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A review of open-channel megaflood depositional landforms on Earth and Mars

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Summary

Catastrophic out-bursts of water from lakes impounded by glacial ice or debris such as moraines have caused large freshwater floods on Earth in recent times at least back to the Quaternary. Resultant large-scale depositional sedimentary landforms are found along the courses of these floodwaters. On Mars, similar floods have resulted from catastrophic efflux of water from within the Martian crust. This latter conclusion is based on large-scale and mesoscale landforms that appear similar to those identified in flood tracts on Earth. Both on Earth and on Mars, these landforms include suites of giant bars – 'streamlined forms' – of varying morphology that occur primarily as longitudinal features within the floodways as well as in flooded areas that were sheltered from the main flow. Flow-transverse bedforms, notably giant fluvial dunes and antidunes also lie within the floodways. The flood hydraulics that created these forms may be deduced from their location and morphology. Some other fluvial landforms that have been associated with megafloods on Earth have yet to be identified on Mars.

3.1 Introduction

Exceptionally large freshwater floods on Earth are associated with the catastrophic draining of glacial lakes Missoula and Agassiz amongst others in North America (Teller, 2004). Other glacially related large floods occurred in the mountains of Eurasia, which have only recently received attention (Grosswald, 1999; Montgomery *et al.*, 2004), and geomorphological evidence of other large floods may be discovered in formerly glaciated terrain on other continents. There is a general knowledge about what landforms are associated with flood action but there is relatively little knowledge of what complex and different suites of depositional landforms might result from many floods of different magnitudes. Although several studies have estimated power expenditure by large floods, there has been little critical appreciation of the detail of the distribution of power throughout a flood (Costa and O'Connor, 1995) and the timing of deposition and/or erosion including defining the threshold phenomena (Benito, 1997) required to develop specific landforms in given environments. Similarly, the effect of large sediment loads on the hydraulics has not been explored widely (Carling *et al.*, 2003) and there is little knowledge of the relationship of the hydraulics to the stratigraphic associations, although the spatial variation in the former can be modelled (e.g. Miller, 1995; Clarke *et al.*, 2004) and the latter may be well recorded (e.g. Sridhar, 2007; Duller *et al.*, 2008).

Here, is presented an overview of some key considerations relevant to identifying alluvial landforms on Earth and other planets. These considerations include the mode of sediment transport and the granulometry of the deposits. This synopsis includes depositional landforms and the known conditions of formation and serves as both a summary of past work and a foundation for future research. An analysis of the sedimentology and stratigraphy of landforms that can provide useful insights into formative mechanisms is given elsewhere (see Marren and Schuh, this volume Chapter 12). Firstly, basic terminology is discussed, starting with the issue of scale of flooding.

Having peak discharges of $10^6\ m^3\ s^{-1}$ or larger (Baker, 2002), megafloods might be deemed catastrophic either with respect to origin (e.g. ice-dam, subglacial efflux, rock-dam failures, or volcanic fissure eruptions) or effectiveness in changing the landscape 'irreversibly'. Considering megaflood tracts on Earth and Mars, an exact definition of the term 'large-scale depositional landform' presently cannot be provided owing to a lack of defining criteria. On Earth, alluvial bedforms in river channels are classified as microforms, mesoforms and macroforms (Jackson, 1975) and this typology can be adopted for similar scale forms on Mars. Being unobservable from orbit, microforms fall outside the purview of this chapter. Mesoforms scale with water depth and are typified by subaqueous river dunes. Macroforms scale in a general sense with channel width (Bridge, 2003) although there often is a distinct and important depth limitation to the height of the sediment accumulation. The latter class of bedforms is typified by channel bars that may occur centrally within channels or along the margins of channels. The scale of some mesoforms and macroforms on Earth and Mars and the position

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of these features relative to the main flood channel mean that the appellation 'bedform' often is not apposite. Rather, for megaflood systems, the term 'landform' is to be preferred as this latter term has neither spatial nor genetic association with a particular portion of a channelway. In a similar sense the adjective 'diluvial' may be a useful precursor to the term 'depositional landform' inasmuch as the term may be used to signify an association with exceptionally large floods. However, some scientists object to the biblical connotations that the word 'diluvial' carries. Such definitions may not apply well to all systems but, with the exception of 'diluvial', are used herein. Further discussion of the unresolved issue of terminology applied to large floods (e.g. catastrophic, cataclysmic etc.) and the effects on sediment transport and landform change is provided by Marren (2005), but see also Papp (2002) and Russell (2005). Closed-conduit flows (such as esker deposition beneath icesheets) and small-scale jökulhlaups, are excluded from consideration.

Figure 3.1A applies to proglacial environments on Earth as the most common terrestrial environment to produce periodic catastrophic floods. The two main observations with respect to Figure 3.1 are: (i) no precise quantitative scale can be added to either axis of the graph (the abscissa is scaled approximately from 10^0 to 10^9 hours), and (ii) that megafloods on Earth are of low frequency and associated with large-scale climate change, affecting the hydrological system at a regional scale (i.e., $10^6\,km^2$) rather than basin scale (10^2 to $10^4\,km^2$) (see O'Connor *et al.*, 2002; Hirschboeck, 1988). Yet, two conclusions related to megafloods on Earth result. Firstly, given a frequent climate-change trigger, evidence of megafloods will not be confined to one basin but extend to several basins within a region where conditions allowed water to accumulate. Secondly, geomorphologic changes should occur in the landscape such that the suites of postflood landforms contrast to preflood ones. The large size of many of these landforms resist postflood modification by ordinary processes and these landforms persist in the landscape.

A similar diagram for Mars (Figure 3.1B) lacks information on variability, because satellite images observe the geomorphology integrated over the history of the planet. The time scale is replaced with the frequency of formation, estimated as the ratio of the number of flood channels formed during an epoch to the time length of the epoch. The history of Mars is divided into three time-stratigraphic epochs, which, from oldest to youngest, are the Noachian, Hesperian and Amazonian. Two Noachian-aged Martian flood channels start at large intercrater basins. These basins may have been filled by rainwater and/or groundwater flow (Irwin and Grant, this volume Chapter 11) but the immediate floodwater source was surface-ponded water. The Hesperian saw a peak in flood-channel formation, most of the channels of Mars being formed during this epoch. These flood channels originate either at chasmata, that may have been filled with ponded water, or at chaos terrain interpreted as geothermally triggered groundwater release (summarised by Coleman and Baker, this volume Chapter 9). Thus, the immediate source of floodwater during the Hesperian may have been both surface ponds and groundwater. The four megaflood channels inferred to have flowed during the Amazonian originate at fissures (as discussed by Burr *et al.*, this volume Chapter 10). These fissures may have been induced by dyke injection or by tectonic stresses (see Wilson *et al.*, this volume Chapter 16). In either case, the Amazonian-aged channels originate from groundwater discharges. Like Earth, Mars experiences smaller flows. High-resolution imagery shows small gullies, inferred to have been created recently by flowing water, although the origin of the very youngest examples (formed within the last decade) is less uncertain (Malin *et al.*, 2006; McEwen *et al.*, 2007). High-resolution imagery of slope streaks also permits their formation by flowing liquid, although dry mass wasting is an equal possibility (Chuang *et al.*, 2007; Phillips *et al.*, 2007). The origins of these two types of feature are an area of active research but are included on Figure 3.1B for completeness. Beyond the basic floodwater source, the specific release mechanisms and flow processes for Martian floods are inferred from geomorphology (see Wilson *et al.* this volume Chapter 16). More detailed mapping of depositional bedforms on Mars will provide additional constraints on the surface hydraulics, subsurface groundwater flow and erosion and sedimentary processes. Other issues that require consideration for the correct identification of sedimentary landforms as depositional bedforms are detailed below.

