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Palaeoflow reconstruction from fan delta morphology on Mars

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ABSTRACT

Alluvial fans and deltas on Mars record past hydrological conditions. Until now these conditions have been inferred from the morphology of the feeder channels and the deposits from images and digital terrain models (DTMs), and from calculations of the bulk fluxes of water and sediment based on the dimensions of upstream channels. Neither method can distinguish between dilute (river-like) flows and dense (sediment-laden) flows, however, while the formation time scales for these two sediment transport modes differ by orders of magnitude. The objective of this paper is to compare DTM data quantitatively with a morphological model to infer sediment transport mode and formative duration.

We present a quantitative morphological model for fan and delta formation that assumes as little as possible. The model calculates the growth of a sedimentary body in a crater lake, represented by a low-gradient, subaerial cone on top of a high-gradient, subaqueous cone. The volume of the cone is constrained by the influx of sediment while the elevation of the break in slope, that is, the shoreline, is constrained by the influx of water. The water and sediment fluxes were calculated with physics-based predictors based on the feeder channel. Small-scale morphology, such as crater wall irregularities, concavity of the fan surface and channel avulsion, is ignored. The model produces alluvial fans, stair-stepped fan deltas and Gilbert fan deltas as well as hitherto unidentified crater wall drapes. The parameters that determine which morphology emerges are the supply of sediment and water to the basin, the size of the basin and the duration of the flow.

A direct comparison between the cone model and HRSC DTM data for five deltas and an alluvial fan demonstrates that single-event dilute flows of short duration (days to years) have created all of the deposits. Two Gilbert fan deltas were formed in overspilling crater lakes from long low-gradient upstream channels. One alluvial fan was formed in a similar manner except that the damaged crater did not lead to ponding. Three stair-stepped deltas were formed from short high-gradient upstream channels that only partially filled the crater lakes.

1. Introduction

Many alluvial fans and fan deltas have been identified on Mars over the past decade as the image resolution increased (Grin and Cabrol, 1997; Ori et al., 2000; Cabrol and Grin, 2001; Malin and Edgett, 2003; Moore and Howard, 2005; Fasset and Head, 2005; Irwin et al., 2005; Mangold and Ansan, 2006; Di Achille et al., 2006b; Weitz et al., 2006, and references therein). Deltas and fans form when a water–sediment mixture enters a sudden expansion. Thus, they record past hydrological conditions in various manners. The most obvious is their total volume, which must have taken a certain amount of time to be deposited, with the reasonable assumption that a delta or fan is a perfect sediment trap. The formation time can be calculated as the ratio of the volume and a volumetric sediment transport rate. But this ignores the information recorded in morphology, which is considered quantitatively in this paper.

To calculate sediment transport rate, modelling of the flow is required. Input parameters are derived from geometry and gradient of the feeder channel upstream of the fan or delta. In the flow modelling, the friction is a rather crucial problem that can be overcome by careful study of bar height and terrace height in the data to infer water depth, as well as general hydraulic roughness predictors that include gravitational acceleration, surface particle size and the potential for bed states such as ripples, dunes or antidunes (Wilson et al., 2004; Kleinhans, 2005). An order of magnitude estimate of the transport rate itself can be made with sediment transport predictors that have been nondimensionalised carefully (including gravitational acceleration, of course) (Komar, 1979; Kleinhans, 2005). Such analyses yielded the surprising result that the fan deltas of Mars formed in very short periods of the order of days to decades (Kleinhans, 2005; Kraal et al., 2008; Hauber et al., 2008). By implication, flowing water

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was only present for very short periods and, given the flux compared with Terrestrial systems, rather catastrophical.

The second obvious key to the formative history of fan deltas is their morphology and the morphology of the upstream feeder system. Kraal et al. (2008), Hauber et al. (2008) and many others (Kleinhans, 2010, for review) describe systems with a wide range of surface morphologies, including fans covered with channels, lobed fans and dendritic fans. The key conditions that must have led to these morphologies are the rising water levels in lakes where they formed as well as the upstream rate of water and sediment discharges. The morphology of the upstream systems provides some clues for this. Box canyons with amphitheatre-shaped upstream ends may have been formed by groundwater sapping or by overland flow or a combination (Howard et al., 1988; Lamb et al., 2006; Kleinhans, 2010), which would probably not have resulted in an extreme flow filling the box canyon up to the brim. Quasi-dendritic drainage networks (Goldspiel and Squyres, 1991; Craddock and Howard, 2002), either formed by eroding overland flow or by groundwater sapping, may have provided relatively more water than box canyons with similar channel widths. Ma'adim Vallis is thought to have formed during a catastrophic lake overflow event (Goldspiel and Squyres, 1991; Cabrol et al., 1996; Irwin et al., 2004). Steep and short canyons dissecting crater walls, on the other hand, perhaps could have provided large amounts of sediment relative to the water flux (Kraal et al., 2008), perhaps from backward migrating steps (or knickpoints) (Kleinhans, 2010). Similarly, small contributing areas yield steep alluvial fans whereas larger areas yield more gentle fans on Mars and Earth (Moore and Howard, 2005). Perhaps both mechanism and rate of sediment supply may have varied dramatically through the course of time within a single event, and it is not obvious that a single representative constant condition is meaningful.

