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A Multi-Evidence Verification Protocol for Human-Triggered Avalanche Circumstances: Satellite Remote Sensing and Physical Consistency Checks at Palandöken Ski Area, Türkiye

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Abstract

Snow avalanches at ski areas are frequently linked to recreationists, yet a specific trigger is rarely verified independently. We present a multi-evidence protocol for verifying avalanche-trigger circumstances, applied to two avalanches outside the managed runs of the Palandöken ski area (Erzurum, Türkiye), 2024–2025 season: Sultan Sekisi (21 December 2024), reported in national media during athlete training on the release terrain, and Yusufun Deresi (15 February 2025), officially attributed by Erzurum’s municipality to skiers entering a closed area. Treating these documented circumstances as reference cases, we tested whether an independent reconstruction — combining terrain, meteorological, satellite, and Voellmy-Salm runout evidence — is physically consistent with human triggering at each site. At Sultan Sekisi, the terrain lay below the 30° spontaneous-release threshold, with no natural trigger in the preceding 72 hours, and forest-drag runout modelling reproduced the observed extent to within 25%. At Yusufun Deresi, terrain and snow-loading conditions alone were ambiguous and direct snowfall loading could not be quantitatively excluded; a windward wind configuration ruled out wind-transported loading specifically, while Sentinel-1/2 detected a robust, localised debris signature (SAR backscatter +1.01 dB, $p < 0.001$) confirming a disturbance at the documented location and time, though the runout model underestimated the extent (a 1-D limitation). The physical evidence at both sites is consistent with the documented circumstances; as satellite evidence indicates occurrence rather than trigger mechanism, it corroborates location and timing rather than the trigger itself. The protocol offers a transferable, open-data route for verifying avalanche-trigger circumstances at under-instrumented ski areas.

Keywords: Snow avalanche; Sentinel-1 SAR; Voellmy-Salm model; wind-slab formation; avalanche release zone; ski area hazard

1. Introduction

Snow avalanches are among the most consequential natural hazards in seasonally snow-covered mountain regions, and the great majority of avalanches that cause injury or death are released by the victims themselves or by a member of their own group rather than occurring spontaneously (Strapazzon et al. 2021). A recent systematic review and meta-analysis of backcountry avalanche fatalities confirms that asphyxia and trauma remain the dominant causes of death, underscoring that human presence in avalanche terrain — and not avalanche frequency alone — governs risk to life (Rong et al. 2025). This human dimension of avalanche risk is not expected to diminish under a warming climate: recent regional and global assessments converge on a broadly similar picture of declining dry-snow avalanche activity at low elevations, a growing share of wet-snow events, and persistent or even locally increasing risk at specific, exposed sites, even as overall activity trends downward (Eckert et al. 2024; Mayer et al. 2024; Ortner et al. 2025). Beyond the Alps, a tree-ring-based reconstruction of avalanche activity in the Western Himalaya similarly links climate warming to increased avalanche frequency, indicating that this pattern is not confined to a single mountain system (Ballesteros-Cánovas et al. 2018). Together, these studies indicate that understanding when and why a specific avalanche was released — including the extent to which human loading acted as the determining trigger — remains a pressing question even as broad-scale avalanche activity evolves under climate change.

The mechanics of human- or skier-triggered slab avalanche release have been studied since the introduction of the classical skier stability index, reviewed comprehensively by Schweizer et al. (2003), which modelled the additional stress imposed by a skier on a buried weak layer as a static load on an elastic slab, later refined to account for skier penetration depth into the snow cover (Jamieson and Johnston 1998) and validated against field data on snowpack and terrain properties at skier-triggered avalanche sites in Canada and Switzerland (Schweizer and Jamieson 2001). A probabilistic treatment building on these indices related the likelihood of skier-triggering directly to snowpack stability and the magnitude of the imposed load (Pfeifer 2009).

Subsequent work has shown that classical stability indices alone are insufficient predictors of triggering: the anticrack model demonstrated that fracture propagation, rather than local failure alone, governs whether a skier-induced collapse develops into a full slab avalanche (Heierli et al. 2008), a mechanism developed specifically for skier loading and further refined through

combined failure-initiation and crack-propagation criteria, a mixed-mode shear-compression failure criterion for weak layers, and instability indices that jointly account for weak-layer failure and slab tensile support (Heierli et al. 2011; Gaume and Reuter 2017; Reiweiger et al. 2015; Reuter and Schweizer 2018). A cluster of recent, closely related experimental and numerical studies has further refined how crack propagation is measured, arrested and can transition between regimes: the geometry of the propagation saw test itself measurably affects the critical cut length recorded, slab touchdown can arrest an otherwise propagating anticrack, and on steeper slopes a transition to supershear crack propagation has been identified through combined numerical and field measurements (Bergfeld et al. 2025; Rosendahl et al. 2025; Bobillier et al. 2025). Forensic application of these fracture-mechanical principles to historical, non-instrumented events has demonstrated that terrain and snowpack evidence alone can support retrospective reconstruction of avalanche release mechanisms (e.g. the 1959 Dyatlov Pass incident; Gaume and Puzrin 2021), a methodological precedent for the retrospective, evidence-based attribution approach pursued in the present study. This body of work establishes that whether a given slope releases under human loading depends jointly on terrain steepness, snowpack structure, and the magnitude of the imposed load, providing the physical basis for using terrain and meteorological reconstruction to assess the plausibility of natural versus human triggering at a site where direct snowpack observations are unavailable.

Establishing the physical plausibility of a human-triggered release does not by itself explain why people were present in the terrain where an avalanche occurred; a substantial literature on recreational risk-taking indicates that such presence typically reflects documented and measurable behavioural patterns rather than isolated or anomalous decisions. Positional and social factors have been shown to influence risk-taking in avalanche terrain, with backcountry riders' desire for social status associated with an increased willingness to take risk (Mannberg et al. 2020), and the widely adopted “heuristic traps” framework for explaining avalanche accidents has itself been critically re-examined, with calls for more rigorous empirical grounding (Johnson et al. 2020), as synthesised in a recent scoping review of this broader literature (Hetland et al. 2025). This behavioural literature does not itself form part of the physical evidentiary framework applied in the present study, which does not analyse decision-making directly; it is used here only to note that the two events examined below involve two distinct human-factor patterns rather than a single undifferentiated one — an apparently organised training activity at Zone-1, whose institutional authorisation this study cannot establish, and an individual boundary violation at Zone-2, for which an administrative

enforcement record exists — and that recreational risk-taking of both kinds is a documented, measurable pattern in avalanche terrain generally, rather than an anomalous circumstance requiring separate explanation at either site.

Wind-transported snow represents an important secondary loading mechanism distinct from human loading, and its formation has been characterised through both process-based modelling and long-term field monitoring: coupled snowpack–atmosphere models can now simulate wind-induced snow transport and sublimation in complex alpine terrain at the event scale (Vionnet et al. 2014), and multi-year meteorological monitoring in High Arctic Svalbard has related specific wind and temperature variables to the regional slab avalanche regime (Eckerstorfer and Christiansen 2011). This literature provides the physical basis for the wind-transport assessment applied in the present study to evaluate whether wind loading, rather than human loading, could plausibly explain the observed avalanches.

Terrain susceptibility to avalanche release has been extensively mapped using GIS-based multi-criteria methods, an approach with a well-established tradition in Turkish mountain regions. Eastern Türkiye, where the present study area is located, sustains a substantial and long-duration seasonal snow cover: field measurements at four high-elevation sites (2070–2600 m a.s.l.) in the region, including a site within the Palandöken massif itself, have documented snow depths approaching one metre and snow densities ranging from 192 to 424 kg/m³ during the accumulation season, with good agreement found among snow-pit, snow-tube and automatic Snow Telemetry (SnoTel) observation methods (Ertaş and Şorman 2024). Early documentation of avalanche incidents in north-western Anatolia already highlighted the interaction of topography, snowpack and settlement exposure in Turkish mountain terrain (Gürer et al. 1995), and this foundation has since been developed through systematic susceptibility mapping and back-calculation of historical events. A RAMMS-based back-calculation of two Turkish avalanche events found that 87% of avalanche fatalities in Türkiye occurred inside buildings rather than in open terrain, a markedly different exposure pattern from the recreational, open-terrain events examined here (Aydin et al. 2014). Combining slope, aspect, vegetation density, land-use and other terrain and meteorological factors within GIS-based multi-criteria decision frameworks, a series of studies has mapped avalanche susceptibility across several Turkish provinces — Bitlis, Van, the Uzungöl winter tourism area of Trabzon, and the Ayder resort area of Rize — with slope and elevation consistently emerging as the most heavily weighted susceptibility factors (Selçuk 2013; Nasery and Kalkan 2021; Varol 2022; Kurt 2022). More recently, the field has moved toward machine-learning-based

susceptibility mapping, applied for example via analytic-hierarchy-process modelling in the Šar Mountains of Serbia and ensemble tree-based learners in the Himachal Pradesh Himalaya (Durlević et al. 2022; Thakur et al. 2024). Most directly relevant to the present study, a short communication has recently documented the historical record of fatal avalanche events at Palandöken since 1974 and called for improved early-warning and safety-training measures (Torpuş et al. 2025), but did not undertake the terrain, meteorological or satellite-based analysis of individual events pursued here. While these susceptibility-mapping, snow-characterisation and historical-documentation studies robustly establish where avalanche-prone terrain exists, how the regional snowpack behaves, and that Palandöken has a documented avalanche history, none directly addresses the attribution of a specific, recently observed avalanche event to human triggering — the question motivating the present study.

Satellite remote sensing has become central to avalanche detection and monitoring at scales inaccessible to field survey. Sentinel-1 synthetic aperture radar (SAR) backscatter change detection has been used to map avalanche debris independently of daylight and cloud cover, combined where possible with optical imagery for validation, with detection performance consistently shown across multiple independent studies to depend strongly on avalanche size (Eckerstorfer and Malnes 2015; Eckerstorfer et al. 2019; Keskinen et al. 2022). Recent work has extended this approach through statistical prediction of avalanche danger informed by satellite-derived activity records (Eiselt and Graversen 2025). In parallel, optical Sentinel-2 imagery has been used for snow-cover characterisation in avalanche-relevant settings, including combined SAR-optical mapping of ice-avalanche-affected snow cover (Wang et al. 2018); snow-cover mapping via the Normalized Difference Snow Index (NDSI) rests on a well-established spectral basis (Salomonson and Appel 2004) and has been validated against independent snow-cover reference datasets in high-elevation Alpine catchments and against airborne lidar-derived snow cover across a spectrum of forest and terrain conditions (Hofmeister et al. 2022; Stillinger et al. 2023), with the broader state of mountain snow remote sensing recently reviewed by Gascoin et al. (2024). These studies collectively establish Sentinel-1 and Sentinel-2 as complementary tools for confirming pre-event snow-cover conditions and detecting post-event debris signatures, while also showing that detection reliability for SAR-based methods decreases markedly for small avalanches, a limitation relevant to interpreting satellite-based debris evidence for events of modest size.

