



From cyclic steps to humpback dunes: bedforms created by glacial lake-outburst floods

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The largest known terrestrial floods, with immense geomorphological impacts, are linked to flood events from sub- and proglacial lakes. Flows are commonly unstable, turbulent and may be pulsed. The most commonly reported flood-related sedimentary landforms are large bars and (anti)dune fields deposited at sites of spatial flow deceleration. However, the facies architecture of these flood-related deposits has not yet been described in much detail. Reported field examples include sandy and gravelly bedforms that comprise laterally and vertically stacked deposits of cyclic steps, chutes-and-pools, breaking antidunes, stationary antidunes, plane beds and humpback dunes. The dimension and stacking pattern of described bedforms are often very similar and indicate deposition under highly aggradational flow conditions.

Deposits of cyclic steps are characterised by shallow, lenticular scours infilled by gently dipping backsets, indicating erosion and re-deposition on the downstream side of the step, which is Froude-supercritical. The cyclic-step deposits are laterally and vertically truncated and unconformably overlain by deposits of chutes-and-pools and (breaking) antidunes. Deposits of chutes-and-pools and breaking antidunes comprise lenticular scours infilled by steeply dipping backsets, gently dipping sigmoidal foresets and concentric trough-fills. Bedforms of the relatively slow moving subcritical zone on the upstream side of cyclic steps are commonly not preserved. In contrast to the gravelly cross-stratification of cyclic steps, chutes-and-pools and breaking antidunes, the (sub)horizontal lamination of transcritical bedforms (plane beds, stationary waves and antidunes) generally consist almost completely of sand, due to gravel overpassing.

Under waning flow conditions deposits of chutes-and-pools and antidunes form laterally more extensive bedsets that are interbedded with deposits of humpback dunes and 3D dunes. The gradual lateral and vertical facies changes between bedforms of antidunes and humpback dunes indicate the transition between supercritical and transcritical flow conditions, which are mainly controlled by bedform topography and the related hydraulic roughness.