Experiments on sedimentation in wide reservoirs and erosion following dam removal

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ABSTRACT: Sedimentary deposits in reservoir lakes record the sediment transport capacity of the upstream river and past water levels of the downstream basin. Volumes and morphologies of deltas can be used to calculate flow and sediment dynamics. We constructed circular basins to which we fed constant flow discharge over a feeder channel of gravelly sand with different ratios of added silica flour. During water level rise, the fan radius decreased over time. During water level fall, after dam removal, the deltas were partially destroyed. Surprisingly, for low discharges the channel markedly destroyed the deposit through transverse movements of the initial channel whereas for higher discharges the terraces were preserved for a longer time. Our results indicate that dam removal at wide lakes may lead to an unexpected inverse relation between discharge and erosion of the deposit, which has consequences for the subsequent sediment pulse magnitude. Point-modelling of sediment transport capacity yielded volumes in good agreement with observed volumes, proving that the time scale of activity can be inferred from feeder channel dimensions and delta volume. Our results suggest that these parameters can yield consistent reconstruction of formative time scale also on Mars, which has consequences for interpretation of ancient climate.

Keywords: dam failures, sediment transport, deltas

1 INTRODUCTION

Sediment is deposited where rivers enter plains or lakes. For plains and lakes much wider than the river, these deposits are fan-shaped because discharge spreads out as un-channelized sheet flow or channels avulse over the plain (Bull 1968; Blair and McPherson 1994; Leeder 1999; Parker 1999). We study delta formation and destruction and apply it to two completely different contexts: in crater lake sedimentation on Mars and in delta sedimentation and erosion in reservoirs following dam removal on Earth.

Deltas are found all over the Earth in various different environments, including in wide hydropower reservoirs. Deltas are also found all over Mars, usually in impact craters, indicating that these must have been lakes. Some crater rims were breached, causing water to flow out of the lake. If water level remained constant then a delta built out analogous to reservoir sedimentation. If the water level fell then the delta eroded analogous to those found in wide reservoirs on Earth upon dam removal.

Our objectives are twofold. Firstly, to understand the morphodynamics and formative time scale of deposits in a lake while the lake fills with water, so that we can predict past hydrology in cases on Mars where this is unknown. Secondly, to understand the morphodynamics and erosive time scale of these deposits while the basin empties following dam removal or basin rim breaching, so that we can predict the fate of the deposit following dam removal on Earth and again so that we can interpret past hydrology from the morphology of Martian deltas.

As the sediment accumulates in the reservoir, the reservoir loses its potential to store water (McCully 1996; Cantelli et al. 2004). Trap efficiency of reservoirs depends on the ratio between storage capacity and inflow, the reservoir age and shape, the types and number of outlets, and the properties of the sediment (Brune 1953). When large amounts of catastrophic discharge are released, the sediment trap efficiency may go down with 30% as more sediment, especially fines, is washed out of the reservoir (Brune 1953). If the reservoir traps less sediment, a smaller delta deposit may therefore be formed. Using measured delta volume, sediment transport predictors and the properties of the upstream feeder channel, we can obtain a first-order estimate of the length of time required to form such a sedimentary body (Kleinhans 2005a) and hence we can speculate about the type of climate that might have been present at the time of formation. This is relevant for Mars where we can measure the delta volume but would like to infer the amount of discharge and the implications for past climate.

On Earth, in cases of dam removal, both formative discharge and volume of the deposit is known, but sediment delivery is not well understood, especially not in the cases of wide reservoirs (Cantelli et al. 2004). The deposit provides a large source of sediment to the downstream river upon basin rim breach or dam removal. Hence, not only is it important to understand how much sediment is trapped in the reservoir, but also what the nature of this sedimentary deposit is. Fine sediments such as silt and clay can be a problem for ecosystems as it may cover vegetation, kill fish species or raise water levels (Doyle et al. 2002). It might also affect local downstream structures such as bridge foundations or irrigation channels. Not many experiments with fines (silt and clay particles less than 0.075 mm in diameter) in the sediment feed have been done (Cantelli et al. 2004), hence our experiments also shed light on the grain size distributions and profiles for rivers that may contain significant percentages of fine material. The longitudinal profile of a reservoir delta is characterised by a coarse-grained topset and fine-grained bottomset (Leeder 1999; Cantelli et al. 2004). The coarser, heavier sediments, such as gravel and sand, tend to settle out at the upper end of the reservoir, forming a "backwater" delta which gradually advances toward the dam. The lighter sediments, the silt and clay, tend to be deposited nearer to the dam (McCully 1996). This longitudinal grain size profile is typical in the formation of deltas on Earth and could be also for those formed on Mars, if the grain size distribution is bimodal at least. In systems with many narrow feeder channels (line feeders as defined by Postma 1990), this simple upward fining sequence is often displayed, but in systems with a single wide feeder channel (point feeders as defined by Postma 1990), the fining upwards cycle repeats and also intersects laterally as the channel on the surface of the fan migrates and avulses (Kleinhans 2005b). Either way, since the coarse grains are located within the delta topset and foreset, and it is particularly the topset and foreset that is eroded by the down-cutting channel, we hypothesise that the majority of the sediment that is delivered to the downstream system will be coarse-grained.