3.2 Geomorphological considerations

Scale Is the size of a sedimentary landform commensurate with formation by megafloods?

Location Firstly, is the landform located where hydraulics and sediment transport suggest a depositional bedform would occur and be preserved? Secondly, is there sufficient accommodation space to allow an alluvial bedform to have been deposited? Accommodation space is especially important where there have been successive flood episodes, as space can be filled already by landforms from earlier events.

Geometry Is the body geometry of the landform recognisable as having been formed by flowing liquid? Full analysis of body geometry considers three dimensions. On Mars, data of the third dimension (i.e., from Mars Orbiter Laser Alimeter (MOLA), photoclinometry or stereo imagery)

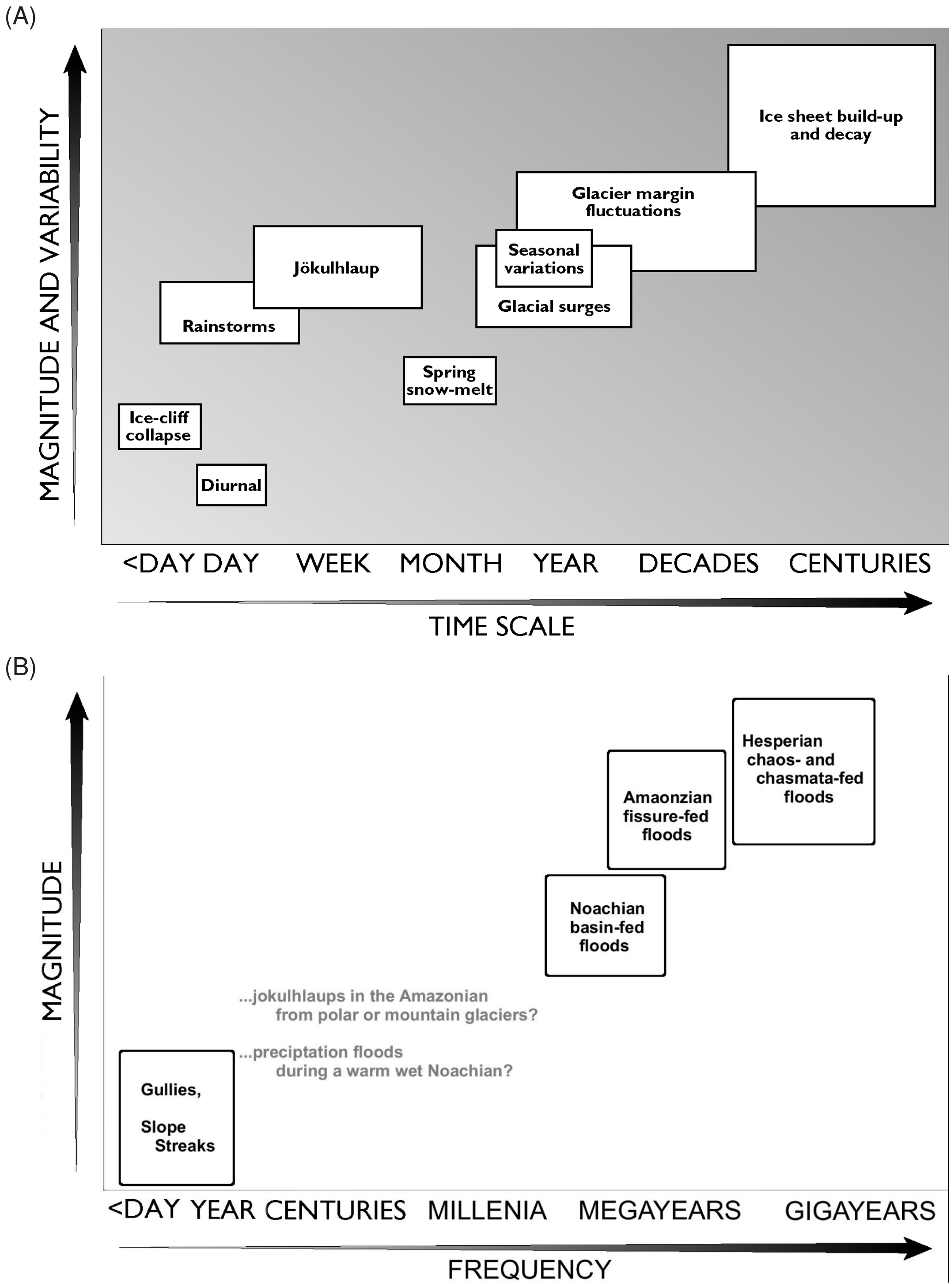

Figure 3.1. (A) Cartoon of variability in water release mechanisms in proglacial environments. The boxed area for each type encompasses the range of time scales and discharges. Increasing magnitudes are associated with increasing variability. (Redrawn from Marren (2005).) (B) Plot showing broad trend with time in Martian flooding. Megaflood channel formation peaks during the Hesperian, when ponded water sourced from chasmata and groundwater sourced from chaos terrain may have combined.

are in some locations sparse or missing, so that often only planform analyses are possible.

Stratigraphy and sedimentology On Earth, the stratigraphy and detailed sedimentology define the formation mechanisms for the landform. For example, grain size, orientation, coarsening/fining trends, regional relationships etc. may indicate the associated fluid and the detailed processes of emplacement (Duller *et al.*, 2008). On Mars, these analyses only occasionally can be explored, but analyses of Martian surface data (e.g. Squyres *et al.*, 2006) suggest the utility of applying terrestrial-style stratigraphic and sedimentological analysis to extraterrestrial landforms.

Association Association refers to whether the sedimentary landform is contiguous to or associated with other landforms, including self-similar forms (e.g. trains of dunes), that would reasonably have resulted during flood formation. The presence or absence of associated landforms has to be compatible and explicable. The current generation of computational fluid dynamics (CFD) models can be used to explore association, although there has been little consideration of detailed and quantified flood hydraulics with respect to landforms to date.

Correct identification of a landform as an alluvial bedform requires that alternative explanations be significantly less likely. This process should entail consideration of the specific processes and fluids responsible, including whether the scales of landforms and fluid flow inferences are compatible. For example, subcritical or supercritical flows may be inferred from flow modelling and the landforms present have to be compatible with such flows.

At the basin scale, alluvial depositional landforms appear rare on Mars in comparison with the frequency of erosional landforms on Mars (Carling *et al.*, this volume Chapter 2) and with the well-described alluvial landforms on Earth (e.g. Baker, 1973a, b; Baker and Nummedal, 1987; O'Connor, 1993; Carling, 1996a; Carling *et al*., 2002). The rarity of such deposits might suggest that, unlike on Earth, climate change did not drive megafloods on Mars. Additionally, or alternatively, this rarity may be a function of conditions specific to Mars. Under Martian gravity, finer-grained sediment tends to travel as washload in comparison with the same sized sediment under terrestrial gravity (Komar, 1980). The morphology of Martian megaflood channels has been interpreted as indicating that, unless the flow is impeded, this washload sediment remains in suspension for considerable distances, leaving behind fewer depositional landforms (Rice *et al.*, 2003; Burr, 2005; Burr and Parker, 2006). Where alluvial depositional bedforms are identified, their characteristics can provide indications of sediment transport mode or characteristic flow regimes. For example, fluvial dunes and bars are deposited predominantly from bedload with a usually lesser component of suspended load (Bridge, 2003). On Earth the presence of fluvial dunes indicates subcritical flow whereas the presence of antidunes indicates transcritical or supercritical flow (Carling, 1999). In comparison, subaqueous fans, although often constructed from deposition of traction sediment, in some instances may be due to hypopycnal deposition from suspension, with slow net rates of sediment accumulation from 'rain-out' of the very finest material in the water column. These examples illustrate the potential for understanding palaeoflow hydraulics from the location, form, stratigraphy and sedimentology of megaflood landforms on Earth and on Mars.