Beyond satellite-based detection, statistical and machine-learning methods are increasingly used to support avalanche hazard assessment more broadly: random-forest and related

ensemble models have been used to predict avalanche danger levels operationally, to combine modelled snowpack stability with activity records for avalanche-activity prediction, and to automate terrain-exposure classification for recreational hazard communication (Pérez-Guillén et al. 2025; Viallon-Galinier et al. 2023; Markov et al. 2025). While these tools primarily support forward-looking hazard forecasting and terrain classification rather than the retrospective, event-specific attribution pursued here, they illustrate the broader methodological shift toward data-driven avalanche assessment within which the present multi-evidence framework sits.

Once released, avalanche flow dynamics are commonly represented through the Voellmy-fluid friction relation, which partitions flow resistance into a dry-Coulomb term and a velocity-dependent turbulent drag term (Salm 2004), calibrated against dense-snow avalanche runout observations (Bartelt et al. 1999) and validated using full-scale impact-pressure and flow measurements from the Vallée de la Sionne test site (Sovilla et al. 2008), the leading international facility for instrumented avalanche research, and implemented in three-dimensional terrain within the widely used RAMMS simulation framework (Christen et al. 2010). A substantial body of work has shown that forest cover exerts a strong, spatially explicit braking effect on avalanche flow through tree and branch fracture, overturning and snow entrainment (Bartelt and Stoeckli 2001), and that this effect measurably shortens runout distance as a function of forest structure and avalanche characteristics (Teich et al. 2012); numerical simulations using the material point method have further shown that snow detrainment and braking in forested terrain depend on the mechanics of snow–tree interaction rather than on forest destruction alone (Védrine et al. 2022). This protective role has direct practical value: basal friction associated with forest and silvicultural mitigation measures has been directly quantified for glide-snow avalanches, and GIS-based risk analyses have demonstrated the corresponding practical benefit of protection forest at the scale of individual avalanche paths (Feistl et al. 2014; Teich and Bebi 2009). These findings motivate incorporating a spatially explicit, satellite-derived forest-friction term into Voellmy-Salm runout simulations, rather than assuming spatially uniform friction parameters across forested and open terrain.

Despite this substantial body of work, three gaps motivate the present study. First, few studies apply a comparative, multi-event framework to human-associated avalanches within a single ski area across one winter season, which would allow common versus event-specific patterns to be distinguished. Second, the attribution question — whether a given avalanche would

1 plausibly have released without human loading — is rarely addressed through the joint use of
2 independent evidence streams (terrain susceptibility, in-situ meteorological reconstruction, and
3 satellite-based debris detection) rather than through a single method applied in isolation. Third,
4 despite a documented history of avalanche research and at least one direct account of fatal
5 avalanche events in Turkish mountain regions, including at Palandöken itself (Gürer et al.
6 1995; Selçuk 2013; Aydın et al. 2014; Nasery and Kalkan 2021; Varol 2022; Kurt 2022; Torpuş
7 et al. 2025), detailed multi-evidence case studies of individual avalanche events at Turkish ski
8 resorts — integrating terrain, meteorological and satellite data with physically-based modelling
9 — remain scarce in the international literature. The methodological contribution of the present
10 study is accordingly not a new remote-sensing or modelling technique in isolation — each
11 individual component (DEM-based terrain analysis, Sentinel-1/2 change detection, Voellmy-
12 Salm runout modelling) draws on established methods — but the integration of these
13 independent evidence streams into a single, reproducible reconstruction protocol, and its direct
14 comparison against independently documented circumstances of the triggering event, which
15 existing susceptibility-mapping and single-method detection studies do not provide.

16 This study addresses these gaps through an integrated assessment of two avalanche events that
17 occurred at the Palandöken ski area (Erzurum, Türkiye) during the 2024–2025 winter season,
18 both associated with the presence of people in terrain outside the managed ski runs: an
19 avalanche at Sultan Sekisi on 21 December 2024, and an avalanche at Yusufun Deresi on 15
20 February 2025. For the second event, an official statement by the Erzurum Metropolitan
21 Municipality, reported in national media, attributed the avalanche to skiers and snowboarders
22 who had entered a closed area and cut across the slope (Elips Haber 2025; Gazete Duvar 2025).
23 For the first event, national media reported that a group of athletes was conducting a training
24 exercise on the exact terrain at the time of release, though no single official statement specifies
25 the immediate mechanical cause (DHA 2024). These documented circumstances motivate
26 treating the two events as reference cases against which an independent, physically-based
27 reconstruction can be tested, rather than as unknowns to be inferred from physical evidence
28 alone. We combine DEM-derived terrain analysis to characterise release-zone slope and aspect,
29 hourly in-situ meteorological station records to reconstruct the pre-event snowpack loading
30 history and evaluate wind-transport potential relative to slope aspect, Sentinel-1 SAR
31 backscatter change detection and Sentinel-2 optical snow-cover confirmation to independently
32 verify conditions at each site, and a Voellmy-Salm runout model incorporating a spatially
33 explicit, satellite-derived forest-friction term to test whether the observed avalanche extents are

physically consistent with the reconstructed release and terrain conditions. This multi-evidence framework is used to evaluate the physical plausibility of the documented human-triggering circumstances at each site — providing, for Zone-2, an independent physical check against an officially documented cause, and for Zone-1, a physically-based reconstruction consistent with the reported presence of a group at the release site — and to demonstrate a reproducible protocol for verifying avalanche-trigger circumstances at ski areas that lack dedicated snowpack observation networks.

2. Study Area and Avalanche Events

2.1. Geographic and Climatic Setting

The study area is located within the Palandöken ski area, about 5 km south of Erzurum in northeastern Türkiye (Fig. 1a). The Palandöken massif rises from a height of nearly 2200 m to a peak height of approximately 3176 m and the area of the ski resort is around 26.8 km² of lift-serviced terrain, ranging from above treeline bowls close to the top of the ridge to lower elevation forested slopes (Fig. 1b). Eastern Türkiye, where Palandöken is located, boasts significant and long-lasting seasonal snow cover; the regional snow climate is classified as maritime. Snow depths up to 97 cm and densities ranging from 192 to 424 kg/m³ have been recorded on-site in the Palandöken massif during the accumulation period (Ertaş and Şorman 2024).

Weather data for this research were collected from the automatic weather station maintained by the Turkish State Meteorological Service (MGM) within the ski area, the Palandöken Station (station no. 17777; 39.844°N, 41.290°E; 2615 m above sea level). The station is placed approximately 0.6 km away from Zone-2 and 2 km from Zone-1 (Fig. 1b). Air temperature, wind speed and direction, total precipitation, and snow depth are measured every hour. Terrain analysis was carried out using the Copernicus GLO-30 DEM at 30 m horizontal resolution (European Space Agency 2024).

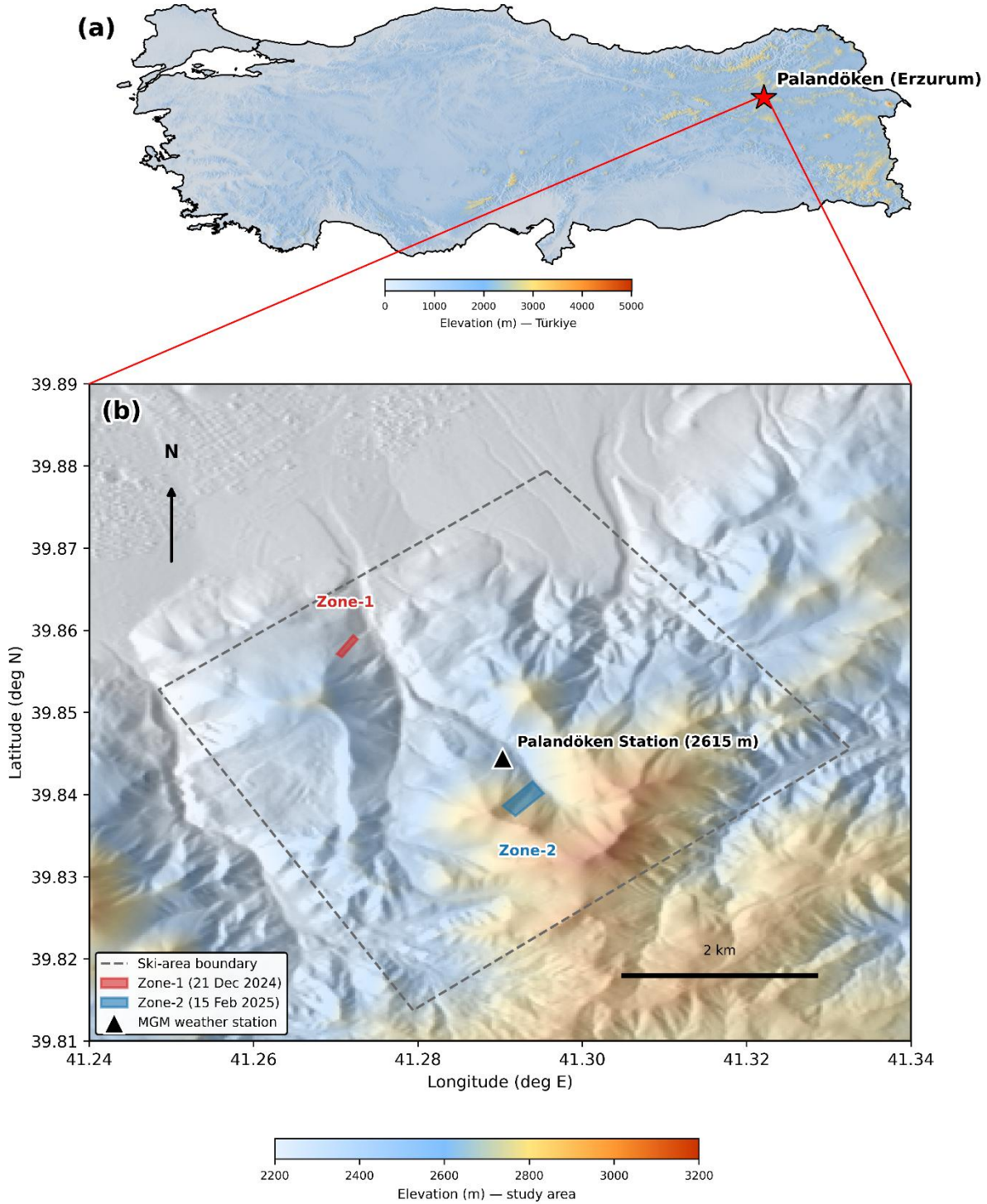


Fig. 1. Location of the study area. (a) Türkiye, with the Palandöken massif (Erzurum) indicated by a star; elevation derived from the Copernicus GLO-30 DEM. (b) Detail of the Palandöken ski area showing the ski-area boundary, the two avalanche polygons (Zone-1, 21 December 2024; Zone-2, 15 February 2025), and the Palandöken meteorological station (2615 m a.s.l.); elevation as in (a) but rescaled to the local range.