Thus, for prediction of reservoir lifetime it is important to understand how the deltaic sedimentary deposits are formed yet for environmental impact it is important to understand how the deposits are modified upon dam removal. The formation of delta deposits and their subsequent modification are not mirror image processes - deposition of the delta fills the entire accommodation space whereas erosion of the delta takes place through a river channel that cuts deeply into the delta and leaves terraces that require time to be removed (Cantelli et al. 2004). To know this timescale of erosion, as well as the subsequent location of the eroded sediment, is of importance for estimating sediment overfeeding to the downstream channel. Though narrow delta deposits (e.g. cases where the feeder channel is almost as wide as the deposit – also described as line feeder systems (Postma 1990)) have been studied experimentally, little is known about sediment terrace erosion in the case of wide delta deposits (e.g. cases where the feeder channel is much narrower than the resulting deposit – also described as point feeder systems (Postma 1990)).

By investigating the geomorphology of fan-shaped landforms (both on Earth and on Mars) one can deduce important features indicative of upstream (e.g. discharge, duration and sediment properties) and downstream (e.g. basin hypsometry) conditions at the time of formation. Furthermore, from studies of this nature, scientists can predict how rivers may react to various conditions in real life.

2 METHODS

The experiments were performed in the Eurotank facility at Utrecht University. The Eurotank is a 6.3x11.4x1.2 m flume that can be filled with any type of sediment. Water flow to the tank is regulated with a series of calibrated valves and pumps and sediment supply (when used) is controlled with a worm screw sediment feeder. Sediment was only added to the system in two experiments; usually the channel was left to erode itself. This was done because we do not know what the sediment availability on Mars was like. It is possible that there was not a large supply of sediment available in the upstream channel and that the channel had to excavate its own supply. We constructed a circular basin with a fixed diameter of two meters, (similar in shape to that of a complex impact crater) that has a feeder channel leading into the basin and that could be breached at any point to let the water out of the basin (Figure 1).

Into these basins we fed constant flow discharge over a feed channel of gravelly sand with different ratios of bed load versus suspended load forced by addition of silica flour.

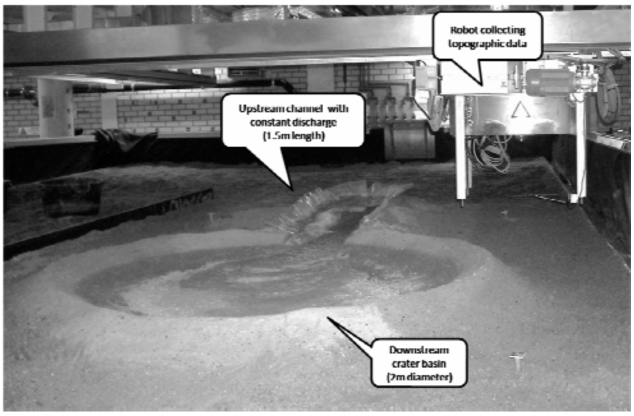

Figure 1. Experimental set-up in the Eurotank Flume.

Each experimental run was performed in two stages (Figure 2). During the first stage, the basin was allowed to fill with water from an upstream feeder channel (basin water level rise). During the second stage, the basin was breached so that some water was lost to the surrounding areas (basin water level fall, or constant in exceptional cases).

