Review on large scale gravel dunes caused by Pleistocene ice-dammed lake outburst floods

J. Herget(1) and P.A. Carling(2)

(1) Department of Geography, University of Bonn, Meckenheimer Allee 166, 53115 Bonn, Germany, e-mail: herget@giub.uni-bonn.de, telephone: #49-228-73-5398, fax: #49-228-73-9099 (corresponding author)
(2) Department of Geography, Highfield Southampton University, SO17 1BJ Southampton, United Kingdom, e-mail: p.a.carling@soton.ac.uk

Abstract

Gravel dunes generated by Pleistocene ice-dammed lake outburst floods seem to be among the largest channel bed features at all. Usually heights of several metres are observed while the largest example reaches a height of 23 m with are related length of 320 m. In this contribution a brief review on the appearance of these structures is given by the sole well investigated locations of Lake Missoula Flood in USA and Altai Mountains, Siberia. Reference to further more detailed studies and a sketch of previous palaeohydraulic interpretations are given.

1. Introduction

Within the variety of bedforms in the fluvial environment gravel dunes are among the largest features. Owing to comparative rarity of occurrence and limited investigations in flumes due to scale problems gravel dunes are rarely reported. A review on the state of knowledge is given e.g. by Carling (1999) and Wieprecht (2001). Even while sand dunes in large rivers like the Parana River, Brazil, have heights of about 4 m and lengths of about 200 m (Santos & Stevaux, 2000) these features are small compared with gravel dunes left over from catastrophic floods in Pleistocene times. Advanced ice shields and valley glaciers generated ice-dammed lakes at several locations worldwide (Baker, 1997). When the ice dams failed, giant floods occurred and occasionally formed gravel dunes of extraordinary dimensions, depending on the topographic conditions of the floods' pathways.

In this review paper, a brief introduction on selected Pleistocene ice-dammed lake outburst floods and the related gravel dunes is given. Pleistocene ice-dammed lakes with outburst floods are numerous (Herget, 2002), but related gravel dunes are only found and investigated for a few events. Hence, a focus is laid on the better documented Pleistocene floods which occurred in northwestern USA (Missoula Flood) and mainly in southern Siberia (Altai Mountains). Previous investigations are summarized while the presentation of new data from Altai Mountains with specific potential for the reconstruction of the flood dynamics is the key subject of the contribution to the workshop. Hence, to keep clarity the description of the left over gravel dunes is separated from palaeohydraulic interpretations.

2. Gravel dune description

2.1 Lake Missoula Flood

Between 16-12 ka BP the Cordilleran Ice Sheet, which blocked the complex valley system in northern Idaho, gave way for a giant outburst flood from the ice-dammed Lake Missoula, named after a town in northern Montana (Baker and Bunker, 1985; Alt, 2001). The maximum lake elevation was 1265 m with a related maximum volume of nearly 2200 km^3. The peak discharge of the flood is estimated as $>17^{x}10^{6}$ m^3/s (O'Connor & Baker, 1992), but varied along the flood's pathway due to the complex topography with several locations of temporary ponding.

Based on previous studies, Baker (1973 and 1978) investigated several of the more than 100 "Giant Current Ripples" trains in some details. The number of individual gravel dunes surveyed in the various trains varied from 3 to 25 and resulted in an empirical relation of average height $\overline{H}$ to average chord $\overline{B}$ as

$$\overline{H} = 0.0029\,\overline{B}^{1.50}$$

with a variety in individual height H_i of 0.5 m < H_i < 15 m and in individual chord B_i of 18 m < B_i < 200 m. The steeper slope of the relationship is explained by coarser sediments compared with other relations. Equation (2) from Allen (1968) and (3) determined by Ashley (1990) are derived from datasets dominated by dunes in sandy fluvial environments and flume experiments.

$$\overline{H} = 0.074\,\overline{B}^{0.77}$$

$$\overline{H} = 0.16\,\overline{B}^{0.84}$$

Note that partly the height of dunes from the Missoula Flood is underestimated due to younger accumulation of loess in the swales between the dune crests. Also some modification are expected to have occurred during the waning flood stages and by post-flood erosional processes. In plan view the dunes are of 2-D character. The dune fields extent of distances of several kilometres in length but usually not more than one kilometre in width.