2.2. Description of the Avalanche Events

Two avalanches occurred within the Palandöken ski area during the 2024–2025 winter season, both releasing in terrain located outside the marked and managed ski runs: one at Sultan Sekisi on 21 December 2024 (Zone-1) and one at Yusufun Deresi on 15 February 2025 (Zone-2), approximately 2.8 km apart on the same massif. For each event, the affected area — encompassing the release, track and deposition zones combined — was delineated as a polygon through visual interpretation of high-resolution satellite and aerial imagery, cross-checked against ground-level and aerial photographs taken at each site (Fig. 2).



Fig. 2. Field photographs of the two avalanche events. (a–b) Zone-1 (Sultan Sekisi), showing the channelized flow path through forested terrain from the release area down to the piste-adjacent deposition zone. (c–d) Zone-2 (Yusufun Deresi), showing the fracture (crown) line and debris (d) and a ground-level view of the debris field with a search-and-rescue team for scale (c).

❖ Zone-1: Sultan Sekisi, 21 December 2024

The Sultan Sekisi (centroid 39.858°N, 41.271°E) avalanche released on an open, above-treeline slope and flowed through a narrow, forested gully that channelized the flow for most of its length before reaching the lower, piste-adjacent area (Fig. 2a–b). The site lies outside the marked ski runs, in terrain not groomed or avalanche-controlled by the ski area operator. The

mapped affected area covers approximately 2.0 ha (217 m × 293 m). National media reported that the avalanche occurred while a group of athletes from a sports team was conducting a high-altitude training exercise on this terrain at the time of release (DHA, 2024); no avalanche-control or explosive mitigation work was identified in the sources reviewed for this site, which lies outside the ski area's patrolled and controlled boundary.

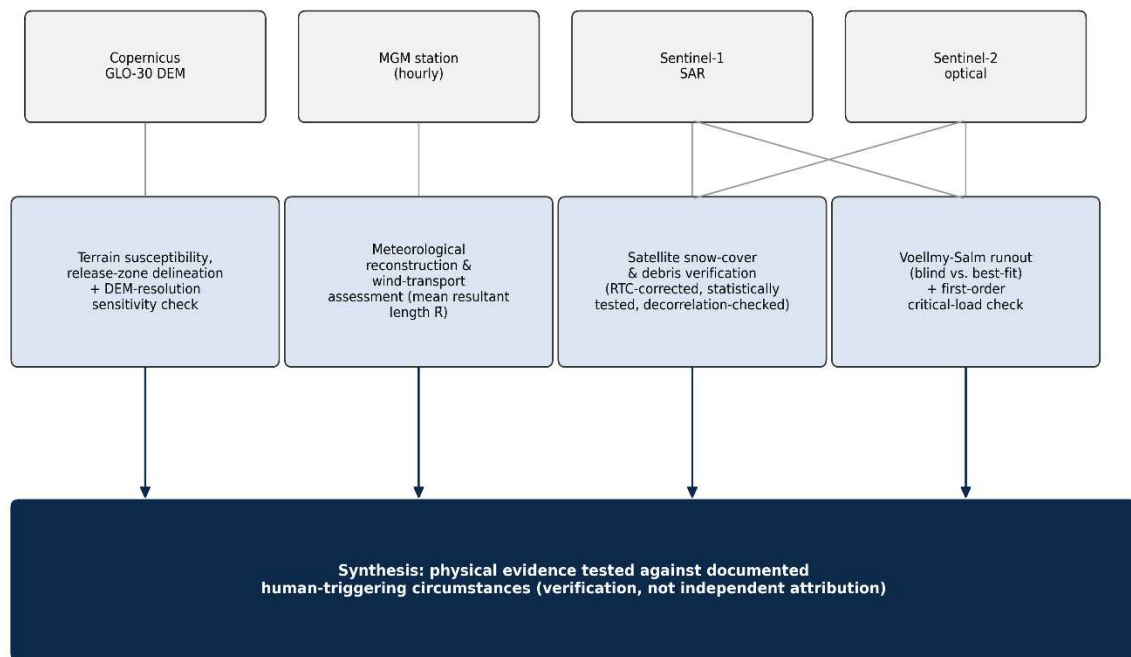
❖ **Zone-2: Yusufun Deresi, 15 February 2025**

The Yusufun Deresi (centroid 39.839°N, 41.293°E) avalanche released on a wider, less confined slope immediately adjacent to ski-lift infrastructure and a groomed piste, with a well-defined fracture (crown) line visible at its upper margin (Fig. 2c–d). As with Zone-1, the release and flow path lay outside the marked and patrolled runs. The mapped affected area covers approximately 8.3 ha (422 m × 466 m), more than four times the extent of Zone-1. According to an official statement by the Erzurum Metropolitan Municipality, reported in national media, the avalanche was caused by skiers and snowboarders who entered this closed, off-piste area and cut across the slope (Elips Haber 2025; Gazete Duvar 2025); four individuals were subsequently issued administrative penalties for entering the restricted zone. No avalanche-control or explosive mitigation work was identified in the sources reviewed for this site on the day of the event. Part of the resulting snow mass flowed onto the ski area's north run, as documented in contemporaneous national media coverage of the event (Anadolu Ajansı 2025).

3. Material and Methods

3.1. Data Sources and Overall Workflow

The attribution question addressed in this study — whether human loading was the determining trigger for each avalanche — is not directly observable from remote or in-situ data alone. We therefore combine four independent, cross-validated evidence streams: terrain susceptibility, in-situ meteorological reconstruction, satellite-based verification, and physically-based runout simulation (Fig. 3). Each stream is derived from a distinct data source (Table 1) and evaluated independently before being synthesised into an overall assessment of the relative plausibility of natural versus human triggering.



1

2 **Fig. 3.** Overall analytical workflow. Four independent evidence streams — terrain
 3 susceptibility, in-situ meteorological reconstruction, satellite-based verification, and
 4 physically-based runout simulation — are each derived from a distinct data source and
 5 combined and tested against the documented human-triggering circumstance at each site.

6 **Table 1.** Data sources used in this study.

Data type	Source	Resolution	Coverage/period	Use in this study
Digital elevation model	Copernicus GLO-30 DEM (European Space Agency, 2024)	30 m	-	Slope, aspect, release-zone delineation
Meteorological	MGM Palandöken Station	Hourly, point	Dec 2024 Feb 2025	Temperature, wind, precipitation reconstruction
SAR imagery	Sentinel-1 (ESA) (Torres et al., 2012)	10 m	Pre-/post-event pairs	Debris backscatter change detection

Optical imagery	Sentinel-2 (ESA) (Drusch et al., 2012)	10-20 m	Pre-/post-event pairs	Snow-cover (NDSI) confirmation
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3.2. Terrain Susceptibility and Release-Zone Delineation

Terrain characteristics of both avalanche locations were characterised using the Copernicus GLO-30 DEM (Table 1). The respective DEM tiles were mosaicked while their original 30 m projection was preserved throughout processing, to ensure accurate slope and aspect calculations without introducing errors associated with reprojection to a coarser resolution. Slope and aspect were derived from the DEM using standard terrain-analysis operators. For each avalanche polygon, zonal statistics — minimum, maximum, mean, standard deviation, and the 10th, 50th and 90th percentiles of both slope and aspect — were computed to characterise the overall topography of the affected area. Because slope estimates derived from moderate-resolution DEMs are known to be systematically attenuated as grid resolution coarsens, a resolution-coarsening sensitivity test was additionally performed: the native 30 m DEM was aggregated to 60, 90 and 120 m, mean release-zone slope was recomputed at each resolution, and the resulting trend was extrapolated toward finer resolutions to indicate the likely direction and order of magnitude of this bias.

Because the mapped polygons represent the total avalanche-affected area — release, track and deposition zones combined — rather than the release zone in isolation, the release zone itself was delineated separately. For dry-slab avalanches, initiation typically occurs on slopes of approximately 30–45°, the range over which a cohesive slab can accumulate sufficient tensile stress for a fracture to propagate across the slope (Schweizer et al. 2003). For each event, upslope buffer bands (100 m, 200 m, and 300 m beyond the polygon boundary, in the upslope direction corresponding to the local aspect) were constructed, and the proportion of each band falling within the 30–45° slope range was computed. This upslope-scan approach identifies whether terrain steep enough for unassisted release is present in the vicinity above the mapped polygon and, where present, approximates the location and extent of the probable release zone.

3.3. In-Situ Meteorological Reconstruction and Wind-Transport Assessment

Pre-event meteorological conditions were reconstructed using hourly records from the Palandöken MGM station (Table 1), including air temperature, wind speed and direction, total precipitation, and snow depth. For each event, a 72-hour window immediately preceding the

reported avalanche time was extracted. Within this window we evaluated: the minimum, mean and maximum air temperature, including whether the record crossed 0 °C (indicating a melt–freeze cycle); the cumulative precipitation; the net change in recorded snow depth; and the mean and maximum wind speed. These indicators were used to screen for the presence of the principal natural avalanche triggers reported in the literature — fresh snow loading, wind-slab formation, and melt–freeze weakening (Schweizer et al. 2003) — independently of any human-loading hypothesis. Snow-depth records were visually inspected for physically implausible short-duration spikes consistent with sensor noise during precipitation or high-wind periods; where such spikes occurred, the net snow-depth change was instead estimated from the stable baseline immediately before and after the affected interval.

Wind-transport potential was assessed by comparing the dominant pre-event wind direction with the slope aspect obtained in Section 3.2, following the general principle that wind-transported snow is preferentially deposited on the lee (downwind) side of a ridge and scoured from the windward side (Eckerstorfer and Christiansen 2011; Vionnet et al. 2014). For the hourly wind vectors (v_i, θ_i), with θ_i the direction from which the wind blows and v_i the wind speed, recorded within the 72-hour pre-event window ($i = 1, \dots, n$), the speed-weighted mean wind direction was calculated as a circular mean (Mardia and Jupp 1999):

$$\bar{x} = \sum_{i=1}^n v_i \cos \theta_i, \bar{y} = \sum_{i=1}^n v_i \sin \theta_i \quad (1)$$

$$\bar{\theta} = \text{atan2}(\bar{y}, \bar{x}) \bmod 360^\circ \quad (2)$$

The corresponding leeward (deposition-favourable) direction is then obtained by adding 180° to the mean wind direction from Eq. (2):

$$\theta_{lee} = (\bar{\theta} + 180^\circ) \bmod 360^\circ \quad (3)$$

The angular difference between the leeward direction from Eq. (3) and the mean slope aspect α of each release zone was then computed as:

$$\Delta = \min(|\alpha - \theta_{lee}|, 360^\circ - |\alpha - \theta_{lee}|) \quad (4)$$

was used to classify each slope as leeward (wind loading favoured, small Δ), windward (scour favoured, Δ close to 180°), or intermediate, providing an independent check on whether wind-transported snow could plausibly have contributed to loading at each release zone. To assess

how well-defined (rather than diffuse) the dominant wind direction was over each 72-hour window, the mean resultant length $\bar{R} = |\sum v_i e^{i\theta_i}| / \sum v_i$ was also computed (Mardia and Jupp 1999); $\bar{R}$ ranges from 0 (directionally uniform, uninformative wind record) to 1 (a single, perfectly consistent direction), and is reported alongside the mean direction to indicate the reliability of the leeward/windward classification.