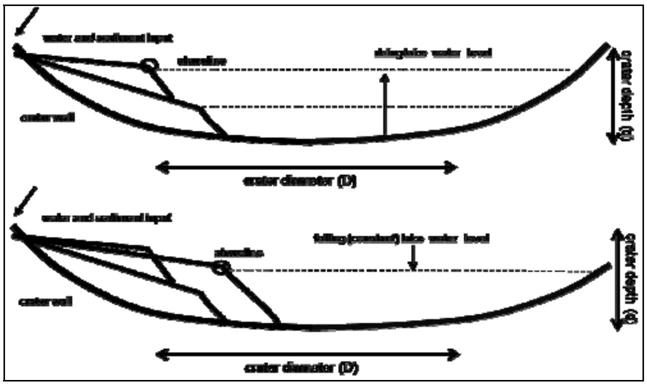

Figure 2. Schematic drawing of the two stages in each experimental run. Basin is constructed in the shape of a complex impact crater with diameter D (2 m) and depth d.

Between the two stages, the experiment was paused, the water drained and the deposit measured and photographed. In order to continue with the second stage as if no interruption took place, the crater lake was again filled with water (with use of an external hose pipe) after which flow in the original channel was recommenced.

Important parameters such as water discharge and sediment grain size were varied systematically (Table 1). These variations were responsible for further small morphological differences in the deltaic deposits. However, during the experiments discharge was kept constant. Furthermore, we also varied the degree of sorting through removing the course tail as well as the volume percentage of fine material (silica flour) in the upstream feeder channel and in the downstream basin rim in order to experiment with bank strength.

Table 1. Experimental conditions and variables.

Run	Discharge (Q) (m^3/s)	Grain Size (D_{50}) (mm)	Silica (%)
A	0.07	0.475	0
B	0.21	0.475	0
C	0.35	0.475	0
D	0.35	0.450	0
E	0.07	0.450	0
F	0.35	0.225	0
G	0.07	0.225	0
H	0.07	0.400	0
I	0.35	0.400	0
J	1.08	0.450	0
K	0.35	0.450	20
L	0.07	0.450	20
M	0.35	0.450	40
N	0.35	0.450	40

Most of the experiments were done with no addition of fines (0% silica), but only river sand or beach sand. The unsieved river sand can be classified as very coarse or even gravelly due to the presence of grains with larger than 4.75 mm diameters, even though the average grain diameter is only 0.475 mm. The sieved river sand (both with D_{50} = 0.450 mm and D_{50} = 0.400 mm) can by classified as coarse sand and medium sand respectively due to the presence of grains with larger than 2 mm diameters in the first and their absence in the second. The beach sand with an average grain diameter of 0.225 mm can be classified as fine sand. Some experiments were thus done with poorly sorted, bimodal river sand (D_{50} = 0.475 mm); some with slightly better sorted, yet still bimodal river sand (D_{50} = 0.450 mm); some with much better sorted, almost unimodal river sand (D_{50} = 0.400 mm); and some with well sorted, unimodal beach sand (D_{50} = 0.225 mm). The sorting in the river sand was improved by dry-sieving with different sieves. Further experiments were done with a 20% or 40% volumetric concentration of silica flour mixed into the bimodal river sand(original D_{50} = 0.450 mm, new D_{50} is not measured, but should be considerably less). We did not experiment with volumetric ratios of silica flour higher than 40% because Kleinhans et al. (this volume) found that above 40% silica flour the sediment either hardened completely or entirely fluidized, as expected from the decrease in porosity due to infilling of silica flour into the pore spaces of the sand.

Morphology before, during and after each experiment was measured by photogrammetry on an automated positioning system, designed to make high-resolution scans (0.5 mm). DEMs were created from stereo pairs using the dedicated software SANDPHOX and analysed in Matlab.

We created fourteen deltaic deposits in the flume laboratory, all of which were formed as the basin filled with water (Table 1). Once full, the basin was breached by manually removing the crater wall (similar to dam removal) and in all cases the sedimentary deposit was at least somewhat destroyed by the incising stream. Incision into the deltaic deposit was more intense with higher discharges, leaving large terraces in the basin.