Komar (1979, 1980) laid the foundation for understanding of flood sediment transport on Mars and for comparing putative water-laid Martian landforms with terrestrial analogues. Komar (1979) drew analogy between fan-like features on Mars and subaqueous fans on Earth. Such interpretations may provide explanation for some of the new SHARAD (radar sounding) data being returned from the Mars Reconnaissance Orbiter (Seu *et al.*, 2004). Chapman *et al.* (2003) argue that some features on Mars are morphologically similar to gravel bars and dunes in Iceland. Burr *et al.* (2004) show that the morphology of channelised Martian dunes is similar to that of terrestrial flood dunes and Burr (2005) argues that clustered streamlined forms in Athabasca Valles are at least in part depositional (see section on 'Large-scale bars').

At a simple level of analysis, depositional landforms result from bedload and/or suspended load transport. A better consideration of the modes of transport that lead to the deposition of given landforms might aid the modelling and interpretation of the hydraulics associated with suites of megaflood landforms. These issues are considered next.

3.3 Theoretical background to sediment transport and deposition

Sediment may be moved by flowing water in three modes. The coarsest sediments move as bedload, with individual grains rolling or sliding along the bed more-or-less in continuous contact with the bed (traction transport). In more energetic flows the bedload may bounce along the bed (saltation transport). Finer sediments move as suspended load, lifted above the bed by turbulence and moved downstream within the water column, making rare contacts with the bed. The finest sediment may remain within the water column for extended downstream distances and this portion of the suspended load has traditionally been termed 'washload'. The term is one of conceptual convenience rather than a mechanistic distinction from suspended load (Woo *et al.*, 1986).

The distinction between bedload, suspension load and washload is useful in understanding flood sedimentation processes. Mode of transport determines the relative speeds of sediment movement. Bedload moves slowly because of its continuing or frequent contact with the bed, whereas suspended sediment travels at practically the rate of the water. An identified transport mode, along with other considerations, may be used to estimate the size of the sediments that are incorporated into depositional bedforms. Most fluvial bedforms consist predominantly of bedload with a variable component introduced from suspension, whilst some bars in slack-water areas may form from suspension fall-out onto weakly mobile beds. Thus identification of a transport mode can help identify the bedforms that are present within a channel and vice versa. In some instances identification can indicate whether the location is proximal or distal relative to the original source of fluid. However, few studies have considered what the presence of specific landforms might indicate in respect of changes in the power distribution through the system and how the landforms might relate to the palaeoflood hydraulics and flood behaviour (e.g. Benito, 1997). This limitation is despite a variety of studies that have calculated the stream power expenditure at a variety of locations within large floodways (e.g. Kale and Hire, 2007).

Paola (reported in Church, 1999) characterised the primary controls in down-channel sedimentation over short time scales as the hydraulics of the transport system, the size distribution of the sediment supply and the distribution of sediment deposition. An example of a system where the Paola controls apply well is the sudden failure of a man-made dam and the consequent deposition of a sediment slug in the valley downstream. Similarly, these controls pertain to individual megafloods, which are singular events with a distinctive source, definitive depositional tract and short duration. Thus down-system sediment sorting and distribution of deposition will be primarily the result of spatial changes in flow hydraulics (Paola *et al.*, 1992; Seal *et al.*, 1997), primarily driven by gradient changes (Gomez *et al.*, 2001) and mediated by temporal changes in the flood hydrograph. In such a simple system, Church (2006) argues that the expected landforms in a channel can be inferred through forward modelling (i.e., from process to landform) or from inverse modelling (from landform to process). In both modelling approaches, the partitioning of the total sediment load between bedload and suspended load may vary down system in accord with the expenditure of the total power (Dade and Friend, 1998; Dade, 2000). A threshold function may be used to delimit when sediment is moving as bedload or in suspension (e.g. Equation (3.1)).

At the simplest, the modes of sediment transport may be distinguished by a ratio of the settling velocity of the particle in still water to the flow frictional shear velocity (a proxy for the turbulence acting to suspend particles):

$$Ro = \frac{w_s}{ku_*}, \tag{3.1}$$

where Ro is the Rouse number, k is the von Kármán constant, (usually about 0.4, although k values in the range 0.12 to 0.65 have been reported), w_s is the settling velocity, and u_* is the frictional shear velocity.

The frictional shear velocity is given as

$$u_* = \left(\frac{ghS}{\rho}\right)^{\frac{1}{2}} = \left(\frac{\tau}{\rho}\right)^{\frac{1}{2}}, \tag{3.2}$$

where h is the water depth, S is the gradient, τ is the shear stress and ρ is the density of the fluid.

Like u_*, w_s is also a function of the square root of gravity (see e.g. Komar, 1980). Thus, the critical values of k for distinguishing modes of sediment transport are the same on any planet. However, because the settling velocity, w_s, varies with gravity, the mode of transport for different grain sizes is not necessarily the same on different planets (Komar, 1980; Dade, 2000; Burr *et al.*, 2006).

Generally (e.g. Valentine, 1987):

- $u_* > 2.5w_s$, then particles will be entrained; i.e. $\sim 0.4u_*/w_s > 1$;
- $\tau > \rho 2.5\, {w_s}^2$, then particles will be entrained.

Thus:

- Bedload: $Ro > 2.5$
- 50% suspended: Ro 1.2 to 2.5
- 100% suspended: Ro 0.8 to 1.2
- Washload: $Ro < 0.8$

Theoretical modelling of flood flows on Mars has indicated that sediments on Mars would tend to move more readily (e.g. with a lower minimum water depth) than for comparable conditions on Earth (Komar, 1980; Burr *et al.*, 2006). The lower gravity on Mars produces a slower water flow, which tends to result in less sediment movement, but also a lower settling velocity, which tends to result in more sediment movement. Modelling shows that, in these two countervailing tendencies, the effect of lower settling velocity predominates (Komar, 1980; Burr *et al.*, 2006). The result is that for a given flow and grain size, the mode of sediment transport is more likely to be suspension or washload on Mars in contrast to bedload on Earth. Conversely, it may be stated that coarser grain sizes are more readily transported on Mars in contrast to Earth. Thus, all other conditions (e.g. channel slope, volumetric discharge, grain size available) being equal, coarser sediment can be expected to constitute Martian depositional bedforms in comparison with terrestrial depositional bedforms and proportionately more material can be expected to have moved in suspension or as a washload. The exact sizes and proportions of material in each transport mode depend on the conditions of a given flow. Although the criteria for the modes of sediment transport have been addressed, curiously, given that sedimentary landforms cannot exist without deposition, little attention has been given to the detail of depositional processes on Earth and Mars. Rather it is assumed that when the threshold for motion defined by the Rouse number or another threshold function (such as the Shields criterion) is not exceeded, deposition will occur.