3.4. Satellite-Based Snow-Cover and Debris Verification

Pre- and post-event snow-cover conditions at each site were confirmed using Sentinel-2 (Drusch et al. 2012) Level-2A surface-reflectance imagery. For each event, available scenes within a ± 20 -day window were ranked by cloud cover, and the least-cloudy scene before and after the event date was selected. The Normalized Difference Snow Index (NDSI; Salomonson and Appel 2004) was computed from the green and shortwave-infrared bands, and the mean NDSI and fractional snow cover were extracted within each avalanche polygon to confirm that sufficient snow was present both before and after each event.

Avalanche debris was independently assessed using Sentinel-1 (Torres et al. 2012) Ground Range Detected (GRD) SAR imagery in Interferometric Wide swath mode. Because fresh, rough avalanche debris typically increases radar backscatter relative to smooth pre-event snow (Eckerstorfer and Malnes 2015), pre- and post-event scene pairs were selected from the same relative orbit and pass direction (ascending or descending) to avoid geometric artefacts associated with differing viewing geometry in steep terrain, choosing the pair that most tightly bracketed the event date. Backscatter images were despeckled using a focal-median filter (30 m radius) prior to differencing. Candidate scenes were searched within a ± 24 -day window of each event; the selected same-orbit pairs were 9 December 2024 (pre) and 21 December 2024 (post, same day as the event) for Zone-1 (relative orbit 145, ascending), and 6 February 2025 (pre) and 18 February 2025 (post, 3 days after the event) for Zone-2 (relative orbit 123, descending). The analysis used the VH (cross-polarised) channel rather than VV, as cross-polarised backscatter is generally more sensitive to the volume scattering produced by rough, heterogeneous debris than the co-polarised VV channel, which responds more strongly to surface (specular) scattering from smooth, undisturbed snow. For each event, the change in VH backscatter (post-event minus pre-event, in dB) was computed, and the mean change within the avalanche polygon was compared against the mean change in a surrounding 500 m buffer ring to quantify a polygon-to-background contrast; a substantially positive contrast was interpreted as consistent with the presence of avalanche debris, while a contrast within the

background noise range was interpreted as a non-detection attributable to event size relative to sensor resolution (Keskinen et al. 2022).

3.5. Avalanche Runout Simulation with Forest-Friction Effects

Once released, avalanche flow dynamics were represented using the Voellmy-fluid friction model, which partitions flow resistance into a dry-Coulomb term and a velocity-dependent turbulent drag term (Salm 2004). At Zone-1, the flow path is narrow and quasi-linear, for which a one-dimensional centre-line implementation is a reasonable simplification of the full three-dimensional formulation used in frameworks such as RAMMS (Christen et al. 2010). Zone-2's wider, less confined morphology does not meet this condition as well, and the one-dimensional implementation was nonetheless applied there for methodological consistency between the two events; this mismatch is consistent with the model's known structural limitations in representing flow across wider, less-confined terrain, and the Zone-2 runout result is accordingly treated as illustrative of this limitation rather than as a diagnostic test of the triggering hypothesis at that site. Along a flow-path coordinate s , the velocity evolves as:

$$\frac{dv}{dt} = g \sin \psi(s) - \mu g \cos \psi(s) - \frac{g}{\xi} v^2 \quad (5)$$

where $\psi(s)$ is the local slope angle, g is gravitational acceleration, μ is the dry-Coulomb friction coefficient, and ξ is the turbulent friction coefficient.

For each event, a centre-line elevation profile was extracted from the DEM, beginning above the mapped polygon in the release zone identified in Section 3.2 and extending downslope beyond the polygon boundary. Profile orientation was verified against the true elevation gradient and reversed where necessary, and the profile was smoothed with a moving-average filter to remove step-like artefacts introduced by the 30 m DEM resolution before being used as model input. Equation (5) was solved by explicit time-stepping, with the flow initiated at the first point along the profile where the local slope reached 30° , the lower bound of the 30 – 45° release-prone range defined in Section 3.2, used here as a conservative, earliest-possible flow-initiation point rather than as a single release criterion. Deposition was defined as the point beyond which the local slope remained below the Coulomb friction angle ($\arctan \mu$) and the flow velocity remained below a low threshold for a sustained interval, rather than at the first instant of zero velocity; this avoids spurious arrest on short, locally flat segments that the flow's momentum would in reality carry across.

Because forest cover exerts a strong, spatially localised braking effect on avalanche flow through tree and branch fracture, overturning and snow entrainment (Bartelt and Stoeckli 2001), with basal friction attributable to forest cover quantified in previous work (Feistl et al. 2014), a spatially explicit forest-friction extension was implemented. Forest cover along each profile was identified from a summer (leaf-on) Sentinel-2 (Drusch et al. 2012) NDVI composite, using a threshold of $\text{NDVI} > 0.4$ to distinguish forested from open terrain. Distinct friction parameters were applied depending on local forest cover: an open-slope parameter set ($\mu_{\text{open}}, \xi_{\text{open}}$) and an elevated-friction forested set ($\mu_{\text{forest}}, \xi_{\text{forest}}$), with the appropriate pair selected at each point along the profile according to the forest mask.

As the friction parameters cannot be measured directly and instead depend on unobserved snow and vegetation properties, the model was run across a range of values bracketing those reported in the literature for dense-snow avalanches, rather than relying on a single deterministic parameterisation: $\mu_{\text{open}} \in [0.15, 0.30]$, $\xi_{\text{open}} \in [500, 2000] \text{ m/s}^2$, and $\mu_{\text{forest}} \in [0.30, 0.50]$, with ξ_{forest} held at 400 m/s^2 to reflect the higher aerodynamic roughness of forested terrain. Two forest-friction results are reported for each site (Section 4.4): a best-fit value, in which μ_{forest} is selected within this range to minimise the discrepancy with the observed affected-area extent, and a non-tuned ("blind") value, in which μ_{forest} is fixed a priori at 0.40 — a literature-typical value for dense forest stands (Feistl et al. 2014; Bartelt and Stoeckli 2001) — without reference to the observed extent at either site. The blind value is used to assess the extent to which the correspondence reported at Zone-1 depends on calibration rather than reflecting an independent, a priori physical prediction.

4. Results

4.1. Terrain Characteristics and Release Zones

The affected-area polygons at both sites exhibit slope distributions centred below the classic $30\text{--}45^\circ$ dry-slab release range (Fig. 4). Zone-1 shows a median slope of 23° (range approximately $18\text{--}30^\circ$), while Zone-2 shows a median of 29° (range approximately $21\text{--}34^\circ$), with neither distribution's bulk extending into the release-prone band. Aspect within the affected area is predominantly north-easterly at Zone-1 and more broadly distributed across the north to east sector at Zone-2 (Fig. 4), orientations that limit direct solar loading and favour the persistence of weak layers through the accumulation season.

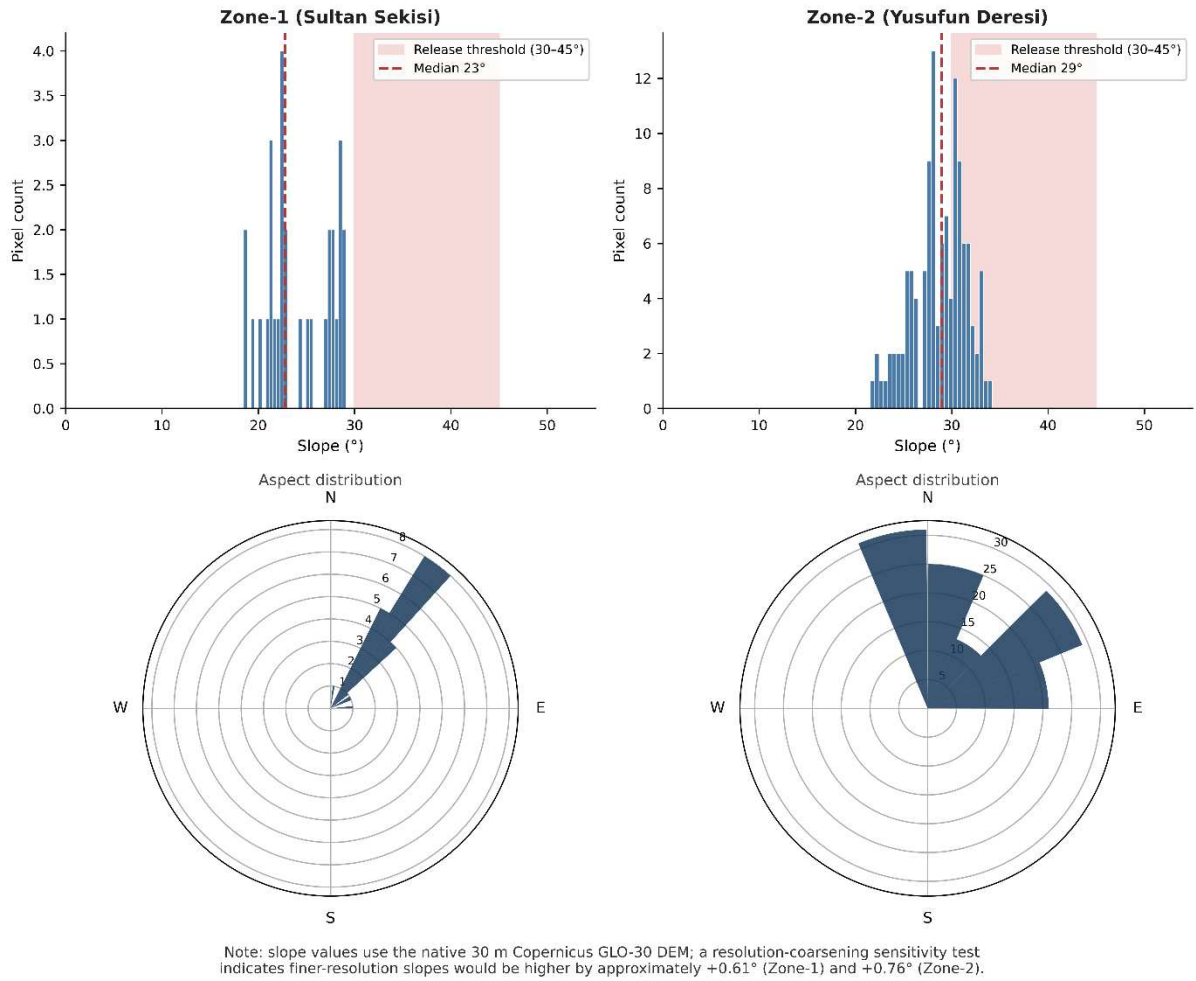


Fig. 4. Slope and aspect distributions within the affected-area polygon at each site. Top: slope histograms, with the 30–45° dry-slab release range shaded and the median slope indicated; the DEM-resolution sensitivity range noted below the panels is discussed in Section 3.2. Bottom: aspect (compass direction the slope faces) distributions.