Sediment transport rates and volumes were calculated for all experiments with the use of sediment transport predictors (overview in Kleinhans 2005a). We assumed that Froude number is close to unity ($Fr \approx 0.9$) based on occasional observations of localised non-moving antidunes and we calculate the depth of the stream from the measured discharge and width. We also measured the channel slopes. By using a poorly sorted mixture, including coarse sand and fine gravel, the flow remained hydraulically rough or at least transitional, so that scour holes and tendency to form ripples were prevented (Kleinhans et al., this volume). Flow was transitional to turbulent in all experiments. To calculate velocity, the Chézy law was used:

$$u = C\sqrt{RS} \tag{1}$$

where u = flow velocity (m/s), C = Chézy roughness coefficient ($m^{0.5}/s$), R = hydraulic radius (m), calculated as Wh/(2h+W) where h = water depth and W = channel width, and S = channel gradient. Colebrook-White was used to calculate hydraulic roughness:

$$C = 18\log\left(\frac{12R}{k_s}\right) \tag{2}$$

where k_s = Nikuradse roughness length (m). The k_s can be calibrated (ranging from $k_s = D_{90}$ to $k_s = 7D_{90}$). We used Meyer-Peter and Müller (1948) for bed load transport predictions:

$$\varphi_b = \alpha(\theta' - \theta_c)^\beta \tag{3}$$

where φ = non-dimensional transport rate, α = 8, θ' = Shields number assuming skin friction following Van Rijn (1984) and β = 1.5. The values for α and β are non-dimensional calibration coefficients and were derived from flume experiments with well-sorted gravel, however, these values can be modified to optimise the transport prediction.

We assumed a perfect trapping of sediment in the basin and we used the Exner equation for the sediment mass balance. The volumes of all deposits were measured from DEMs (if possible) and compared to the values predicted by bed load sediment transport predictors.

3 RESULTS

3.1 *Phases of Development*

Two stages of system development were created. First, the crater was allowed to fill with a constant discharge delivered through the upstream channel. This resulted in a rising water level. At the same time, sediment deposited as a delta, where the rising water level caused back-stepping of the delta deposit (Fig. 3 top). We found that all basin deposits exhibit a decreasing fan radius over time during water level rise as transport capacity of the feeder channel decreased with decreasing gradient.

Second, the experiment was continued after measurements and refilling by creating a breach in the crater wall and allowing the water to escape from the basin whilst maintaining upstream flow discharge. In most cases, the crater rim eroded in a short time period and the water level dropped rapidly. This resulted in a lowering water level which caused incision on the delta deposit. Deep incisions occurred on the fan surface and terraces were formed as the channel cut down rapidly into the deposit (Fig. 3 bottom).

Our results showed firstly that different types of deltas emerge as the result of the rising or falling of the base water level, which agrees well with the fact that it has been often stated that water level in the receiving basin is an important parameter in the study of fan architecture (e.g. Leeder 1999). The mere differences between rising, constant and falling water levels are responsible for large morphological differences and can be used to classify different types of deltas. Stepped deltas (with multiple steep foresets) and Gilbert-type deltas (with single steep foresets) are thus created when the water level is rising (transgression) or falling (regression), respectively.

Formation of incisions and terraces on the fan surface can only be avoided if the water level is kept constant for some time, i.e. the water leaves the basin at the same rate that it enters, whilst maintaining some ponding water in the basin. This was never the case in our experiments because the crater rim was easily erodible and continued to erode much faster than expected, even when cohesive materials such as silica flour were added to the gravelly river sand. Had the rim not been eroded, a Gilbert delta would have formed under constant water level. We demonstrated this in a different setup, not further reported here, wherein the water level was kept constant for a certain period, resulting in a Gilbert-type delta.

3.2 *Effect of discharge*

During the ponding event (water level rise), high discharges showed much less channelization on the delta surface than low discharges. This was possibly due to the tendency for a wide sheet flow to dominate in these cases, and resulted in a more evenly distributed stepped-sheets delta with smooth edges. Low discharge experiments clearly showed channelization on the delta surface and resulted in a more erratic, lobate stacking due to nodal avulsion (Figure 3). The profiles of these deposits also clearly show their stepped nature.