The detailed controls imposed by the geometry of the flood channel on the deposition process and the relationship of some landforms to deposition from subcritical or supercritical flows are issues that have not been explored widely in the case of superfloods, although Druitt (1998) provides a framework from which approaches might be developed. Within such a context, flood landforms are considered below.

3.4 Megaflood depositional landforms

Meinzer as early as 1918 had noted that the Columbia River had at some time performed exceptional work in transporting large boulders many miles downstream from the source area but it was Bretz in his classic paper of 1923 concerning 'The Channeled Scabland of the Columbia Plateau' who made the first report of megaflood depositional landforms. Bretz made reference to 'great river bars' constructed in 'favourable' situations associated with a monstrous flood, which he termed the Spokane flood. Latterly it was recognised that many floods had occurred and the term Spokane was dropped. Bretz (1925a, b) recognised the process of slack water deposition and also argued that the floods receded rapidly leaving the bars unmodified. During fieldwork in the region of the Channeled Scabland and in the basin of Lake Missoula, Bretz also identified large-scale 'ripple marks' formed in gravel (Bretz *et al.*, 1956), initially identifying puzzling wavy bedforms on the top of bars (Bretz, 1928a). The significance of the forms became clear with their subsequent interpretation as fluvial dunes (Baker, 1973a). Ripples and dunes are distinct bedforms related to specific hydrodynamic conditions (see Carling, 1999). Although the term 'ripples' has been applied loosely to some large-scale megaflood dunes in the older literature, the two bedforms should not be confused as a correct identification can aid in determining the palaeoflow regime. The widespread preservation of the dunes indicated that the flood must have receded rapidly and the presence of dunes indicates that a lower flow regime pertained during the formative flow event (Baker and Nummedal, 1987; see also Carling, 1996a, b).

Pardee (1942) described transverse and arcuate ridges of gravel on Camus Prairie, interpreting them as giant current dunes. He related a progressive change in the height of the dunes to a reduced flow speed from the basin margin towards the basin centre, thus linking landform geometry and location with inferred flood pathways and processes. In similar vein he described flood-deposited expansion bars and indicated mechanisms of deposition. This insight provided important information in identifying megaflood landforms, and influenced acceptance of Bretz' flood origin hypothesis for the Channeled Scabland (see Chapter 2).

As noted by Marren and Schuh (this volume Chapter 12) there is a broad range of sedimentary landforms and bedforms that might be related to large-scale floods but that might also develop for smaller-scale flood events. Thus taken alone, the presence of a particular feature is not necessarily diagnostic of megaflooding. Potentially, there are solutions to this conundrum. Firstly, the scale of the landform, especially the amplitude of the feature, might indicate an exceptional water depth as flood-formed bars frequently develop close to the maximum water depth (Costa, 1984; Carling and Glaister, 1987) and such an assumption has been used to constrain megaflood hydraulic reconstructions (O'Connor, 1993; Burr, 2003; Herget, 2005). Secondly, associations or suites of features may occur, which taken together might be used to make a stronger case for megaflood deposition. At the time of writing there is only a nascent understanding that the consideration of suites of landforms may have diagnostic capacity (Marren and Schuh, this volume Chapter 12).

3.4.1 Large-scale bars

Bars form readily during large-scale floods but those within the main floodway are often severely modified or destroyed on the recession limb of flood hydrographs. In addition, these landforms are subject to further erosion or burial by later small-scale discharges unless they are exceptionally large or composed of unusually large material. For example, the Missoula and Altai Quaternary-flood tracts show only local evidence of such massive landforms completely blocking the main floodway (e.g. the huge Komdodj bar, Altai; Carling *et al.*, this volume Chapter 13). Conversely, examples of coarse component bars that resist further erosion are provided by Fahnestock and Bradley (1973), Russell and Marren (1999), Marren *et al.* (2002) and Marren (2005). Thus it is reasonable to suppose that Holocene reworking, incision and alluviation have effaced most evidence of this kind of landform, leaving only stratigraphic evidence at the base of later valley fill (Carling *et al.*, 2002; Smith, 2006; Carling *et al.*, this volume Chapter 13).

It follows that bars that are useful for diagnostic purposes need to have been deposited within areas of the floodway that are protected from further reworking. Where sediment can be deposited in areas sheltered from the main flow, a variety of large-scale bars may be observed as they persist through time. The literature has suggested a typology of expansion bars, pendant bars (Malde, 1968) and eddy bars (Baker, 1973a; O'Connor, 1993; Maizels, 1997). Expansion bars form in areas where the flood channel widens suddenly downstream of a valley constriction (e.g. Baker, 1973a; Russell and Knudsen, 1999, 2002). Often there is a region of non-deposition between the bar and the valley wall, which was illustrated by Bretz (1928b) and termed a 'fossa' by Bretz *et al.* (1956). Carling (1987, 1989) provides field and experimental flume examples of expansion bar deposition and fossae formation. Expansion bars are often incised or streamlined by subsequent flows. For example, the sedimentology and stratigraphy of bars in the Quincy Basin in the Channeled Scabland indicate formation through deposition of a large deltaic deposit with subsequent incision during the waning stages of the flood or by later floods (Bretz, *et al.* 1956 pp. 969–974; Baker, 1973b pp. 39 *et seq.*). A similar origin was inferred for a cluster of streamlined bars on Mars (Burr, 2005). Pendant bars form in the lee of obstacles, such as bedrock hills in the flood channel (Baker, 1973a; Lord and Kehew, 1987; Rudoy and Baker, 1993; O'Connor, 1993) or impact craters on Mars. Eddy bars form in the re-entrants of sheltered back-flooded tributary valleys but importantly may extend far up the tributary with consequences for the sedimentary signature (Plate 11). All prior descriptions of the morphology of these bars assume that their modern day topography is more or less the same as that which was present after flood recession (except for incision by later floods, e.g. Bretz *et al.*, 1956), and indeed in some cases they may be streamlined to form lemniscate forms that minimise skin and form drag (Baker, 1973b; Baker and Nummedal, 1987; Komar, 1983). However, Carling *et al.* (this volume Chapter 13) suggest that in some cases bars might be remnants of a sediment body that originally completely filled valleys. Later incision then cut out the majority of the valley fill, leaving marginal remnants as apparent 'bars'. A similar idea was also proposed by Baker (1973a) with respect to a fan-complex fill within the Quincy Basin, Washington State (Bretz *et al.*, 1956, Figure 4). The detailed styles of deposition and hence hydraulic environment of deposition might be adduced through detailed study of the bar stratigraphy using geophysical techniques.

Associated with giant bars in the Altai are prominent so-called run-up deposits (Plate 11). These are wedge-like landforms consisting of 'smears' of fine well-rounded fluvial gravel found draping valley side alcoves at elevations up to 100 m above bar tops. Often these deposits have very steep slopes facing the main river channel. They are interpreted to represent the deposition of sediment above the main bar tops and peak water level of floods by initial surges or by the inherently unsteady flow of highly turbulent flood waves circulating around spurs and other headlands in the valley-wall alignments (Herget, 2005). Similar run-up deposits have not been identified in association with the Missoula floods.