Because the affected-area polygons represent the combined release, track and deposition zones rather than the release zone alone, the terrain immediately upslope of each polygon was scanned separately (Table 2). At both sites, the absolute area of 30–45° terrain within the upslope band, and the maximum slope encountered within it, increase with search distance: at Zone-1, the steep (30–45°) area grows from 7,853 m² within 100 m of the polygon to 61,199 m² within 300 m, with the maximum slope encountered rising from 32.3° to 40.3° over the same distance; Zone-2 shows a comparable pattern, with steep area increasing from 19,981 m² to 132,643 m² and maximum slope from 33.3° to 35.2°. This reflects a widening search band progressively capturing more, and locally steeper, terrain rather than a uniform steepening of the band as a whole: the band's own mean slope does not increase over the same distance (Table 2) — at Zone-1 it decreases from 26.5° to 24.2°, and at Zone-2 it remains essentially flat (27.3–

27.8°) — because each wider band still includes substantial non-release-prone terrain alongside the steeper patches it newly captures. A representative centre-line elevation and slope profile for each site (Fig. 5) illustrates one such transect, though, as a single line, it does not necessarily intersect the specific steep patches identified by the areal scan in Table 2, nor does it reproduce the band-mean trend. Taken together, these results indicate that terrain capable of unassisted dry-slab release becomes progressively more prevalent, in absolute extent and at its steepest points, upslope of the mapped affected area at both sites — most clearly at Zone-1, where the affected area itself remains below the release threshold throughout — even though this is not visible as a rise in the upslope band's own average slope.

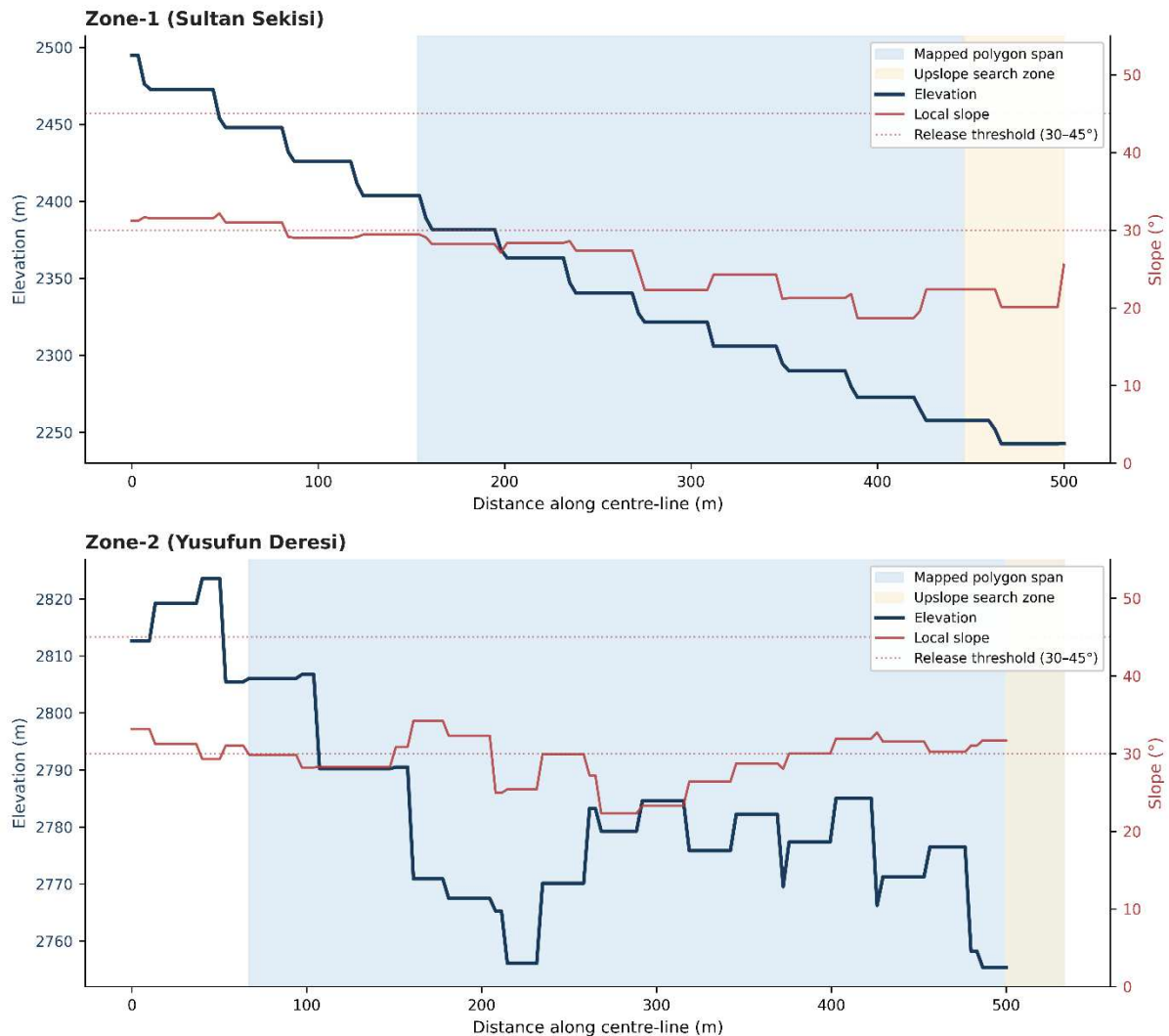


Fig. 5. Representative centre-line elevation and slope profiles extending from the release-zone search area, through the mapped affected-area polygon (shaded blue), to the upslope search zone (shaded yellow). The 30–45° release-prone slope range is shaded on the right-hand axis.

Table 2. Areal upslope-band statistics: band-mean, maximum and 90th-percentile slope, and the absolute area of 30–45° (release-prone) terrain, within successive upslope search bands above each polygon.

Zone	Upslope band	Mean slope (°)	Max slope (°)	90th percentile (°)	30–45° area (m ²)
Zone-1	+100 m	26.5	32.3	30.2	7,853
Zone-1	+200 m	25.0	35.0	30.9	27,307
Zone-1	+300 m	24.2	40.3	31.4	61,199
Zone-2	+100 m	27.8	33.3	30.9	19,981
Zone-2	+200 m	27.3	34.6	32.1	75,330
Zone-2	+300 m	27.7	35.2	32.2	132,643

4.2. Pre-Event Meteorological Conditions and Wind Loading

Neither event was preceded by a natural trigger of the magnitude typically associated with spontaneous dry-slab release (Table 3, Fig. 6). At Zone-1, air temperature remained below 0 °C throughout the 72-hour pre-event window (maximum −0.3 °C), precluding a melt–freeze weakening cycle, and cumulative precipitation was negligible (1.0 mm). At Zone-2, temperature likewise remained fully below freezing, but precipitation was more substantial (11.2 mm), consistent with a net snow-depth increase of 13.0 cm recorded at the station over the same window — a moderate fresh-snow loading signal, though one recorded at a single point roughly 0.6 km from the release area rather than at the site itself. Wind speeds were broadly comparable between the two events (mean 4.2–5.5 m/s, maxima around 13 m/s).

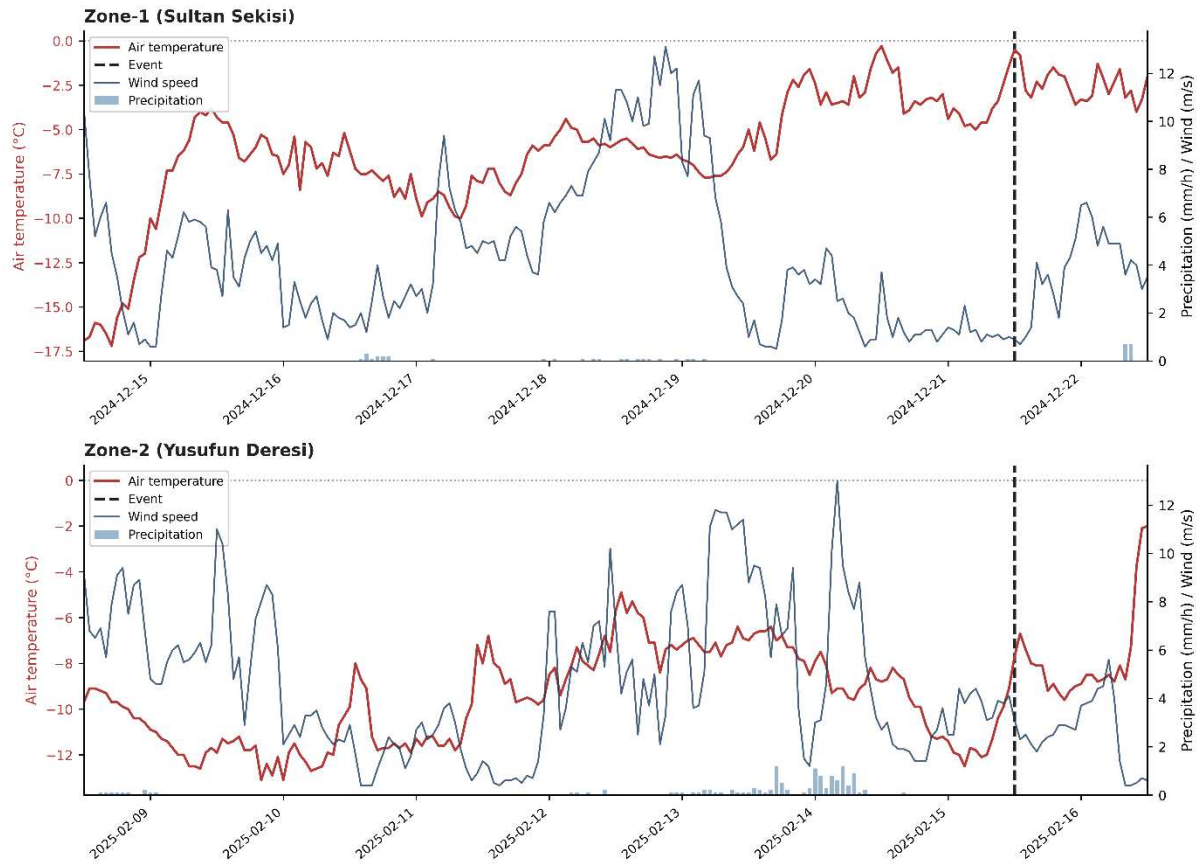


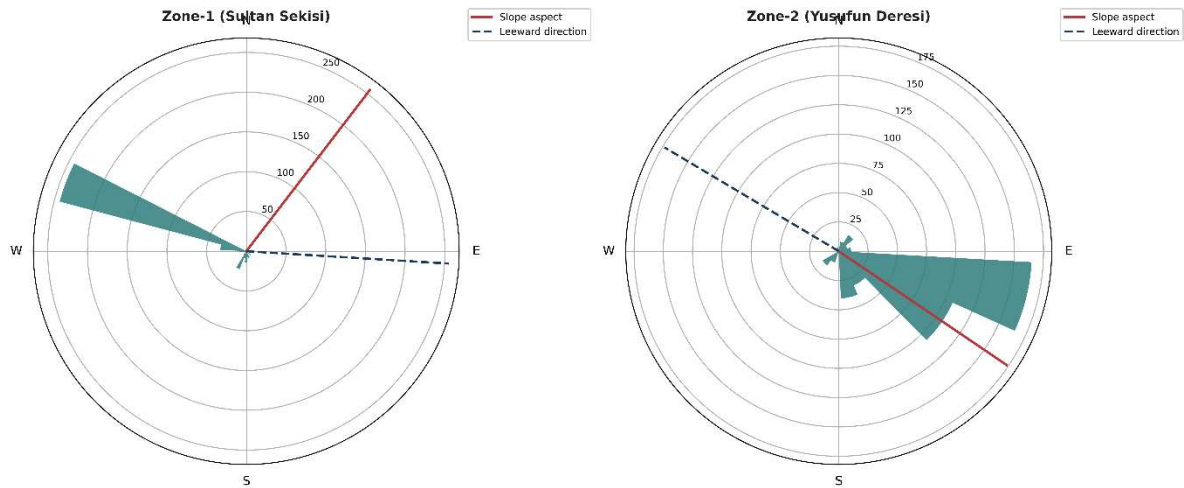
Fig. 6. Hourly air temperature, precipitation and wind speed at the Palandöken station, 7 days before to 1 day after each event.