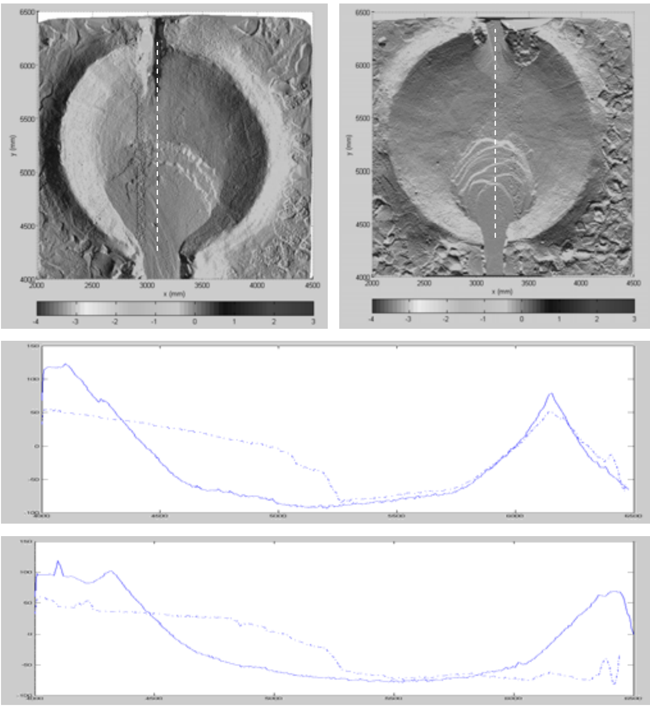

Figure 3. Top: Shaded DEMs of the circular crater-shaped lakes (diameter 2 m) with deltas. Flow is from the bottom (breach was manually created after the flow event). Left panel: low discharge (0.07 m^3/s); right panel: high discharge (0.35 m3/s). Bottom: Profiles of the respective deltas (location of profile shown by white dashed lines in DEM). Flow is from left to right. Upper profile is of the delta in the left panel above, lower profile is of the delta in the right panel above.

During the breaching event (downstream water level fall), it seemed that the higher discharges created deeper incisions into the deltaic deposit. This could be due to higher transport capacity, allowing more change in a short period, and due to the higher momentum which did not allow much transverse movement. Incision occurs regardless of discharge amount; however we do observe morphological differences in the incisions based on the amount of discharge. Figure 4 shows the formation of a prograding delta under low discharge conditions, and Figure 5 shows the formation of a prograding delta under high discharge conditions. Both deltas were formed with relatively well-sorted, course-grained sediment with D_{50} of 0.4 mm. In both cases the original stepped delta is eroded, but in the high discharge case, much of the original deposit is preserved in the form of terraces.

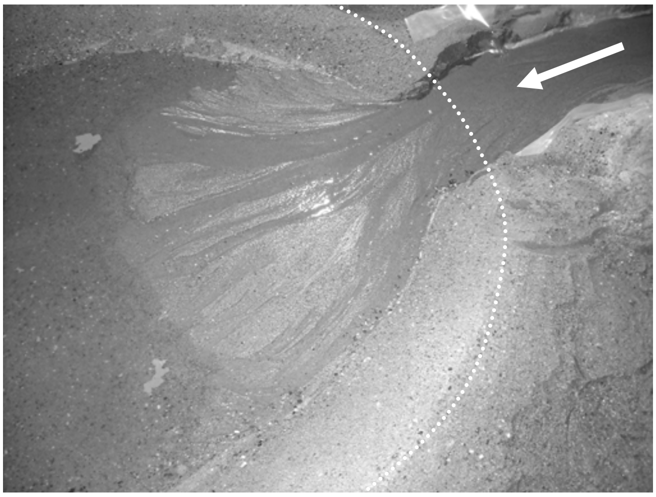

Figure 4. Numerous small incisions on the delta within the crater basin, with hardly any visible terraces. Flow is from top right to bottom left. D_{50} was 0.4 mm and discharge was 0.07 m^3/s. Flow direction indicated by white arrow, crater rim outlined with white dotted line.

Figure 5. In contrast to Figure 4, large incised channel on the delta within the crater basin, with clearly visible terraces on each side of incised channel. Flow is from top left to bottom right. D_{50} was 0.4 mm and discharge was 0.35 m3/s. Flow direction indicated by white arrow, crater rim outlined with white dotted line.

Based on our observations, lateral variability due to channel avulsion is crucial in the development of a wide-basin delta after dam removal, especially during low discharge events.

3.3 *Effect of particle size*

In both the ponding and the breaching events, coarser grain sizes resulted in a more lobate delta shape and exhibited less developed steps. Finer grained experiments showed better developed steps due to the higher mobility of the sediment, but the overall shape is less lobate (Figure 6). Profiles of these deposits also clearly show their back-stepping morphology.