Large-scale streamlined bars in the giant, Hesperian-aged circum-Chryse outflow channels were perhaps the most obvious indicator of megaflooding on Mars, but these streamlined forms have been interpreted consistently to be erosional (e.g. Baker, 1979; Baker and Kochel, 1979; Rice *et al.*, 2003). Large-scale bars specifically identified as depositional are more limited in imagery available to date. A medial bar in the Noachian-aged Ma'adim Vallis flood channel (Irwin and Grant, this volume Chapter 11) is interpreted as depositional, based on layering visible in an impact crater on the bar (Irwin *et al.*, 2004). This context is similar to that of giant bars along the Chuja River valley, which were deposited during backflooding of tributaries at their confluence with the main trunk channel (Carling *et al.*, 2002).

A cluster of streamlined bars in the Amazonian-aged Athabasca Valles outflow channel is hypothesised to be largely depositional, formed by sediment deposition during hydraulic damming. This hypothesis is based on (a) a similarity of bar upper elevations with another palaeoflow water-height indicator several kilometres up-channel, which is indicative of ponding; (b) the clustering of bars upslope of a flow obstacle, which is interpreted to reflect hydraulic damming by the obstacle; and (c) the morphology of the bars, which shows a difference between obstacles upslope and finely layered tails downslope (Burr, 2003, 2005). This suggested mechanism is analogous to that which produced the streamlined forms in the Quincy and Pasco Basins during the Channeled Scabland flooding (Baker, 1973a; Baker *et al.*, 1991; Bjornstad *et al.*, 2001). Although the tendency towards suspended sediment transport on Mars might preclude deposition from suspension in locations proximal to flood sources, Martian floods should have carried more coarse sediment than terrestrial floods (Burr and Parker, 2006), as the reduced gravity results in a reduced settling velocity that more than offsets the reduction in flow velocity. Thus, on Mars as on Earth, the coarser bedload component of floods should largely be deposited proximally. Consequently, the apparent lack of giant bars in putative Martian floodways may not be entirely explained by the theoretical arguments presented above. Explanations for the absence of bars might include an absence of a source for coarse bedload in some Martian channels and the effect of local conditions such as the large width-to-depth ratio of channels like the Grjotá Valles (Burr and Parker, 2006)

(A) (B)

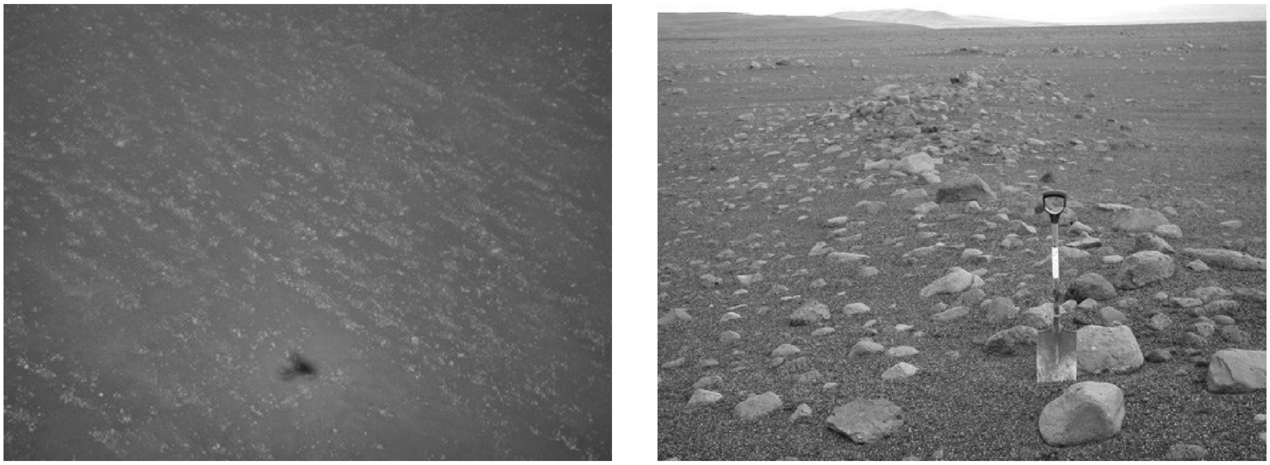

Figure 3.2. (A) High-angle oblique aerial view of regularly spaced gravel ridges at Modrudalur in Iceland that have been interpreted to be transverse ribs or antidunes. The features have average wavelengths of 27 m, heights of 0.8 m and breadths of 14 m. Shadow is of a light aircraft. (B) View along a ridge shown in A. Largest boulders are 1.8 m long. Spade for scale is *c*. 1 m in length. (Photographs courtesy of Dr. Jim Rice and caption information from Rice *et al*. (2002).)

wherein flood waters would have spread widely and dissipated the transporting power to move coarse sediment.

3.4.2 Transverse ribs, hydraulic jumps and antidunes

Transverse ribs are regularly spaced gravel ridges formed in relatively shallow, high-energy fluvial systems and oriented transversely to the current direction (see Carling (1999) for key references). The crestlines are distinctive, being generally straight and continuous over long distances relative to the breadth of the bedforms, and only locally are crest bifurcations recorded. Koster (1978), amongst others, has interpreted relatively small-scale transverse ribs (i.e. heights <0.3 m and wavelengths *c*. 1 m) to be relict antidune bedforms, which formed within transcritical or supercritical flows, although this interpretation is disputed (Allen, 1983; Whittaker and Jaeggi, 1982). Koster demonstrated that using an antidune analogy (see Equation (3.3)), key palaeohydraulic parameters, such as the mean velocity, mean depth and Froude number, can be calculated from transverse rib data. Rice *et al.* (2002a; see also Chapman *et al.*, 2003, Figure 15b) describe bedforms from Holocene-aged Icelandic jökulhlaups (Waitt, 2002) with average wavelengths of 27 m and average heights of 0.84 m as large-scale transverse ribs and use the antidune analogy to calculate palaeoflood data (Figure 3.2). However, there are no reports of modern transverse ribs of similar scale to use as analogues and sections cut in the Icelandic ridges by one of the present authors (DB) reveal an internal stratification that dips downslope and may be more consistent with dune formation. In addition, these particular examples may be erosional remnants rather than pure accumulative features.

Baker and Nummedal (1987) tentatively ascribed a large fan downstream of the Soap Lake topographic constriction within the Channeled Scabland as a depositional landform established beneath a hydraulic jump but did not provide additional comment. In this respect there is potential to use other landforms developed in association with putative hydraulic jumps and hydraulic drops. For example, push bars are the bars that develop downstream of waterfalls (Levson and Giles, 1990) and some of these may be ‘fossil’, i.e., associated with former flow regimes (Jacob *et al.*, 1999). Such bars may be seen, for example, on topographic maps and satellite images of Dry Falls, near Coulee City, Washington State. Nott and Price (1994) have explored the significance of push bars for deducing palaeoclimate and Carling and Grodek (1994) have used the characteristics of push bars to calculate hydraulic indicators of past floods. However, the utility of push bars for large flood reconstructions remains largely unexplored.