Table 3. 72-hour pre-event meteorological summary (Palandöken station).

	Zone-1	Zone-2
Temperature min/mean/max (°C)	−7.7 / −4.4 / −0.3	−12.5 / −8.4 / −4.9
0 °C crossing (melt–freeze)	No	No
Total precipitation (mm)	1.0	11.2
Snow depth change (cm)	No data	+13.0 (86–99 cm)
Wind speed mean/max (m/s)	4.2 / 13.1	5.5 / 13.0
Leeward–aspect angular difference Δ	56° (intermediate)	177° (windward)
Wind-direction concentration (mean resultant length $\bar{R}$)	0.75	0.78

The dominant pre-event wind direction differed markedly in its relationship to slope aspect between the two sites (Fig. 7). At Zone-1, the angular difference between the leeward (deposition-favoured) direction and the mean slope aspect was 56°, an intermediate configuration in which wind-transported loading of the release area cannot be excluded but is

not strongly favoured. At Zone-2, the angular difference was 177° — the release slope faced almost directly into the dominant wind, a windward configuration under which snow is preferentially scoured rather than deposited, making wind transport an implausible contributor to loading at this site. The wind direction was well-defined at both sites over the 72-hour window (mean resultant length $\bar{R} = 0.75$ at Zone-1, $\bar{R} = 0.78$ at Zone-2, both well above the $\bar{R} \approx 0$ expected for a directionally uniform record), indicating that both classifications are based on a consistent, rather than diffuse, prevailing wind direction.



Directional concentration of pre-event wind (speed-weighted mean resultant length, Mardia & Jupp, 1999; Eq. 4): $\bar{R} = 0.75$ (Zone-1), $\bar{R} = 0.78$ (Zone-2). Station: MGM No. 17777 (Palandöken), 72-h pre-event window.

Fig. 7. Wind rose (speed-weighted, direction from which the wind blows) over the 72 hours preceding each event, with the mean slope aspect and corresponding leeward (deposition-favoured) direction indicated; the mean resultant length $\bar{R}$ quantifying directional concentration is noted below the panels.

4.3. Satellite Verification of Snow Cover and Debris

Sentinel-2 imagery confirmed that both sites carried substantial snow cover immediately before and after each event. At Zone-1, mean NDSI within the polygon was 0.79 in the pre-event scene and 0.70 post-event, corresponding to a fractional snow cover of 100% and 91% respectively; at Zone-2, NDSI remained at 0.88 in both the pre- and post-event scenes, with 100% fractional cover throughout. These values confirm that snow was present in the quantity required for avalanche release at both sites, independent of the terrain and meteorological evidence presented above. To test whether the polygon-averaged NDSI decline at Zone-1 reflected a spatially localised disturbance rather than a scene-wide effect, the pre-to-post-event change in NDSI was additionally compared inside each polygon against a surrounding 500 m buffer. At Zone-1, NDSI declined significantly more inside the polygon than in the buffer in

this pixel-population test (mean $\Delta = -0.095$ versus -0.051 ; Welch's $t = -3.29$, $p = 0.002$, $n = 50$ and 1971 pixels respectively). At Zone-2, the polygon showed essentially no net NDSI change while the surrounding buffer registered a small increase (mean $\Delta = +0.001$ versus $+0.039$; $t = -9.96$, $p < 0.001$, $n = 207$ and 2006 pixels). Because neighbouring pixels in both datasets are spatially autocorrelated, both contrasts were additionally tested on a spatially decorrelated subsample (systematic grid spacing of 80 m, exceeding the native pixel size several-fold). At Zone-2, the contrast remained significant under this stricter test ($n = 14$ and 221 decorrelated samples; $t = -3.10$, $p = 0.003$), increasing confidence that it is not solely a spatial-autocorrelation artefact. At Zone-1, however, the contrast did not survive this check ($n = 4$ and 181 decorrelated samples; $t = -0.78$, $p = 0.49$); given the small polygon size, this decorrelated test is itself severely underpowered rather than a confident negative result, so the Zone-1 NDSI contrast is treated as inconclusive rather than as corroborating evidence.

Sentinel-1 SAR backscatter change showed a clear contrast between the two events (Fig. 8). To account for radar-geometry effects on this steep, mixed-aspect terrain, backscatter was corrected to a local-incidence-angle-normalised (γ_0) value prior to comparison, and the resulting polygon-versus-surrounding-buffer contrast was tested statistically rather than compared as raw means alone. At Zone-2, the incidence-angle-normalised VH backscatter increased inside the polygon by $+1.01$ dB relative to the surrounding 500 m buffer (polygon: mean $= +1.25$ dB, SD $= 1.79$, $n = 833$ pixels; buffer: mean $= +0.24$ dB, SD $= 2.31$, $n = 2000$ pixels; Welch's $t = 12.55$, $p < 0.001$), a statistically robust, spatially localised increase consistent with the rougher surface expected of freshly deposited avalanche debris relative to smooth pre-event snow. At Zone-1, the corresponding incidence-angle-normalised VH contrast was -0.17 dB and not statistically distinguishable from zero (polygon: mean $= -0.42$ dB, $n = 201$; buffer: mean $= -0.25$ dB, $n = 1913$; $t = -1.45$, $p = 0.148$); no comparable visual or statistical debris signal was found at this site. This asymmetry is consistent with the roughly four-fold difference in affected area between the two events (Section 2.2) and with previous findings that SAR-based avalanche detection reliability decreases markedly for smaller events (Keskinen et al. 2022); Zone-1's non-detection is accordingly interpreted as a sensitivity limitation of the method at this event size, now supported by a formal non-significance test, rather than as evidence against an avalanche having occurred. The co-polarised (VV) channel showed small but statistically significant negative contrasts at both sites (Zone-1: -0.19 dB, $p = 0.025$; Zone-2: -0.14 dB, $p = 0.030$); given their small magnitude, opposite sign to the cross-polarised debris signal at Zone-2, and lack of a consistent physical interpretation across sites,

these VV contrasts are not treated as informative about debris presence and are reported here for completeness only. Because pixels within a polygon are spatially autocorrelated, the VH contrasts above were additionally tested on a spatially decorrelated subsample (80 m systematic grid spacing); the Zone-2 contrast remained significant ($n = 25$ and 394 decorrelated samples; $t = 3.56$, $p = 0.001$) and the Zone-1 null result was confirmed ($n = 6$ and 321 decorrelated samples; $t = 0.45$, $p = 0.67$), increasing confidence in both findings. Applying an azimuth-aware local-incidence-angle correction, which additionally accounts for satellite look direction rather than slope and aspect alone, reproduced these contrasts to within 0.01 dB of the simpler correction reported above; because both the pre- and post-event scenes in each same-orbit pair share an essentially identical acquisition geometry, static geometric correction terms largely cancel in the post-minus-pre differencing used throughout this study, which limits the sensitivity of these particular change-detection results to the choice of terrain-correction scheme.

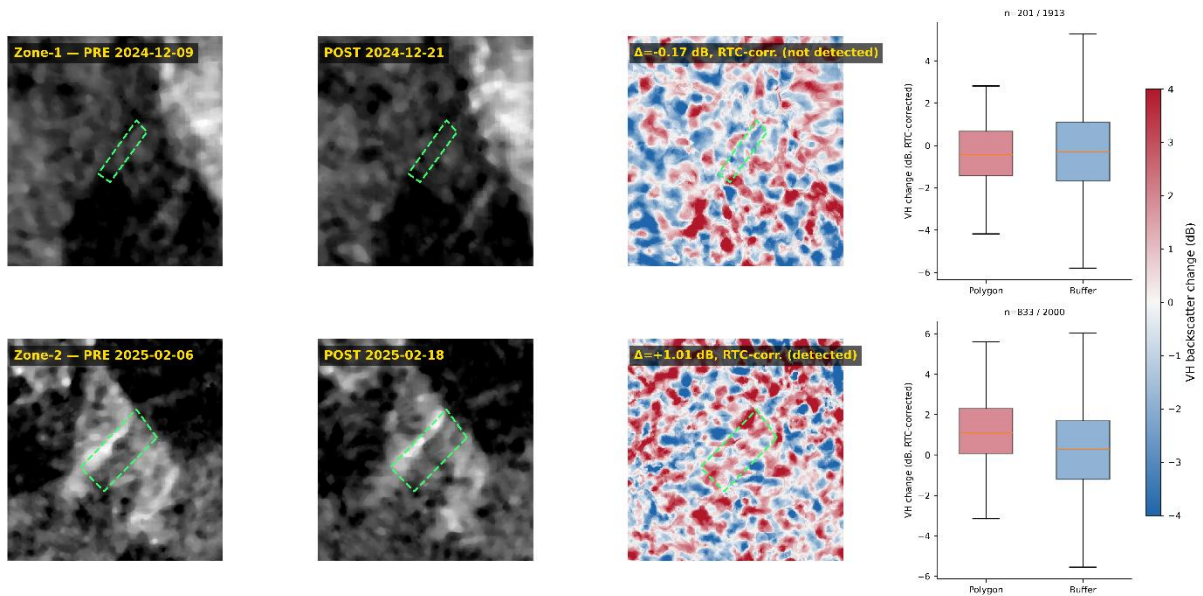


Fig. 8. Sentinel-1 VH backscatter (dB, azimuth-aware incidence-angle-normalised) before and after each event, the corresponding change (post minus pre) for same-orbit, despeckled image pairs, and a boxplot comparing the pixel-value distribution inside the mapped avalanche polygon against the surrounding 500 m buffer ring. The mapped avalanche polygon is outlined in green in the image panels. Red in the change panels indicates a backscatter increase consistent with rough avalanche debris.