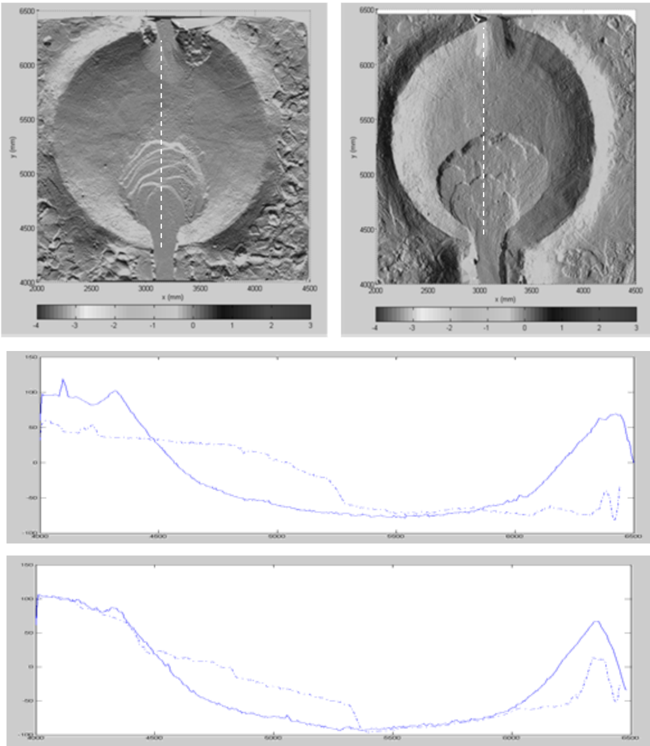

Figure 6. Top: Shaded DEMs of the circular crater-shaped lakes (diameter 2 m) with deltas. Flow is from the bottom (breach was manually created after the flow event). Left panel: small particle size (0.225 mm); right panel: large particle size (0.45 mm). Bottom: Profiles of the respective deltas (location of profile shown by white dashed lines in DEM). Flow is from left to right. Upper profile is of the delta in the left panel above, lower profile is of the delta in the right panel above.

Deltas formed with a clear sorting pattern in the poorly sorted sediments. The topset was coarse and often armoured. The foreset was locally fining-upward but varied strongly spatially as each lobe and avulsion formed its own foreset. The toeset, overrun by the delta to form a bottom set, consisted of very fine sand to silt (when a significant amount of fine material was supplied to the system). Upon manual crater rim breaching most of the erosion took place in the relatively coarse topset and foreset whilst the fine bottomset was commonly largely preserved.

3.4 *Effect of silica flour*

The river sand with silica flour eroded much slower in the upstream feeder channel, yet it did not have much impact in the erosion rate of the downstream crater rim. Furthermore, little difference was observed in the erosion rates between 20% and 40% silica flour (in agreement with Kleinhans et al., this volume).

In Figure 7 one can see the slightly more elongate nature of the individual lobes, as derived from small channels on the delta surface. These channels are more stable than those on the previous deposits due to the added silica flour. As expected, the whole deposit was covered in fine material from settling when the water in the crater was left to evaporate rather than overflow. Figure 8 shows the thin draping of fine sediment that is found throughout the basin after evaporation. If released instantaneously, these fines could potentially be a problem for downstream ecologies. However, the experiments show that most of the fine material is not removed from the basin at the time of incision due to the relatively fixed location of the incising channel. Figure 8 also shows partial erosion of the fine material and indicates that the fines were not completely flushed downstream but most of the fine material was left in the basin and was only slowly released back into the downstream environment with time. In both figures, flow direction is indicated by the white arrow and the crater rim outlined with a white dotted line.

Figure 7. Thin layer of fine sediment draped over the deltaic deposit in the crater lake basin. Note the distinct elongate nature of the individual lobes, brought on by the increase in channel cohesion. Flow from right to left, with low discharge, and 20 % volumetric percentage of silica flour mixed with river sand.

