta involves the inability of the feeder alluvial system to extend to the distal end of the previous/underlying one, but was subject to transgression by back-stepping. The supplied sediment inevitably failed to reach the previous shoreline position that was drowned.

Finally, in Run 12, the water level was lowered again at a constant rate (Table 1, $R_{wlr} = 0.00712$ cm/s) after the end of Run 11. The rate of sand and water supply was the same as in Run 11 ($Q_w = 4.68$ cm³/s; $Q_s = 0.361$ cm³/s). As the water level dropped, the channel eroded the stepped fan formed in Run 11, creating an incised valley (Fig. 3a).

When the water level rises and forms a stepped fan-delta, the following equation holds^{39,40}

$$\Lambda_{3D}^2 = \frac{Q_s}{|R_{wlr}|} \quad (1)$$

where Λ_{3D}^2 is the characteristic area scale, Q_s is the rate of sand supply, and R_{wlr} is the rate of water level rise. During stepped fan-delta development, step area decreases upstream toward Λ_{3D}^2 (Table 1). Using the actual area would make the results dependent on the supply rate and the rate of water level rise. Therefore, we used this equation to eliminate scale dependence and make the area dimensionless for comparison (Fig. S4).

Exploration of the Martian deltas

We identified deltas similar to those formed in our experiments using the Martian global delta catalog². Then, we plotted their distribution using ArcMap and observed their shape (Fig. 4 and Tables S1, S2). We used High Resolution Imaging Science Experiment (HiRISE⁸⁰; ~ 25 m/pixel), Context Camera (CTX⁸¹; ~ 6 m/pixel), Thermal Emission Imaging System (THEMIS⁸²; ~ 100 m/pixel), and High Resolution Stereo Camera–Mars Orbiter Laser Altimeter (HRSC–MOLA^{83,84}; ~ 200 m/pixel) datasets. We assumed that those deltas (developed in the plains, open basins, or in closed basins) maintain the morphological characteristics close to the original forms without significant modification. We also examined the distribution of other landforms (e.g., channelized SFDs, smooth SFDs, alluvial fans and valley networks)^{2,69}. Among the channelized SFDs identified by ref. 2, four channelized SFDs located in the plain are classified as lobe-extruding deltas in the plain (ID 1–2, 1–3, 1–5, 1–6, 1–7), and two channelized SFDs located in the open basin are classified as lobe-extruding deltas in the open-to-closed basin (ID 1–1, 1–4). One of the channelized SFDs identified in ref. 2 did not exhibit delta-specific slope changes, so we classified it as an alluvial fan (Figs. 5a, S9 and Table S3).

Estimating crater age

We used the crater size-frequency distribution (CSFD) measurements to estimate the ages of lobe-extruding deltas (Fig. S6), stepped fan-deltas (Fig.

S8), and channelized SFDs located in the plains⁷¹ (Fig. S10). We identified craters with a diameter exceeding 20 m (avoiding secondaries) on delta surfaces using CTX images and counted them by Map projection independent Crater Tools⁸⁵ on ArcGIS. Counted craters were analyzed by Craterstats II software¹⁴, using the crater production function (PF)⁸⁶ and chronology function (CF)¹⁴ to derive the surface age. Only deltas with sufficient crater density were included in the analysis.

Data availability

All primary datasets used in this study are publicly available through the NASA Planetary Data System (PDS; <https://pds.nasa.gov>), including HiRISE⁸⁰, CTX⁸¹, THEMIS⁸², and HRSC–MOLA^{83,84} products. For Figs. 1–3, S5, S7, and S9, CTX⁸¹ images were used. All original datasets in this paper (Supplementary Videos and Crater Counting Files) are available at https://figshare.com/articles/dataset/Original_data_for_Kito_et_al_/30110344. Supplementary figures (Figs. S1–S10) and tables (Tables S1–S3) are included in the Supplementary Material.

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Author contributions

H.H. designed this research. T.M. and R.K. conducted a tank experiment. R.K. and T.R. conducted crater counting. H.H. and R.K. made a visualization. H.H., R.K., and T.R. wrote the manuscript, with discussion of T.M., G.G.O., and G.K.

Competing interests

The authors declare no competing interests.

Additional information

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