The gravel dunes show the characteristic pattern of steep lee-sides (about 12°-25°) and gentle stoss-slopes (about 3°-12°). The slopes increase with gravel dune height. Due to the dimension of the features only limited data about their internal structure is available. Cross-strata visible in several pits are apparently dipping parallel to the steep lee-sides with angles varying from 10°-27°.

The median grain size of dune sediments occurs in the pebble fraction while occasionally boulders with diameters of more than 1.5 were found. Less than 10 percent of the sediments are as fine as granule gravel. The coarsest fraction of the sediments (boulders and cobbles) usually from an armor on the dunes' stoss slopes. The armor consists of imbricated pavement that probably acted to decrease flow resistance on the dune surface during waning stages of the flood.

2.2 Outburst floods in Altai Mountains

In the Altai Mountains the valley glaciers extended during Pleistocene time and blocked e.g. at the village of Aktash the course of the River Chuja, one of the sources of the Ob River. During the maximum stage of the glaciation the ice-dammed lake inundated the intramountainous basins of Kuray and Chuja, which are located close to the modern time border to Mongolia (Rudoy and Baker, 1993; Baker et al., 1993; Carling et al., 2002). Based on evidence by shorelines and dropstones the lake reached a maximum level of 2100 m with a related depths of up to 650 m. The maximum volume was about 607 km³. Approximately between 28-20 ka BP the ice dam failed and rebuilt repeatedly and gave way to at least three giant outburst floods along the valleys of Chuja and Katun River. Giant bars deposited at local enlargements of the valley and in the mouths of tributaries indicate depths of flow of up to nearly 400 m in upper Chuja valley and about 250 m in the wider valley of Katun River downstream. By various approaches peak discharge is estimated as about $10^{x}10^{6}$ m³/s with typical flow velocities in the magnitude of about 30 m/s and more (Herget, 2002).

Gravel dunes are found at several places along the floods' pathway and within the former lake bottom. Previous descriptions (Carling, 1996 a; Herget, 2002) can be updated in this paper by unpublished data based on additional fieldwork. Data on the dune fields given in table 1 can be summarized as follows:

Location	**Height, H_i**	**Length, L_i**	**Median grain size**	**2-D / 3-D dunes**
Kam-Sug	1.3 – 4.0 m	43 – 59 m	5 – 8 cm	2-D
Chagan-Uzun	6.3 – 23.0 m	139 – 320 m	~20 – 25 cm	2-D
Kuray	1 – 16 m	30 – 200 m	3.5 – 20 cm	2-D
Akturu	0.3 – 4 m	23 – 220 m		2-D
Upper Baratal	0.6 – 2.0 m	30 – 46 m	~4 cm	2-D
Lower Kara Kol	max. 3 m	max. 70 m	~1 cm	2-D / 3-D
Upper Kara Kol	1.4 – 4.5 m	15 – 84 m	3.5 – 20 cm	3-D
Little Jaloman	max. 3 m	max. 38 m	(max. 20 cm)	3-D
Platovo	1.65 – 2.8 m	44 – 89 m	~10 cm	2-D
Kongay	1 – 4 m	45 – 80 m		2-D
Ak-Koby	1 – >6 m	35 – 93 m	1 – 2 cm	2-D
Zamulta	1 – 5 m	mean 63 m		2-D

Tab. 1 – Data on fluvial gravel dunes in Altai Mountains, Siberia

Most of the Pleistocene gravel dunes in this area are of 2-dimensional transverse character while the 3-D trains consist of cuspate and lunate dunes. Heights of the dunes reach up to maximum values of 23 m with related lengths of 320 m (Fig. 1) which seem to be the largest fluvial dunes described yet. More frequent are lower values for heights of 4 – 6 m and lengths of 50 – 70 m which are not everywhere obvious due to post-flood loess deposition in the swales of the dunes. Based on a previous dataset from Altai Mountains and considering surveyed dunes along the pathway of Lake Missoula Flood a relationship of dune height $\overline{H}$ to dune length $\overline{L}$ is developed (Carling, 1996 a)

$$\overline{H} = 0.0073\overline{L}^{1.50}$$

The algebraic similarity of the equations (1) and (4) is obvious.