4.4. Simulated Runout and the Role of Forest Drag

1 The open-slope Voellmy-Salm simulation substantially overestimated the observed extent at
2 Zone-1, predicting a runout of 643 m against an observed affected-area span of 293 m (Table
3 4, Fig. 9) — more than double the mapped extent. Incorporating the spatially explicit forest-
4 friction term, using the forest cover mapped along the flow path (50%), reduced the simulated
5 runout substantially. With μ_{forest} fixed a priori at the literature-typical, non-tuned value of 0.40
6 (Section 3.5), the simulated runout was 220 m — a 25% underestimate relative to the observed
7 span, but a 66% reduction from the open-slope prediction, indicating that the forest-friction
8 mechanism itself, independent of calibration, accounts for most of the improvement in fit.
9 Allowing μ_{forest} to vary within the tested range and selecting the value that minimises the
10 discrepancy with the observed extent (best-fit $\mu_{\text{forest}} = 0.35$) brought the simulated runout to
11 294 m, closely matching the observed span. Because this closer correspondence was obtained
12 by calibrating against the observed extent rather than by an independent prediction, it is best
13 interpreted as a physical consistency check — confirming that a flow released from the terrain
14 identified in Section 4.1, moving through the mapped forest cover, can plausibly account for
15 the observed extent — rather than as blind validation of the release scenario; the non-tuned
16 result above provides the corresponding independent check.

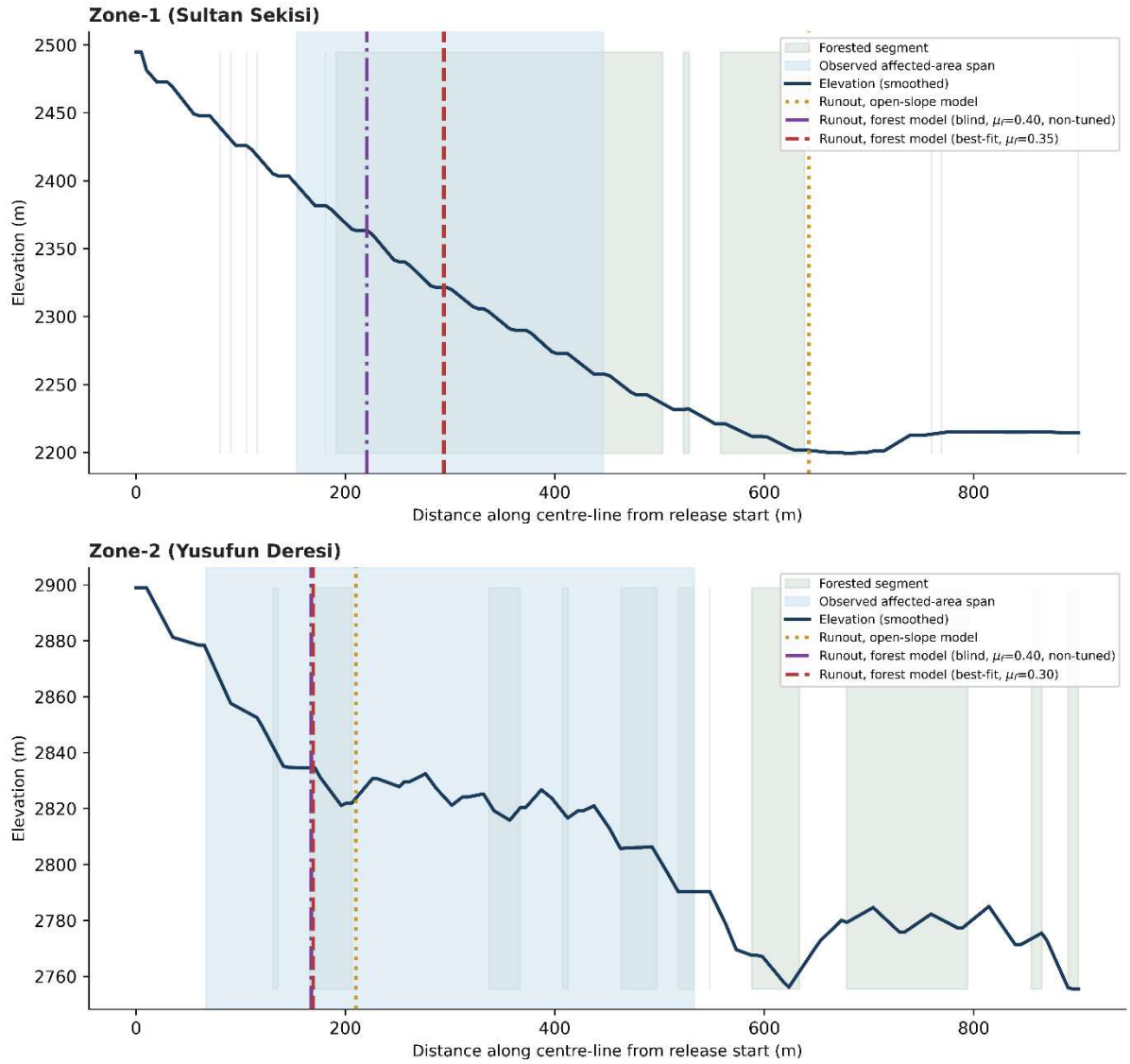


Fig. 9. Simulated Voellmy-Salm runout profiles for each event, showing the open-slope model (gold, dotted), the blind forest-friction model (purple, dash-dot; literature value $\mu_f=0.40$, not calibrated to either event), and the calibrated best-fit forest-friction model (red, dashed), forested segments along the flow path (green shading), and the observed affected-area span (blue shading).

At Zone-2, neither the open-slope model (210 m) nor the forest-friction model reproduced the observed extent: simulated runout ranged from 166–169 m across the tested range of forest friction values, against an observed span of 466 m. The open-slope-to-forest-friction transition still reduces runout by roughly 20% (210 m to 166–169 m), but this reduction is small relative to the roughly two-fold reduction achieved by the same mechanism at Zone-1 (Section 4.4), and, within the forest-friction model, runout was comparatively insensitive to the specific friction coefficient — the non-tuned ($\mu_{\text{forest}} = 0.40$) and best-fit ($\mu_{\text{forest}} = 0.30$) results differed

by only 2 m (167 m versus 169 m) — confirming that the roughly 300 m shortfall against the observed extent reflects a structural limitation of the model rather than a specific choice of friction parameter. This is consistent with the lower forest cover along this flow path (41%) and its more open, less-confined morphology. The underestimation is attributed to a known limitation of the one-dimensional, point-mass Voellmy formulation: it does not represent the momentum of a large flowing mass carrying itself across a local flattening in the terrain, an effect that a full three-dimensional model such as RAMMS would capture more accurately. The Zone-2 result is therefore interpreted as a limitation of the simplified runout model rather than as evidence against the mapped extent of that event.

Table 4. Voellmy-Salm runout simulation results.

	Zone-1	Zone-2
Forest cover along profile	50%	41%
Runout, open-slope model	643 m	210 m
Runout, forest-friction model (best-fit)	294 m	169 m
Runout, forest-friction model (blind, $\mu_{\text{forest}} = 0.40$, non-tuned)	220 m	167 m
Best-fit forest friction μ_{forest} (tuned)	0.35	0.30
Observed affected-area span	293 m	466 m

5. Discussion

5.1. Synthesis of Evidence for Human Triggering

At Zone-1, the physical evidence is consistent with the documented circumstances of the event. National media reported that a group of athletes was conducting a high-altitude training exercise directly on the affected terrain at the time of release (DHA 2024); no official statement identifies the specific mechanical trigger, and this account is treated here as contextual rather than as evidence in its own right. Independently of this account, the physical reconstruction supports the plausibility of a human-triggered release on terrain that would not be expected to fail spontaneously. Consistent with the classical understanding that dry-slab release requires the joint occurrence of a weak buried layer, a cohesive slab, and terrain steep enough for a fracture to propagate across the slope (Schweizer et al. 2003), the affected-area terrain here lies entirely below the 30° threshold at which this last condition is typically satisfied, and steeper

(30–45°) terrain becomes prevalent only 200–300 m upslope of the mapped polygon (Section 4.1); a DEM-resolution sensitivity test (Section 5.2) indicates this slope estimate may itself be a conservative underestimate, but by at most about 0.6°, which does not materially change this terrain classification at Zone-1. This does not, however, rule out human triggering: skier-stability formulations model the additional load of a person as a static stress superimposed on the snowpack (Föhn-derived indices reviewed in Schweizer et al. 2003; Jamieson and Johnston 1998; Schweizer and Jamieson 2001), and more recent fracture-mechanical work has shown that it is the propagation of a crack once initiated, rather than the local stability margin alone, that determines whether a collapse develops into a full slab release (Heierli et al. 2008, 2011; Gaume and Reuter 2017; Reuter and Schweizer 2018) — a mechanism by which a human load can trigger release on terrain that would not fail spontaneously. This is not, however, a guaranteed outcome once a collapse initiates: slab touchdown onto the underlying bed surface can arrest an otherwise-propagating anticrack before it develops into a full release (Rosendahl et al. 2025), a documented competing outcome that this study cannot rule out at Zone-1 in the absence of event-specific snow-depth and bed-surface data; the channelised, forest-confined flow path identified at this site (Section 2.2) is offered as a qualitative reason a full-depth release is plausible here, but this remains an acknowledged uncertainty in the triggering-mechanism argument rather than a resolved one. No natural trigger of the magnitude normally associated with spontaneous release was present in the 72 hours before the event (Section 4.2), and no avalanche-control or explosive mitigation work was identified in the sources reviewed for this site (Section 2.2). Sentinel-1 did not detect a statistically significant debris signature at this site (incidence-angle-normalised VH contrast -0.17 dB, $p = 0.148$; Section 4.3); given the documented size-dependence of SAR-based avalanche detection, in which path length, destructive size and average slope are the strongest correlates of successful detection (Keskinen et al. 2022), and Zone-1's comparatively small (2.0 ha) extent, this null result is treated as uninformative about triggering mechanism rather than as supporting or contradicting evidence. An independent Sentinel-2 NDSI check found a significant contrast in a pixel-population test, but this did not survive a spatially decorrelated robustness check (Section 4.3); given Zone-1's small (2.0 ha) polygon, that stricter test is itself underpowered rather than a confident negative result, and the NDSI evidence at this site is accordingly treated as inconclusive rather than as corroborating evidence, consistent with the null SAR result discussed above. The runout simulation incorporating literature-based forest-friction parameters closely reproduced the observed affected-area extent, and a non-tuned cross-check still recovered a runout within 25% of the observed span (Section 4.4). Because this correspondence holds even without calibration,

1 the forest-friction mechanism itself — not merely the choice of calibrated value — is what
2 accounts for most of the improvement over the open-slope model; the additional precision
3 obtained by calibration is a consistency check on top of that mechanism, not an independent
4 prediction. Taken together, the terrain, meteorological and modelling evidence does not
5 contradict — and is physically consistent with — the documented presence of a group at the
6 release site at the time of the event.

