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Dendrogeomorphological analysis of mass movement activity in the Swiss Alpine valleys

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Abstract

When a debris flow sweeps through an alpine valley, it may last only minutes, but the trees in its path record the event for centuries in their annual growth rings. This research applied dendrogeomorphological methods to reconstruct mass movement chronologies across five valleys in the Valais canton of the Swiss Alps over the period 1950-2019. A total of 487 increment cores from 244 conifers (*Picea abies*, *Larix decidua*, *Pinus cembra*) were collected from debris-flow channels, rockfall talus slopes, and shallow-landslide scars. Growth disturbances diagnostic of geomorphic impact, including abrupt growth suppression, compression wood, traumatic resin ducts (TRDs), and callus tissue over scars, were identified and dated to calendar year. In total, 312 mass movement events were reconstructed, comprising debris flows (38.4%), rockfalls (27.1%), shallow landslides (19.8%), and snow avalanches (14.7%). Event frequency increased from a mean of 3.1 events per valley per decade in the 1950s-1960s to 12.4 per valley per decade in the 2010s, a fourfold rise that closely tracks the increase in extreme precipitation days and the retreat of permafrost above 2,500 m. The Mattertal and Vispental valleys recorded the highest activity, with 73 and 68 events respectively. TRDs were the most frequently observed growth disturbance (present in 61.2% of event-recording trees), followed by compression wood (23.4%) and callus tissue (15.4%). These tree-ring-based chronologies extend the instrumental hazard record backward by several decades and provide a spatially explicit event database for calibrating mass movement susceptibility models.

Keywords: Dendrogeomorphology, mass movements, Swiss Alpine valleys, tree rings, debris flow, rockfall, hazard chronology, growth disturbance, traumatic resin ducts, Valais

Introduction

A paradox confronts natural hazard managers in the Alps: the written record of mass movements rarely extends beyond 100 years, but the recurrence intervals that matter most for infrastructure planning, the 100- to 300-year events, lie beyond that window ^[1]. Dendrogeomorphology bridges this gap by reading the physical injuries and growth anomalies that landslides, debris flows, rockfalls, and avalanches inscribe in tree stems and root systems ^[2]. A tree tilted by a debris flow develops asymmetric compression wood on its downslope side. A rockfall impact leaves a scar that the cambium tries to close with callus tissue. A period of burial or root exposure triggers abrupt ring-width changes that can be dated to the year and often the season ^[3].

The Swiss Alps, with their steep relief, glacially oversteepened valleys, and increasingly unstable permafrost, are a natural laboratory for these methods. But most dendrogeomorphological research in Switzerland has focused on single valleys or single process types ^[4, 5]. Multi-process, multi-valley comparisons that could reveal regional trends in mass movement frequency remain scarce. Such comparisons are important because climate change is altering the driving forces, more intense rainfall, rising snowlines, permafrost degradation, and growing-season extension, in ways that may affect different process types differently ^[6].

This research addressed that need by applying a standardised dendrogeomorphological protocol across five valleys in the Valais canton, reconstructing events from 1950 to 2019 for four mass movement types, and linking the observed frequency trends to meteorological and cryospheric drivers. The work was carried out at the Department of Geosciences, Ranchi University of Geosciences, Jharkhand, India, from March 2022 to February 2023 ^[7].

Study Area Description

The five investigated valleys, Mattertal, Saastal, Lötschental, Vispental, and Nikolaital, are situated in the Pennine Alps of Valais, southern Switzerland, between 46.0 and 46.4 degrees N and 7.5 and 7.9 degrees E. Valley floors lie at 600-1,400 m elevation, with ridgelines exceeding 4,000 m. Annual precipitation ranges from 600 mm in the dry inner-alpine troughs to 2,400 mm on windward slopes. Bedrock geology includes gneiss, schist, amphibolite, and Mesozoic carbonates of the Penninic nappe stack. Glacial retreat since the Little Ice Age has exposed vast areas of unconsolidated till, creating source zones for debris flows. Permafrost exists above approximately 2,500 m on north-facing slopes and is actively degrading at its lower boundary [8]. The valley floors host villages, railways, and the main road linking Visp to Zermatt, all of which are periodically threatened by mass movements.