The morphology of the 2-D transverse dunes is best described by the example of Kuray dune field. The crests are straight or slightly sinuous. The slopes of lee sides vary from 3° for small dunes up to 17-19° for larger ones. Stoss slopes are typically 3-10°. Missing sections and the dimensions of the dunes limit information on the internal structure of the dunes and prevent successful explorations. Within the largest dune at Kuray, cross-bedded foresets dipping down-current are ubiquitous. Beds on the lee side dip parallel to the slope at 15-16°. The thickness of individual beds is 10-15 cm for cobbles and up to 10 cm for occasional pebbles. Based on local topographic conditions the dune field near Chagan-Uzun probably consists of antidunes.

At the 3-D barchanoid dunes of Little Jaloman more complex pattern are found. Beds dip down-current at variable angles even within individual dunes such that bedding is quasiparallel for short distances but often fades out. For example, in one section dips range between 11-38° while about 13° is a frequent value and also represents the preserved lee slope angle.

Fig. 1 – Gravel antidunes (?) near Chagan-Uzun in Altai-Mountains, Siberia
Note coarse sediments of the 23 m high dune in front (car for scale)

More complex are the sedimentary structures of the three dunes fields located upstream of the confluence with Chuja River in the valley of the River Katun (last locations in table 1). E.g. the dunes at Ak-Koby show a characteristic dipping of 14° upstream against the slope of the valley. This fact is interpreted as indicator for the flood wave from the outburst flood moving upstream Katun valley from the confluence with Chuja River. In Kongay the situation is more complicated. In one of the dunes beds in the lower part consisting of gravels and silts dip upstream Katun River by about 22° while sediments above dip downstream the valley indicating the backwash-effect of reversal flow. This sedimentary structures support the idea of flood water reaching Uimon-Basin from the outburst in Chuja valley, stay in the basin for some time and deposit silty layers of lake sediments before flowing back according to the slope of the valley when the water levels downstream decreased after the flood.

The spans of the dune fields reach values of up to 2400 m (Kuray), but incised river channels of occasionally destroyed parts of them. Some of the dune fields were developed on plateaus of steep mountain slopes which limits their lateral extension. Depending on these topographic limits dune fields developed over several kilometres mainly in locations of the former lake bottom (e.g. Kam-Sug, Kuray but also in the wide valley of Katun River) or extent only over a few hundreds of metres along mountain slopes (Baratal, Lower Kara Kol).

2.3 Other attempts and investigations

Several examples of Pleistocene and modern times outburst floods are described in the literature. Accumulated bedform features are rarely found and analysed. In most cases local topographic conditions, especially too narrow valley conditions, seem to be the main reason for missing gravel dunes.

One exception is currently described from Grisons in the Swiss Alps near Filisur (Schoeneich and Maisch, 2003). About 16-15 ka BP the ice dam of the Great Lake of Davos failed and gave way for an outburst flood in western direction. After the flood passed a narrow valley branch of about 15 km length the water reached the wider valley of Albula River and generated distinct "Megaripples" of some 40 m wavelength and 0.5 m height on a river terrace. Unfortunately no further details are known yet, but investigations on the gravel dunes seem to continue.