Spectacular standing waves often form in both large and small rivers (Plate 12). Often they develop in steep channels such as at the head of alluvial fans (Zielinski, 1982), in steep or flood-prone rivers and upstream and downstream of major obstacles to flow such as islands. Antidunes are the bedforms that develop beneath standing waves. The formation process involves both erosion and deposition but, within loose granular beds, usually only the morphology owing to accumulation of sediment is evident. The bulk hydraulics of standing waves are well known but the conditions for the preservation of antidunes is less well understood (Carling and Shvidchenko, 2002). On falling-water stages antidunes typically are erased. Antidunes usually occur as trains of self-similar ridges and intervening troughs that are roughly transverse to the main direction of flow. However, for supercritical flows the standing waves can become increasingly three-dimensional with wavy crest-lines or, for higher flow conditions, more isolated steep waves occur known as rooster-tails. Increasing three-dimensionality of the water waves often produces a rhomboid water surface profile, a condition that is most prevalent in those situations where the channel margins are close-by and waves are reflected from the channel margins. The shape of the antidunes beneath these various water waves is of similar form to the waveform, with steep isolated mounds of sediment occurring beneath rooster-tails.

The identification of large-scale antidunes is important in a number of regards. Firstly, antidunes develop in transitional and supercritical flows when the Froude number is greater than about 0.84 and may be greater than unity (Carling and Shvidchenko, 2002). Thus, identification would preclude the occurrence of subcritical flows, which are characterised by fairly even water surface levels during the formative phase of the bedforms; rather surface water instabilities are necessarily present for supercritical flows. Thus, identification of palaeo-antidunes might indicate the presence of an irregular palaeowater surface slope. Secondly, the morphology of the antidunes, i.e, regular-transverse, wavy-transverse, or isolated mounds indicates progressively higher Froude numbers respectively. The spacing of transverse antidunes scales with the Froude number in a manner that permits an estimation of water depth or velocity; this is a powerful tool for palaeoflow reconstruction. Allen (1984) deduced from the work of Kennedy (1963) that the average wavelength $(\overline{L_w})$ of standing waves scales with the depth (h) of the water flow:

$$\overline{L_w} = 2\pi h. \tag{3.3}$$

Tinkler (1997a, b) and Grant (1997) have used this relationship to reconstruct flood hydraulic parameters from the spacing of observed standing waves. Allen (1984) showed using flume data that the average wavelength $\left(\overline{L_a}\right)$ of trains of antidunes was in accord with the average wavelength of the standing waves with which they were associated. Consequently $\overline{L_a}$ can be substituted into Equation (3.3) to estimate flow palaeodepth from 'fossil' antidune wavelengths. Likewise, flow velocity can also be estimated (Kennedy 1963) using:

$$U = \sqrt{\frac{\overline{L_g}}{2\pi}} \tag{3.4}$$

where $\overline{L_g}$ is the average wavelength of either the standing waves (if observed) or the palaeo-antidunes. Given that gravity is accounted for in Equation (3.4), the expression should be applicable to Mars as well as to Earth. Finally, the presence of preserved antidunes, after flood recession, usually indicates rapid recession of floodflow (Alexander and Fielding, 1997). For example, Reddering and Eserhuysen (1987) provide a brief description of a flood on the Mzimvubu River in South Africa, which produced gravel antidunes (Reddering, personal communication, 2006). Although the paper contains no information on the antidunes themselves, the hydrograph was very abrupt, lasting only a few hours and so rapid draw-down might explain their preservation. The morphology of the Mzimvubu antidunes is similar to those reported by Shaw and Kellerhals (1977). Karcz and Hersey (1980) developed formative theories and examples of rhomboid bedforms such as those that develop beneath the rooster-tails noted above, but these ideas have not been applied to 'fossil' bedforms.

A small ($\sim$1 km^2) but significant field of probable antidunes was discovered recently in British Columbia, Canada (Figure 3.3A; Johnsen and Brennand, 2004). These bedforms have wavelengths of 100 to 230 m and heights of 3 to 7 m. They are two-dimensional bedforms, having fairly straight troughs and crest-lines. Their streamwise long profiles are asymmetrical, with steeper upflow (stoss) slopes (Figure 3.3B) than the downflow (lee) slopes. The bedforms were created during the catastrophic drainage of a narrow, valley-filling, ice-dammed glacial lake approximately 12 kyr BP. Ground-penetrating radar profiles across one bedform in the upflow part of the field show foreset truncations and suggest that this bedform may be partially erosional (Johnsen and Brennand 2004, Figure 3). However, the upper 1.5 m is composed of backset bed couplets (dipping $\sim$15–35° upflow) of normally graded, sandy-matrix-supported medium-grained to fine-grained gravel and openwork gravel. In addition, numerous boulders mantle the bedforms and have their long axes strongly orientated transverse to flow (i.e., deposited during traction transport). Deep scours occur in the troughs of some antidunes (Figures 3.3A and 3.4), suggesting late-stage erosion by vertical flow vortices (e.g. Baker and Komar 1987). Bedforms in the upflow part of the field are the product of phases of erosion and deposition associated with rapid and spatially varying water depth and velocity induced by the topography of the bedforms. Downflow the bedforms increase in size (#4, Figure 3.5), and are composed of gravel backset beds (Figure 3.6). The increase in flow depth and hence accommodation space may explain the apparent downflow transition into fully depositional antidunes. Flutes (Figure 3.3B) ornament these downflow antidunes, indicating late-stage erosion by longitudinal flow vortices (e.g. Pollard *et al.*, 1996). Steep stoss slopes (Figure 3.3B) may have been oversteepened through erosion by roller vortices developing at these upflow-facing steps. The rapidly receding floodwaters led to both the creation and preservation of this antidune field. From Equations (3.3) and (3.4) and the range of antidune