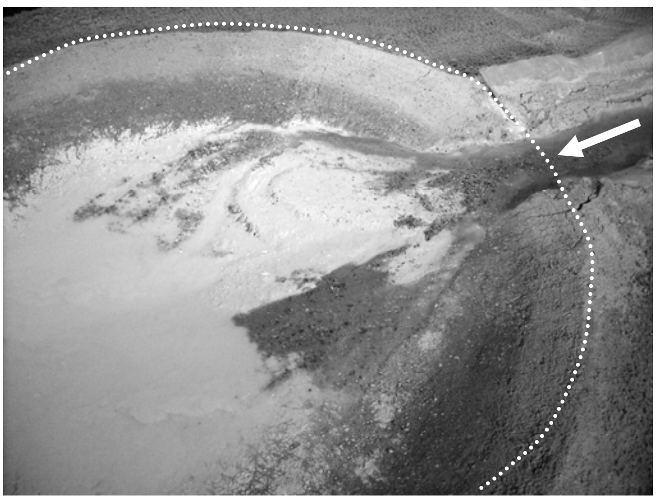

Figure 8. Thin layer of fine sediment draped over the deltaic deposit in the crater lake basin after evaporation, partially eroded by early channel incisions on the delta front. Flow from right to left, with high discharge, and 40% volumetric percentage of silica flour mixed with river sand.

3.5 *Sediment transport*

From the transport rate predictors one can estimate the volume of the delta deposit. We assumed bed load transport to be the major component. Predicted delta volumes differ from measured volumes mostly within an order of magnitude. Sediment transport values were incorrectly predicted, possibly due to armouring in the feeder channel or differences in the expected mobilities, or also possibly due to discrepancies in the time of formation. Due to heavy armouring in run A (Table 1) and due to under-predicted mobility in run F (Table 1), these values are outside the order of magnitude boundaries. When $\alpha = 11$ in equation (3) for sediment transport and $k_s = 7D_{90}$, the delta volumes are best predicted; most lie within an order of magnitude from the predicted value (Figure 9). The outlier above the $y = 10x$ line can be explained by the heavy armouring that occurred in the channels in this experiments (A). Armouring inhibits sedimentation as the system is starved of sediment. The outlier below the $y = 0.1x$ line can be explained by the much higher mobility of the sediment in reality in this experiment (F). We found that mobility is less for the finer grained deltas due to the lesser effect that turbulence has on smaller grains. More mobile sediment yields more sediment in the delta than predicted. Our sediment mobility predictions may have been inaccurate due to insufficient slope measurements while active sediment transport was taking place, or may have been affected by small errors in slope and water depth measurements.

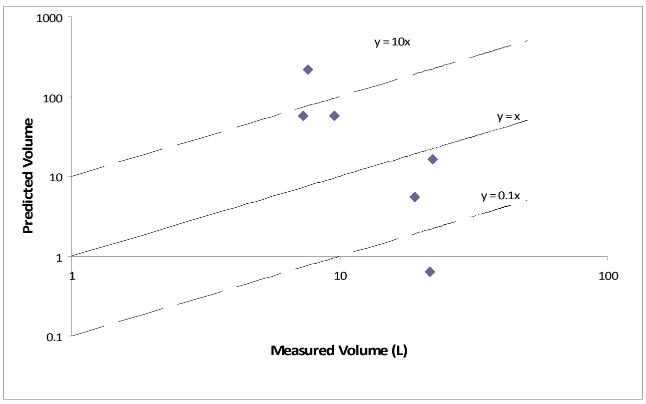

Figure 9. Predicted versus measured delta volumes for some delta deposits. See text for further explanation.

4 DISCUSSION

4.1 *Application to hydrological reconstruction on Mars*

We show that water level in the crater lake determines overall fan shape. Variation in basin water level, caused by the different stages of crater filling and emptying, is enough to stimulate the formation of different types of deltas. They are all basically deposits arrested in a different phase of their development because the hydrological event ended, probably abruptly. Figure 10 shows some of the different types of deltaic deposits that can be found on Mars, including stepped deltas (from rising water levels) and smooth or branched Gilbert-type deltas (from constant or falling water levels).