3. Palaeohydraulic interpretation

Bedforms are frequently used as indicators of palaeoflow conditions. Even though the dependence of fluvial dunes on hydraulics is quite complex, equations describing the relations are derived on physical and empirical base. The degree of consideration of the factors of influence – water depth, slope, particle size and shape, particle sorting, specific gravity of the grains, density and viscosity of the water-sediment mixture, shape of channel – varies and usually not all data for palaeoflow reconstruction can be obtained from field evidence quantitatively. Additionally most of the previous studies are carried out for sediments finer than the gravels forming the dunes of the two areas described above. Hence, the transformation of empirical relationships soon reaches its limits.

For the palaeohydraulic interpretation of the gravel dunes generated by Lake Missoula Flood flow conditions are derived from other evidence and used to explain the characteristics of the dune fields (Baker, 1973 and 1981). E.g. palaeostage indicators were used to determine flow velocity and stream power by slope-area calculations. Problematic on this approach is the assumption that palaeostage indicators are generated at the same stage of the flood as the accumulation of the gravel dunes nearby began or even reached equilibrium stage. The modification of the dunes' shape during waning stages of the flood is already mentioned before.

In Altai Mountains the well investigated dune field in Kuray Basin is used for preliminary modeling of the dune generating flow conditions (Carling, 1996 b). The palaeohydraulic model for the estimation of flow velocity and discharge based on the gravel dunes of Kuray Basin is characterized as preliminary, as further refinement and testing seems to be needed. An important source of information for the model are the process studies by Dinehart (1992) on the evolution of coarse gravel bedforms. Mainly based on physical concepts by considering grain and form roughness and flow separation in the wake of the modeled dune, Carling transfers the observations on several stages of the generation of the largest gravel dune of Kuray dune field. He derives flow velocities in the magnitude of 1.5 – 8 m/s, resulting in discharges of $2x10^4$ m³/s to $7.5x10^5$ m³/s over the span of the dune field. Obviously, these values are significantly below those for peak discharge conditions mentioned above. These difference documents, that the flow draining the lake area within Kuray Basin is not related to peak discharge downstream.
Even though the model was developed for cases of limited input data, it cannot be applied for the other dune fields in Altai Mountains mentioned above, as important variables cannot be quantified. The main problem are detailed representative grain size data for the gravel dunes, as flow competence, grain shapes and form factors of the dunes are key elements.

Another simplistic approach is developed for gravel dunes considering the lack of several data. By assuming that the empirical relationships of dune shapes to depth of flow derived in fine grained fluvial environments can be applied for coarse sediment bedforms at least for magnitudes of flow, an equation for estimating depth of flow over large bedforms (Zanke, 1982) is applied (Herget, 2002). This approach results in ranges of plausible flow velocities (5-10 m/s) and depths of flow above the dune crests (6-80 m) and requires only data on dune height and length, the maximum grain size and the span of the dune field to finally derive a magnitude of discharge related to dune generation. For Kuray dune field discharge values of comparable magnitude ($8.6\text{-}13.4x10^5$ m³/s) like by physical based approach mentioned above are derived.
The aim of the presentation of the palaeohydraulic interpretations of gravel dunes is to discus perspectives of further approaches with the audience focusing on limited data availability.

Acknowledgment

The authors are grateful to Dr. S. Parnachov and Dr. P. Borodavko (Tomsk State University) for joint field work in Altai Mountains. J. Herget thanks the German Research Foundation for financial support on the research in Siberia (DFG: HE 3006/3-1). P. Carling thanks the Royal Society of London and the Royal Geographical Society for financial support.

References

J.R.L. Allen, Current ripples – their relation to patterns of water and sediment motion, Amsterdam (North-Holland Publishing Co.), pp. 1-433, 1968.

D. Alt, Glacial Lake Missoula and its humongous floods, Missoula (Mountain Press Publishing Company), pp. 1-197, 2001.

G.M. Ashley, Classification of large-scale subaqueous bedforms – a new look to an old problem. *J. of Sed. Petr.*, Vol. 60, pp. 160-172, 1990.