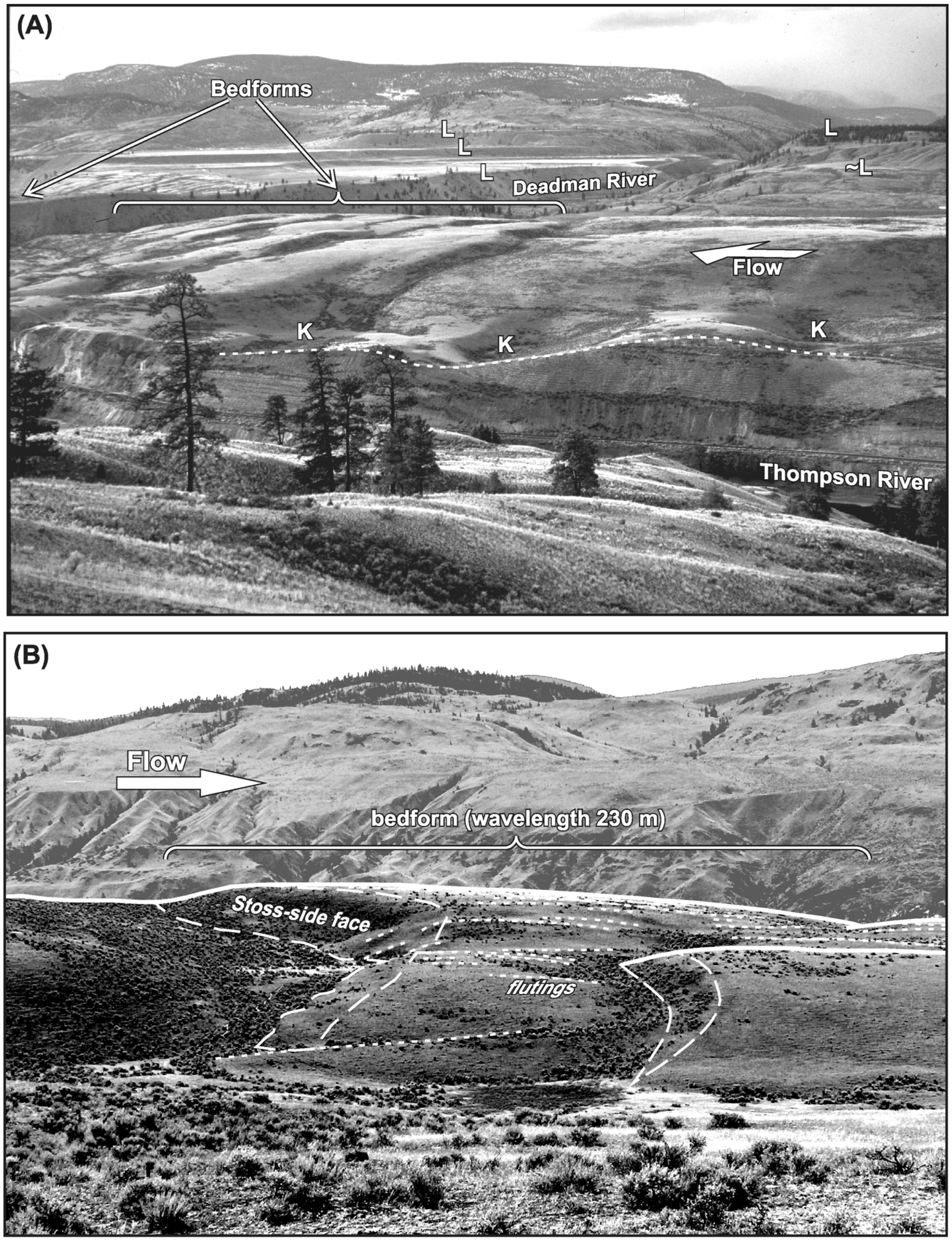

Figure 3.3. Antidune bedforms on the distal portion of Deadman delta produced during catastrophic drainage of glacial Lake Deadman, British Columbia, Canada (Johnsen and Brennand 2004). (A) Bedforms in the upflow (eastern) portion of the field (1–3, Figure 3.5). L, inset delta levels; K, kettle or scour holes. (B) The largest antidune (4, Figure 3.5) in the downflow (western) portion of the field. Note the steep stoss slopes and superimposed flutings (flute residuals).

wavelengths in the field, the minimum water depth during antidune formation was ~16 to 36 m (consistent with computer-modelled water depths) and the flow velocity was ~13 to 19 $m\,s^{-1}$.

Rice *et al.* (2002b) proposed that linear features, observed on the floor of the Athabasca Valles, on Mars, are transverse ribs based on plan-view morphometric analysis of a MOC image and comparison with the Icelandic features noted above. The transverse rib average wavelength, in this region 14 of Mars, is 53.6 m; rib height at that time could not be determined. Rice *et al.* (2002b) applied Equation (3.2) to the Martian features in order to calculate and constrain the velocity, depth and Froude number of the floods and obtained the following results: mean velocity of 6 $m\,s^{-1}$; flow depths ranging from a minimum of 5.5 m to a maximum of 19 m. Froude numbers ranged from 0.7

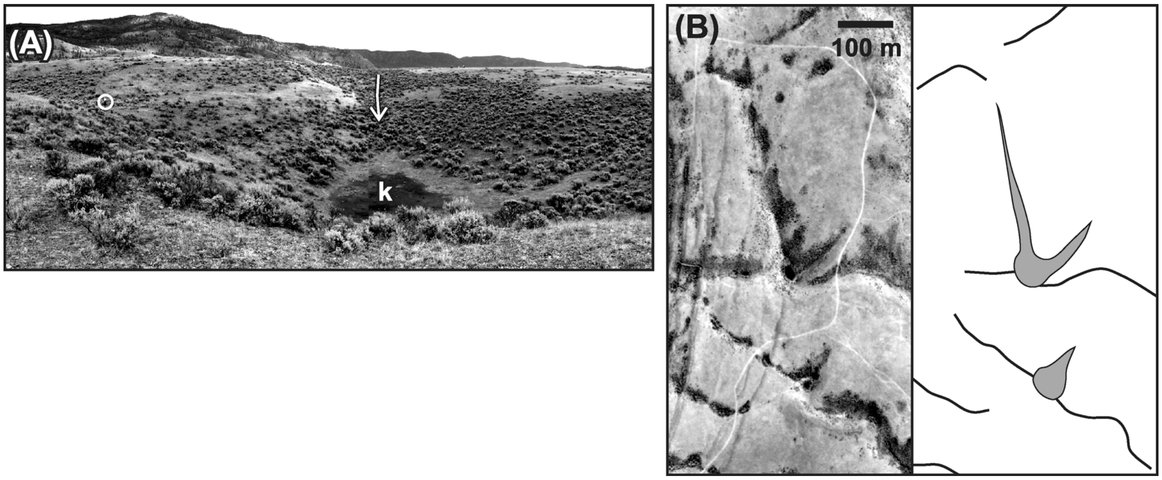

Figure 3.4. (A) Large scour (k) cut into the trough of an antidune in the upflow part of the field (upper scour in B). An associated large groove (arrow) deepens downflow into the scour. A second groove enters obliquely from the right side of the photograph. Person (circled) for scale. (B) Aerial photograph and interpretive sketch of 'scours' (shaded). Solid lines are bedform troughs. Flow from top.

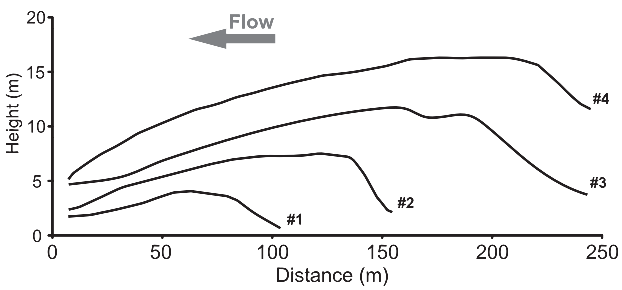

Figure 3.5. Comparison of streamwise long profiles of select bedforms on Deadman delta (5× vertical exaggeration). Average length:height is 30.3, standard deviation is 2.0.

Figure 3.6. Gravely backset beds below the crest of an antidune in the downflow and downslope part of the field. True dips of beds are solid lines and apparent dips are dotted lines. Person is holding a 1 m stick.

to 1.3, which is the range associated with an antidune flow regime. These bedforms probably were deposited during the last and most recent flood through this region. This region of Mars has undoubtedly been subjected to multiple flood episodes (Parker and Rice, 1997). However, using additional MOC images and a photoclinometric technique to measure heights and landform slope angles, Burr *et al.* (2004) have challenged the interpretation of the Athabasca Valles features as antidunes (Rice *et al.*, 2002b), preferring a fluvial dune model. This reinterpretation is based on the clinometric data, which allowed detailed morphological profiles for the Athabasca Valles features to be developed, that were not available to Rice *et al.* (2002b). The analysis of Burr and colleagues shows that the bedforms are strongly asymmetric. Antidunes and transverse ribs are usually symmetrical or show weak upstream or downstream asymmetry. In contrast, fluvial dunes are predominantly asymmetric with respect to the flow, displaying shorter and steeper lee sides in comparison with the longer and less steep stoss slopes (Allen, 1984).