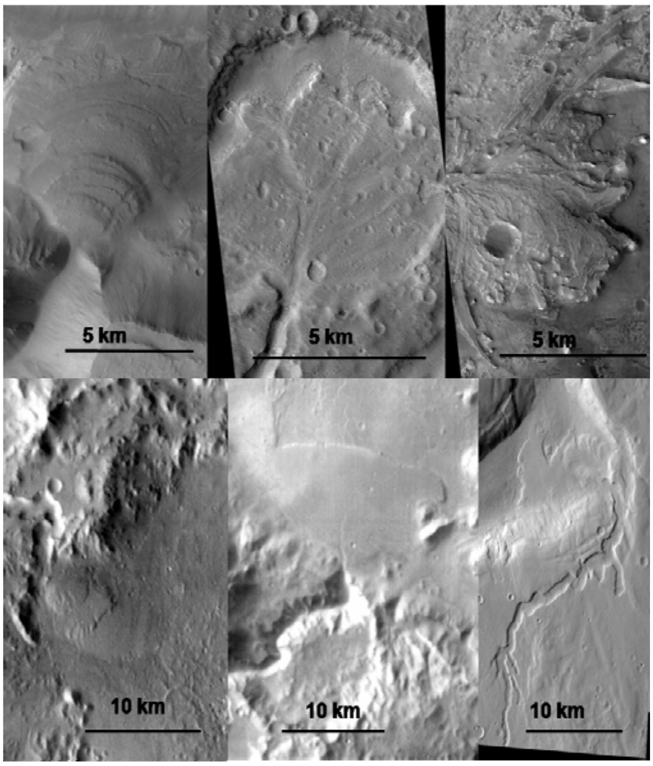

Figure 10. Different types of deltaic deposits on Mars. Clockwise from top left: Stepped delta, branched Gilbert-type delta, branched Gilbert-type delta, smooth Gilbert-type delta, smooth Gilbert-type delta, and stepped delta. These different morphological types of sedimentary deposits can be explained by merely changing the base water level.

Further variations in morphology can perhaps be explained by channel width (discharge) relative to delta size (crater size), and by sediment properties which are basically unknown for Mars.

Finally, these experiments show that all these deltas can have formed in one event. Also evident is that upstream channel characteristics can be used to predict sediment transport capacity, from which, given the relatively easily measurable delta volume, a time scale of formation can be derived. Elsewhere we have compared volumes of Martian deltas for some examples to predicted volumes, and the results indicated that these deposits formed in a very short period of time, on the scale of a few months (Kleinhans et al. 2009).

4.2 *Application to dam removal*

This study investigated the formation and modification of coarse-grained deltas in wide lakes or reservoirs. There are some similarities to course-grained deltas formed in narrow lakes (Cantelli et al. 2004; Kleinhans 2005b). Major differences however, include the increase in the number of channel avulsions due to a larger delta area and thus an increase in lateral variability; as well as the increase in terracing that is observed due to one large channel cutting rapidly very deeply into the deposit. This implies that the concepts of Cantelli et al. (2004) cannot be transplanted on wider delta cases without modification. It also implies that the former delta deposit will not deliver a large amount of sediment instantaneously to the downstream river, but will spread it out over a longer time period (if the terraces are eroded at all).

Surprisingly, for low discharges the incising channel destroyed the deposit through transverse movements and avulsion of the initially excavated channel whereas for higher discharges the terraces were preserved for a much longer time. Our results indicate that dam removal at wide lakes may lead to an unexpected inverse relation between discharge and erosion of the deposit, which has consequences for the subsequent sediment pulse magnitude.

Furthermore, we observed a clear sorting trend in the longitudinal profile of the deltas. Coarse grains are located on the delta topset and foreset, whereas fines are located in the bottomset. However, the down-cutting channel only removes the fine sediment partially, hence also a large amount of fines remain behind in the sediment trap. This effect is much larger with a higher discharge due to the force of the down-cutting channel and its inclination to stick to a certain path once the surrounding terraces are too high to cross with an avulsing channel.

5 CONCLUSIONS

- The volumes of deltaic deposits are predictable within an order of magnitude from total time of formation and upstream channel and sediment characteristics.
- Coarse-grained deltas in wide lakes are mainly formed by lateral channel migration (bifurcations and avulsions). This is in contrast to the formation of coarse-grained deltas in narrow lakes, which are mainly formed by sheet flow. Most of the deltas on Mars are formed in wide lakes (impact crater basins).
- In most cases, a large part of the delta deposit remains in the basin after dam removal. During the period of falling water level, incision of the delta results in terraces. Comparable terraces are not observed in Martian deposits and hence we assume that the water discharge stopped abruptly.

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