



Interactions of rock avalanches and glaciers in high mountains, with particular reference to the Karakoram Himalaya, Inner Asia

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The paper shows how, when catastrophic rockslides descend on to glaciers, there are substantial modifications of ice activity, the landslide, and the fate of its debris. More than a dozen Holocene rock avalanches are identified which spread over Karakoram glaciers, probably a tiny fraction of actual numbers. Four events from the past 30 years, at Bualtar, Chillinji, Aling and Masherbrum Glaciers, strongly affected glacier movement, ablation, hydrology and sedimentation. The behaviour of the rock avalanche, its moisture content and patterns of deposition, were affected by travel over ice. In each case ice movement increased sharply at and below the rock avalanche deposits. In two cases, glacier surges followed within a few months. The surges modified rock avalanche material, rapidly carrying it several kilometers down-glacier. Massive disturbances of the landscape beside and beyond the ice occurred through slope failures, landslides, ponding at the ice-margin and out burst floods from sudden drainage. The events are problematic since investigations elsewhere suggest glacier surges are not triggered by external shocks. Results of monitoring at Bualtar Glacier since 1986 show the rock avalanche debris, covering about 7 km² of the ice, had been carried 8 km down the glacier by 2001. The debris has contributed significantly to ice margin deposition, but ablation-related reworking has made it less and less distinct from the ubiquitous heavy supraglacial moraine of the region's glaciers.

Four prehistoric events are identified that buried the termini of glaciers and sealed large, long-lived dams. Complex sequences of sedimentation, breaching and spillway erosion have left chaotic ice margin landscapes.

Prior to these investigations no rock avalanches had been recognised in the glacial

zone of the region, and very few beyond it. Their interactions with the ice cover have been a missing element in interpretations of the glacial geomorphology and Late Quaternary developments. The composite rock avalanche and glacier dams were formerly attributed to the glacier action alone, much as many prehistoric dams formed by rock avalanches were attributed to glaciers. Also, it had been assumed that the heavy supraglacial debris – a major factor in ablation, ice margin deposition, and the low altitudes reached by Karakoram glacier termini – depends mainly on the extent of avalanche nourishment. If, however, the incidence and behaviour of recent rock avalanches is at all representative of the Holocene, hundreds, possibly thousands, have descended on glaciers in the Karakoram and surrounding ranges. When they occur they make major contributions to supraglacial debris, dust generation and ice-margin sedimentation. Those discussed ranged in volume from $3 \times 10^6 \text{ m}^3$ to over $75 \times 10^6 \text{ m}^3$. The paper concludes with implications for relevant landslide and glacier modeling, and for hazard assessments here and in other high mountain areas with a history of similar events.