V.R. Baker, Paleohydrology and sedimentology of Lake Missoula flooding in eastern Washington, *Geological Society of America Special Paper*, Vol. 144, pp. 1-79, 1973.

V.R. Baker, Large-scale erosional and depositional features of the Channeled Scabland, in: V.R. Baker and D. Nummedal (eds.), *The Channeled Scabland*, Washington (NASA), pp. 81-115, 1981.

V.R. Baker, Megafloods and glaciation, in: I.P. Martini (ed.), *Late glacial and postglacial environmental changes – Quaternary, Carboniferous-Permian and Proterozoic*. New York (Oxford University Press), pp. 98-108, 1997.

V.R. Baker and R.C. Bunker, Cataclysmic late Pleistocene flooding from Glacial Lake Missoula – a review, *Quaternary Science Reviews*, Vol. 4, 1-41, 1985.

V.R. Baker, G. Benito and A.N. Rudoy, Paleohydrology of Late Pleistocene superflooding, Altay Mountains, Siberia, *Science*, Vol. 259, pp. 348-350, 1993.

P.A. Carling, Morphology, sedimentology and palaeohydraulic significance of large gravel dunes (Altai Mountains, Siberia), *Sedimentology*, Vol. 43, pp. 647-664, 1996 a.

P.A. Carling, A preliminary palaeohydraulic model applied to late Quaternary gravel dunes (Altai Mountains, Siberia), in: J. Branson, A.G. Brown and K.J. Gregory (eds.): Global Continental Changes – the context of palaeohydrology, *Geological Society Special Publication,* Vol. 115, pp. 165-179, 1996 b.

P.A. Carling, Subaquaeous gravel dunes, *J. of Sed. Res.,* Vol. 69 (no. 3), pp. 534-545, 1999.

P.A. Carling, A.D. Kirkbride, S.V. Parnachov, P.S. Borodavko and G.W. Berger, Late-Quaternary catastrophic flooding in the Altai Mountains of south-central Siberia, in: P.I. Martini, V.R. Baker and G. Garzon (eds.), Flood and megaflood processes and deposits: recent and ancient examples, *International Association of Sedimentologists, Special Publication,* Vol. 32, pp. 17-35, 2002

R.L. Dinehart, Evolution of coarse gravel bed forms – field measurements at flood stage, *Water Resources Research,* Vol. 28, pp. 2667-2689, 1992.

J. Herget, Reconstruction of Pleistocene ice-dammed lake outburst floods in the Altai Mountains (Siberia), (unpublished habilitation thesis at the Faculty of Earth Sciences, Ruhr-University Bochum – submitted for publication at the Geological Society of America), pp. 1-175, 2002.

J.E. O'Connor and V.R. Baker, Magnitudes and implications of peak discharges from glacial Lake Missoula, *Geological Society of America Bulletin*, Vol. 104, pp. 267-279, 1992.

A.N. Rudoy and V.R. Baker, Sedimentary effects of cataclysmic late Pleistocene glacial outburst flooding, Altay Moutains, Siberia, *Sedimentary Geology*, Vol. 85, pp. 53-62, 1993.

M.L. Santos and J.C. Stevaux, Facies and architectural analysis of channel sandy macroforms in the upper Parana river, *Quaternary International,* Vol. 72, pp. 87-94, 2000.

P. Schoeneich and M. Maisch, A lateglacial megaflood in the Swiss Alps – the outburst of the Great Lake of Davos, in: L.L. Ely, J.E. O'Connor and P.K. House (eds.), *Third international paleoflood workshop abstracts* (1.-7.8.2003, Hood River, Oregon), p. 38, 2003.

S. Wieprecht, Entstehung und Verhalten von Transportkörpern bei grobem Sohlenmaterial, *Mitteilungen des Instituts für Wasserwesen der Universität der Bundeswehr München*, Heft 75, pp. 1-142, 2001.

U. Zanke, Grundlagen der Sedimentbewegung, Berlin (Springer), pp. 1-264, 1982.