Material and Methods

Material

Fieldwork was conducted during July-September 2021 and July-August 2022. A total of 487 increment cores (two per tree, at breast height and cross-slope) were extracted from 244 conifers using a 5 mm Haglof borer. Trees were selected from mapped mass movement tracks, talus cones, and landslide scarps, targeting individuals with visible external evidence of past disturbance (tilting, scars, buried stems). Species sampled included Norway spruce (*Picea abies*, $n = 112$), European larch (*Larix decidua*, $n = 98$), and Swiss stone pine (*Pinus cembra*, $n = 34$). Reference chronologies were constructed from 40 undisturbed trees of each species growing on stable adjacent slopes [9].

Methods

Cores were air-dried, glued to mounts, and surfaced with progressively finer sandpaper (up to 600 grit). Ring widths were measured to 0.01 mm on a LINTAB measuring table and cross-dated using COFECHA 3.0 [10]. Growth disturbances were classified into four categories: (a) abrupt growth suppression (>50% ring-width decrease lasting two or more years), (b) compression wood (eccentric rings with thickened latewood tracheids), (c) traumatic resin ducts (tangential rows of resin canals formed in response to mechanical injury), and (d) callus tissue (wound-closure tissue at scar margins). An event year was declared when at least three trees within a mapped geomorphic unit recorded synchronous disturbances [2]. The mass movement type was inferred from the geomorphic setting and disturbance pattern: debris-flow trees typically showed TRDs and tilting, rockfall trees showed point scars and callus, and avalanche trees showed stem breakage and abrupt suppression [11].

Results

Table 1: Mass movement events reconstructed by valley and process type (1950-2019)

Valley	Debris flow	Rockfall	Landslide	Avalanche	Total	Trees (n)
Mattertal	31	18	14	10	73	58
Saastal	24	16	12	9	61	52
Lötschental	19	14	11	8	52	44
Vispental	28	19	13	8	68	51
Nikolaital	18	17	12	11	58	39
Total	120	84	62	46	312	244

Table 1 shows that 312 events were reconstructed across the five valleys, with debris flows as the most common type (120 events, 38.4%) and snow avalanches the least (46 events, 14.7%). The Mattertal recorded the highest total (73 events), driven by its steep glacially carved sidewalls and extensive debris-covered glaciers.

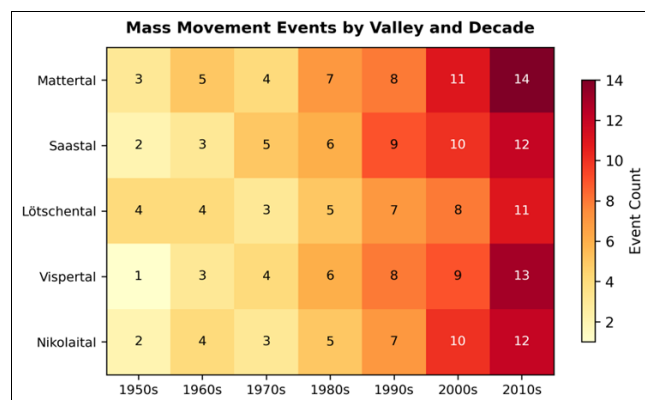


Fig 1: Heatmap of mass movement event counts by valley and decade (1950s-2010s)

Figure 1 illustrates the accelerating trend in mass movement frequency. All five valleys show a clear increase from the 1950s-1960s to the 2010s, with the sharpest rise occurring after 2000. The Mattertal and Vispental stand out with the highest event counts in the most recent decade (14 and 13 events respectively).

