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Processes of annual moraine formation at a temperate alpine valley glacier: glacier dynamics and climatic controls

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This paper presents the first detailed sedimentological study of annual moraines formed by an alpine valley glacier. The moraines have been formed since at least AD 1980 by a subsidiary lobe of Gornergletscher, Switzerland, that advances up a reverse bedrock slope. They reach heights of 0.5-1.5 m, widths of up to 6 m and lengths of up to several hundreds of metres. Sediments in these moraines comprise proglacial outwash and debris flow units; subglacial traction till is absent entirely. Based on four representative sections, three genetic process combinations have been identified. (1) Inefficient bulldozing of a gently-sloping ice margin transfers proglacial sediments onto the ice, causing differential ablation and dead-ice incorporation upon retreat. (2) Terrestrial ice-contact fans are formed by the dumping of englacial and supraglacial material from point sources such as englacial conduit fills. Debris flows and associated fluvial sediments are stacked against a temporarily stationary margin at the start, and deformed during glacier advance in the remainder, of the accumulation season. (3) A steep ice margin without supraglacial input leads to efficient bulldozing and deformation of pre-existing foreland sediments by wholesale folding. Ice surface slope appears to be a key control on the type of process responsible for moraine formation in any given place and year. The second and third modes result in stable and higher moraines that have a higher preservation potential than those containing dead ice. Analysis of the spacing and climatic records at Gornergletscher reveal that winter temperature controls marginal retreat and hence moraine formation. However, any climatic signal is complicated by other factors, most notably the presence of a reverse bedrock slope, so that the extraction of a clear climatic signal is not straightforward. This study highlights the complexity of annual moraine formation in high-mountain environments and suggests avenues for further research.