In short, the ratio of water flux and sediment flux delivered to the basin is determined by the conditions in the feeder system. The sediment load of the flow is not simply determined by the flow strength itself, though. At a given flow velocity, the flow may be either dilute or dense. Any intermediate condition will either evolve to one or the other (Kleinhans, 2005). A dilute flow is similar to river flows on Earth which have volumetric sediment concentrations of less than a thousandth or so. Were a bit more sediment supplied to this flow, then it would settle and cause sedimentation near the supply zone. A dense flow, for instance a hyperconcentrated flow such as in the Yellow River (van Maren et al., 2008), has so much sediment that the shear force of the flow is increased so that it can carry concentrations up to about one third. Were a bit less sediment supplied to this flow, then it would pick up more sediment from the bed, causing erosion. In the past, a dense concentration was simply assumed (Goldspiel and Squyres, 1991; Irwin et al., 2004), but to attain this condition, the flow must either have been incredibly fast just before this time, or the sediment must have been supplied to the flow in massive amounts by, e.g., slope failure of the channel walls (Komar, 1979; Kleinhans, 2005). Although the morphology of the upstream system may provide some clues, this dichotomy presents a problem. Even if we have calculated the flow, then we still do not know whether the flow was dilute or dense, while the two conditions yield formation time scales that differ by many orders of magnitude. Therefore we need a morphological model for fan deltas that quantitatively predicts the different morphologies resulting from dilute or dense flow.

The objectives of this paper are to construct the simplest possible (parsimonious) morphological model for fans and fan deltas and to infer the amount of water involved and the duration of the flow in a number of deltas. The experiments reported in Kraal et al. (2008) and Kleinhans (2010) demonstrate that the morphology of a fan delta is the result of the balance between water filling up a basin of a certain size, and sediment building out the delta, together providing both a minimum and maximum formation time scale based on the water and sediment bulk volumes based on Kleinhans (2005). This hints at the key elements for a novel morphological model presented in this paper. The advancement of a morphological model over the former bulk volume method is that it allows a direct comparison with HRSC digital terrain models (DTMs) which allows a discrimination between dense and dilute flows.

The approach taken in this paper is that we assume as little as possible and use relations based on physics where possible. Thus we reduce the risk of carrying geologic insights from Earth to Mars that are only valid for Earth by force of their implicity underlying assumptions. For Mars, the simplest possible set of initial and boundary conditions is used in combination with the simplest possible physics-based model for a parsimonious model for delta formation on Mars. The quantitative test of the resulting model is the comparison between predictions and the undisputed observation of morphology. If predictions and observations agree well there is no obvious reason to suppose that any more complicated factors were important. Of course our explanation does not exclude the possibility of future, equally good quantitative explanations. But any explanation that assumes more than we did will have to support those assumptions with hard observations that are independent of interpretation through concepts developed and tested for Terrestrial systems (Kleinhans et al., 2005, 2010).

The setup of this paper is as follows. In the next section the model is presented, with an analytical validation method and the notation presented in Appendices A, B and Supplementary data. The flow and sediment transport calculations are not provided here; see Kleinhans (2005) and supplementary data in Appendix C. Next some basic information on a few well-described fan deltas is summarised as well as a formation time scale estimate based on the bulk sediment flux. Then the modelling results are given, both for general dilute and dense scenarios and for specific cases. This is followed by a discussion of the limitations of the model and the inferences from both model success and discrepancies between model and DTM, and the conclusions.

2. Model development

First the general principle of the model is explained, followed by the method of determining the necessary upstream boundary conditions (fluxes). Next the method of determining the initial conditions is presented (crater representation). This is followed by a detailed account of the workings of the model and a description of how this was implemented numerically.

2.1. Principle

The essential characteristic of a fan delta or alluvial fan is that sediment is fed into a basin where it is trapped because of the flow divergence. The horizontal flow divergence leads to a fan-shaped feature. Vertical flow divergence (depth) leads to deposition at the angle of repose. The shape of the alluvial fan and fan delta can therefore at first order be described as a relatively simple geometrical form. The shape of an alluvial fan can be approximated as an upright cone with a small top angle. The shape of the fan delta can be approximated as a truncated cone with a large top angle (namely, the subaqueous dynamic angle of repose) and the subaerial fluvial fan on top of this truncated cone can again be approximated as a cone with a small top angle similar to that of the alluvial fan. The plane where the subaerial cone is deposited on the subaqueous cone is at the water level. This plane is seen as the shoreline on the outside of the fan.

It is well known that the subaerial fluvial fan gradient is generally not constant, but concave depending on the channelisation of the flow on the fan (Parker, 1999; Moore and Howard, 2005). Furthermore the gradient, channel pattern and channel avulsion rate depend on the rate and type of sediment supplied, in particular the amount of cohesive fractions, as well as the nature and density of vegetation (Parker, 1999). For simplicity this will be ignored in the model