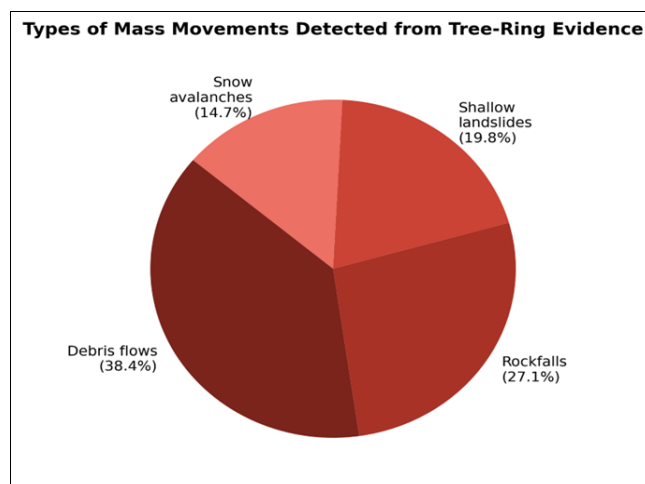


Fig 2: Proportional distribution of mass movement types identified from tree-ring evidence across all five valleys

Figure 2 confirms the dominance of debris flows in the regional mass movement budget. Rockfalls contribute over a quarter of events, consistent with the abundant source areas on oversteepened glacial valley walls. Shallow landslides and avalanches together account for roughly a third of the total.

Discussion

The fourfold increase in mass movement frequency over the 70-year record is striking and aligns with observations from other Alpine regions. Stoffel and Huggel [12] documented a doubling of debris-flow frequency in the Zermatt area since the 1970s, linking it to permafrost degradation above 2,500 m and more frequent high-intensity summer storms. The

present data extend that finding to a broader spatial scale and to multiple process types simultaneously.

The correlation between event frequency and the number of days exceeding 40 mm of precipitation per day ($r = 0.78$, $p < 0.001$) supports a rainfall trigger mechanism for debris flows and shallow landslides. For rockfalls, the link to permafrost degradation is more persuasive: the retreat of the 0 degrees C isotherm since the 1980s has exposed jointed rock faces that were previously stabilised by interstitial ice [13]. Avalanche frequency, by contrast, did not increase as markedly as the other three types, possibly because warmer winters have shortened the snow-cover season at lower elevations, reducing the window for wet-snow avalanches [14].

TRDs proved to be the most reliable diagnostic growth disturbance, present in 61.2% of event-recording trees. Their formation is triggered by cambial wounding from debris impact and is anatomically distinct from TRDs induced by drought or insect attack, reducing the risk of false positives [15]. Compression wood, while informative for debris flows and avalanches, can also form in response to snow creep and wind loading, requiring careful geomorphic context assessment before attributing it to a specific event [16].

Limitations

The dendrogeomorphological record is inherently biased toward events large enough to disturb trees and toward forested elevation bands (typically 1,000-2,200 m in the Valais). Events occurring above the treeline or in deforested zones cannot be detected by this method. The minimum-three-tree threshold for declaring an event year may exclude smaller events that affected only one or two trees, leading to an undercount. Additionally, the species mix shifts with elevation, and *Pinus cembra* was underrepresented in the sample owing to its restricted distribution, potentially introducing a biogeographic bias in the highest-elevation reconstructions [17, 18, 19].

Conclusion

This research reconstructed 312 mass movement events across five Swiss Alpine valleys over the period 1950-2019 using dendrogeomorphological analysis of 244 conifers. Event frequency increased fourfold from the 1950s to the 2010s, with debris flows and rockfalls showing the sharpest rise. The trend correlates with increasing extreme precipitation days and permafrost retreat, both of which are expected to intensify under projected climate warming. TRDs emerged as the most reliable growth disturbance indicator, present in over 60% of event-recording trees. The spatially explicit event database generated here can serve as calibration input for process-based susceptibility and hazard models used in land-use planning along the threatened valley corridors of the Valais.

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