Alt (2001) argues that some of the largest bedforms in the Camus Prairie, Washington State, USA, are antidunes based on their size (height < 10.7 m; wavelength < 91 m) and asymmetry; having their steepest slopes facing upstream. The specific location is also relevant to the interpretation. The bedforms are on steep terrain just downstream of a divide-crossing marked by Markle Pass and Wills Creek Pass between Little Bitterroot Valley and the Camus Prairie. Alt further argues that the stratigraphy illustrated in Pardee (1942) is typical of antidunes. In such a location, the bedforms would readily be preserved as the flood flow would stop abruptly when the water level fell below the level of the passes.

Spectacular putative antidunes occur in the Chuja basin and have been associated with the Altai megafloods

Figure 3.7. Oblique aerial photographs of dunefields produced by catastrophic drainage of Neoglacial Lake Alsek, Yukon, Canada (Clague and Rampton, 1982). (Photographs courtesy of John Clague.)

(Carling *et al.*, 2002; Herget, 2005) but these appear to be erosional features with only a veneer of deposited sediment (see Carling *et al.*, this volume Chapter 2).

3.4.3 Dunes

Well-known examples of large-scale dunes associated with Quaternary megafloods are described by Baker (1973a), Carling (1996a, b), Carling *et al.* (2002) and Clague and Rampton (1982) (Figure 3.7). These examples are developed in cobble-sized gravel and most reports of palaeodunes are from gravel deposits (Carling, 1999). Other published examples of 'fossil' fluvial dunes are less studied than the Missoula and Altai dunefields (see references in Carling, 1999; Carling and Breakspear, 2007) and in some cases the identification as dunes is not verified by detailed study or is disputed (see Munro-Stasiuk and Shaw, 1997; Evans *et al.*, 2006). Other putative palaeodune fields are as follows. Malin (1986) describes enigmatic large 'duneforms' from Antarctica in fine-grained sediments, which he argues could be waterlain deposits. The problem with the latter interpretation is that they occur throughout the TransAntarctic Mountains, occasionally at or near the summits of mountains, without obvious attendant fluvial features. Alternative explanations are that these bedforms are aeolian (Malin, 1986) or formed by subglacial sheetflow (Denton *et al.*, 1984).

On Earth, large-scale dunes related to megafloods are probably more common than the literature would suggest but remain to be identified. For example, Andrea Pacifici of the International Research School of Planetary Science (IRSPS), Italy and one of the authors (PAC) have identified probable long-wavelength 'fossil' fluvial dunefields formed in coarse gravel on the floodplain of the Santa Cruz River at Condor Cliffs, Patagonia, Argentina, downstream of the ice-dammed water body Largo Argentino that is subject to outbreak floods (Pacifici, 2009). These bedforms are visible in satellite images but, being of very low amplitude, are difficult to locate in the field. Schoeneich and Maisch (2003a, b) describe and illustrate 40 m wavelength, 0.5 m high gravel dunes, which they relate to a late glacial outbreak flood near Davos, Switzerland.

The identification of landforms as dunes is significant as dunes can only form in subcritical flow conditions, which prescribes estimates of flow velocities and Froude numbers. Bedform asymmetry may indicate flow direction whilst the width of the dune field may indicate a minimum width of the palaeoflow field. Flow depths clearly cannot have been less than the height of the dunes, and average flood flow depths often scale with dune heights and/or dune wavelengths (Allen, 1984). Thus, a wealth of important palaeohydraulic data may be deduced from the geometry of palaeodunes, which can be of great assistance in estimating flood discharges (e.g. Carling, 1996b).

The most clearly evident depositional bedforms on Mars are sedimentary dunes. The greater majority of these must have formed subaerially as aeolian features. However, dune-like forms seen in the Maja Valles and Athabasca Valles outflow channels have been interpreted as potentially subaqueous in origin (Chapman *et al.*, 2003; Burr *et al.*, 2004). The argument for the aqueous origin of the Maja Valles forms is their qualitative plan-view similarity to flood-formed dunes in the Jökulsá á Fjöllum outflow channel in Iceland (Waitt, 2002). As discussed above, an additional argument for the depositional nature of the Athabasca Valles forms is their dune-like morphology of steeper downslope and shallow upslope slope angles (Burr *et al.*, 2004), a characteristic shared with the gravel flood-dunes from the Altai megafloods (Carling, 1996a, b). However, in other similar channels, where Martian flooding is the suspected cause of erosion, there is a lack of evidence for dunes or other flood features. For example, Gjrotá Valles, which is very similar in age, origin, context and location to Athabasca Valles, does not show any such depositional bedforms (Burr and Parker, 2006).

3.4.4 Longitudinal ridges

A number of young Martian channels show several-kilometre long lineations parallel to the flow direction (Burr *et al.*, 2002; Ghatan *et al.*, 2005; Burr and Parker, 2006). Some of these lineations can be seen to be composed of metre-scale bumps or mounds suggested to be flood-deposited boulders, whose alignment is hypothesised to be due to longitudinal vortices (Burr *et al.*, 2002). Some of these bumps stand on pedestals above the surrounding channel floor and may represent glaciofluvial strata subsequently eroded by flooding (Gaidos and Marion, 2003). In either case, their origin is depositional, although the mechanism of deposition is distinctly different. On Earth, longitudinal ridges have been reported widely in sediments ranging from mud, through sand and gravel, but despite some laboratory studies, which indicate an origin owing to longitudinal vorticity, the exact mechanisms of initiation and maintenance of these bedforms remain ellusive (Williams *et al.*, 2008; Carling *et al.*, 2009).

3.5 Discussion and conclusions

Despite the detailed classification of channel-scale bedforms that can be developed for small modern river systems, relatively few types of large-scale depositional landforms have been described on Earth and Mars. The process-based understanding of how these features develop is therefore poor. Subaerial gullying and Rogen moraines can produce features that in plan view resemble giant fluvial dunes and some moraines and kame terraces can resemble giant flood bars. Consequently, care is required in identification and interpretation of landscape features, especially if they can only be considered remotely such as on Mars and the other planets. In some cases, as with large-scale transverse ridges, it is not clear if these are depositional features or erosional remnants of formerly more extensive gravelly-sand deposits. Every putative interpretation of landforms should consider alternative possibilities. This is especially important when the only information available is drawn from morphological planform data obtained using satellite or aerial photography. Recent studies often allow height data to be derived using techniques such as photoclinometry or shape-shading (Beyer *et al.*, 2003; Burr *et al.*, 2004). Where self-similar, spatially contiguous groups of bedforms occur then suites of morphological geostatistics, such as fractal properties, might help resolve the genetic origins of landforms, as some landforms are scale specific (Evans, 2003). However, further scales might also be present, induced for example by the presence of other flood-depositional bedforms (e.g. giant bars in Missoula and in the Altai floodways) as well non-flood features such as moraines, and these may overprint the signatures of bedforms. As far as is known, this geostatistical approach has not been applied to megaflood erosional landforms as usually within any one fluvial system the population of self-similar features is small (see Carr and Malin (2000) for a perspective). The features so far described exist at a range of scales, including the scale of the channel width. Thus, the issues of considering concepts of 'association' and whether the assumed nature of sediment transport and depositional processes are compatible with the suite of landforms present in any floodway requires closer attention.

In conclusion, although it can be difficult to couple models of fluid flow with sediment transport functions, it seems that simple rules can be applied with respect to whether sediment size fractions will be deposited in specific locations within complex channel geometries from bedload or from suspended load. As noted by Church (2006) and as explained in this perspective, such models can be forward or backward predictors such that better insight into megaflood landscapes will be derived from future consideration of the association landforms and the hydraulic controls.

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