7 At Zone-2, an official statement by the Erzurum Metropolitan Municipality, reported in
8 national media, directly attributed the event to skiers and snowboarders who had entered the
9 closed, off-piste area and cut across the slope, and four individuals were subsequently issued
10 administrative penalties for entering the restricted zone (Elips Haber 2025; Gazete Duvar
11 2025). This is treated here as the primary account of the triggering circumstance, and the
12 physical evidence assembled independently in this study is used to assess whether it is
13 consistent with that account, rather than to establish causation on its own. Terrain here is closer
14 to, though still generally below, the release threshold — and a DEM-resolution sensitivity test
15 (Section 5.2) indicates this 29° median value may itself be a conservative underestimate by on
16 the order of $0.3\text{--}0.8^\circ$, further limiting how confidently terrain alone can be used to argue against
17 spontaneous release at this site — and a moderate natural snow-loading signal was present
18 before the event, unlike at Zone-1 — a combination that, considered in isolation, would leave
19 some ambiguity between natural and human triggering. Wind conditions, however, placed the
20 release slope in a windward, scour-favoured configuration — the near- 180° angular difference
21 computed via Eq. (4), based on a well-defined prevailing wind direction ($\bar{R} = 0.78$; Section
22 4.2), indicating scour rather than deposition (Eckerstorfer and Christiansen 2011; Vionnet et
23 al. 2014) — ruling out wind-transported loading specifically as a contributing mechanism. This
24 leaves direct snowfall loading (13.0 cm depth increase, 11.2 mm precipitation; Table 3) as the
25 only documented natural loading pathway at this site, and a first-order plausibility check was
26 carried out for this snowfall (11.2 mm precipitation-equivalent, ≈ 110 Pa additional normal
27 load). Resolved into an approximate shear-stress increment on a 29° slope ($\Delta W \cdot \sin\psi \cdot \cos\psi \approx$
28 46.6 Pa) and compared against literature-typical weak-layer shear-strength values
29 (approximately 200–3000 Pa; Jamieson and Johnston 1998; Schweizer et al. 2003), the added
30 shear increment falls at or below the lower end of this range — but this comparison uses only
31 the incremental load from the new snowfall, not the total pre-existing slab overburden that
32 governs weak-layer failure in a full stability calculation, and remains too imprecise, in the
33 absence of site-specific weak-layer and slab measurements, to determine whether the snowfall

alone was sufficient or insufficient to trigger release (Section 5.2). The observation that release was confined to a single, closed slope rather than occurring more broadly across the many similarly loaded, similarly exposed slopes of the same massif (Schweizer et al. 2003) is consistent with, but does not on its own establish, a human rather than natural trigger; it is the officially documented account, not the physical loading analysis, that provides the basis for excluding a purely natural origin at this site. Sentinel-1 independently detected a spatially localised debris-consistent backscatter increase at this site (incidence-angle-normalised VH contrast +1.01 dB, $p < 0.001$; Section 4.3; Eckerstorfer and Malnes 2015; Keskinen et al. 2022), and an independent Sentinel-2 NDSI check likewise found a significant, polygon-localised contrast (Section 4.3); both contrasts remained significant under a spatially decorrelated robustness check that addresses pixel-to-pixel spatial autocorrelation (Section 4.3), increasing confidence that they are not artefacts of the pixel-population testing itself. Both confirm that a debris-consistent surface disturbance occurred at the mapped location and timing; as non-discriminating indicators of avalanche occurrence rather than of trigger mechanism, however, they are consistent with, rather than independently diagnostic of, the officially documented human trigger. No avalanche-control or explosive mitigation work was identified in the sources reviewed for this site (Section 2.2); this weighs against, though on the basis of an absence of reporting rather than a confirmed negative, ski-patrol control activity as an alternative explanation for the documented human trigger. Taken together, the terrain and meteorological evidence do not exclude a natural contribution to loading at this site, while the satellite evidence independently confirms that a debris-consistent disturbance occurred at the documented location and time; combined with a wind-transport analysis that rules out one candidate natural loading pathway, this evidence is consistent with, and does not contradict, the officially documented human-triggering account, although — as discussed above — it is not on its own diagnostic of trigger mechanism. The runout simulation is not included in this synthesis: as noted in Section 3.5, its underlying one-dimensional assumption was not expected to hold well at this site, and the resulting underestimate (Section 4.4) is accordingly treated as illustrative of the model's structural limits rather than as evidence bearing on the triggering question here. Table 5 summarises these four evidence streams alongside the documented human-triggering circumstance at each site.

Table 5. Summary of the four independent evidence streams at each site, relative to the documented human-triggering circumstance.

Evidence stream	Zone-1 (Sultan Sekisi)	Zone-2 (Yusufun Deresi)
Terrain (slope vs. 30° release threshold)	Below threshold (23° median); consistent with the need for an external trigger	Near threshold (29° median; DEM-resolution sensitivity test suggests this may be a conservative underestimate); ambiguous on its own
Meteorological (natural trigger & wind-transport loading)	No natural trigger recorded in the preceding 72 h; wind configuration intermediate ($\Delta = 49^\circ$) — cannot be excluded but not favoured	Moderate snowfall (13.0 cm / 11.2 mm; first-order critical-load check inconclusive); wind configuration windward ($\Delta = 176^\circ$, $\bar{R} = 0.66$) — wind-transported loading ruled out
Satellite verification (Sentinel-1 SAR + Sentinel-2 NDSI)	SAR: not detected (-0.17 dB, $p = 0.148$), null result confirmed under spatial-decorrelation check. NDSI: nominally significant in the raw pixel test, but inconclusive after the decorrelation check ($n = 4$)	SAR: detected ($+1.01$ dB, $p < 0.001$), confirmed under spatial-decorrelation check. NDSI: detected; significant contrast confirmed under decorrelation check
Runout simulation (forest-friction Voellmy-Salm)	Reproduces observed extent to within 25% (non-tuned parameterisation)	Excluded from synthesis (Section 3.5); underestimates observed extent by ~64%, illustrating a known structural model limitation rather than bearing on the triggering question
Documented circumstance	Athletes present on release terrain during a training exercise (national media)	Official municipal attribution + administrative penalties (a potential source-conflict-of-interest is discussed in Section 5.2)
Overall	Independent physical evidence is consistent with, and does not contradict, the documented circumstance	Independent physical evidence is consistent with, and does not contradict, the documented circumstance; terrain and loading conditions alone remain ambiguous

These findings carry practical relevance beyond the two events examined. A recent short communication documented a four-decade history of fatal avalanche events at Palandöken and called for improved early-warning and safety-training measures without the benefit of event-specific physical analysis (Torpuş et al. 2025); the present study demonstrates how documented incident circumstances can be independently corroborated with physically-based, open-data analysis, providing a reproducible complement to media and administrative accounts of individual events. More broadly, the recreational, open-terrain exposure pattern examined here contrasts with the building-focused exposure pattern documented for Turkish avalanche fatalities nationally, where the large majority of deaths occur indoors rather than outdoors (Aydin et al. 2014); ski-area avalanche risk in Türkiye is accordingly a distinct hazard category from the rural, structural risk that has received greater attention in the Turkish literature to date (Gürer et al. 1995; Aydin et al. 2014). The two events examined here point to different risk-management gaps rather than a single generic one: Zone-1 involves an apparently organised group activity on marginal, off-piste terrain, for which the relevant question is one of activity authorisation and pre-activity terrain assessment, whereas Zone-2 involves individual

boundary violation into a closed area that was subsequently enforced administratively, for which boundary signage, physical barriers and monitoring are more directly relevant. This study cannot establish how many comparable training sessions or boundary crossings occur at this ski area without triggering a release; the two events analysed here are documented case studies rather than a population-level estimate of risk, and the corresponding base rate of exposure is not known.

5.2. Limitations and Sources of Uncertainty

Several methodological constraints qualify these conclusions. The 30 m resolution of the Copernicus GLO-30 DEM (European Space Agency 2024) is considerably coarser than the high-resolution terrain models typically used in three-dimensional avalanche dynamics studies (Hofmeister et al. 2022; Christen et al. 2010), limiting the precision with which fine-scale release-zone features can be resolved; the areal statistics in Table 2 mitigate but do not eliminate this constraint. A resolution-coarsening sensitivity test — recomputing mean release-zone slope after aggregating the native 30 m DEM to 60, 90 and 120 m and extrapolating the resulting trend toward finer resolutions — indicated that slope is systematically underestimated at coarser resolutions at both sites, by an estimated $0.3\text{--}0.8^\circ$ toward finer resolutions; this is a small effect in absolute terms but is directionally relevant at Zone-2, whose median slope (29°) lies closest to the 30° release threshold (Sections 4.1, 5.1). The Sentinel-1 comparison reported in Section 4.3 applies a local-incidence-angle (γ_0) radiometric terrain correction and a two-sample statistical test (Welch's t) to pixel populations rather than comparing raw polygon-mean backscatter alone; the terrain correction used is a simplified, azimuth-aware local-incidence-angle approximation rather than a full SAR-geometry, layover/shadow-aware correction, though because the compared scenes share an essentially identical acquisition geometry within each same-orbit pair, static geometric correction terms largely cancel in the post-minus-pre differencing used here, which was confirmed by reproducing the reported contrasts to within 0.01 dB under both correction schemes (Section 4.3). An effective-number-of-looks (ENL) characterisation of speckle statistics was attempted using a homogeneous, low-slope reference area near each site but could not be obtained, as no sufficiently large flat reference patch was available in this terrain; this remains an unresolved gap in the SAR uncertainty characterisation. Both the SAR and NDSI pixel-population tests in Section 4.3 initially treat neighbouring pixels as statistically independent, which would understate the true standard error; both contrasts were therefore re-tested on a spatially decorrelated subsample (systematic sampling at a grid spacing several-fold coarser than the native pixel size). The

Zone-2 SAR and NDSI contrasts, and the Zone-1 SAR null result, remained consistent with the pixel-population test under this stricter check; the Zone-1 NDSI contrast did not, and is accordingly treated as inconclusive (Section 4.3, 5.1) rather than as evidence for a localised disturbance at that site. Because the decorrelated subsamples are themselves small (as few as $n = 4$ for Zone-1's NDSI test, reflecting its 2.0 ha polygon), this check has limited power to detect a real but smaller effect and should be read as a robustness screen rather than a definitive test. Finally, the Sentinel-1 post-event scene at Zone-2 was acquired 3 days after the event (18 February 2025, against a 15 February event; Zone-1's post-event scene coincided with the event date itself), so additional snowfall or wind redistribution in the intervening days cannot be excluded as a partial contributor to the observed backscatter contrast at that site. The NDSI polygon-versus-buffer contrasts reported in Section 4.3 are similarly not fully separable from confounding factors such as differential snowfall accumulation, cloud shadow, or illumination differences between the polygon and its surrounding buffer, and are interpreted as indicative rather than conclusive evidence of localised surface disturbance. The first-order critical-load comparison at Zone-2 (Section 5.1) resolves only the incremental shear stress from the new snowfall itself, not the total pre-existing slab overburden, weak-layer type, temperature-gradient metamorphism, prior loading history, or wind redistribution, and should be read as an order-of-magnitude plausibility check rather than a site-specific stability calculation. Meteorological reconstruction relies on a single station 0.6–2 km from the release zones, at a fixed elevation that may not fully represent local wind exposure and snow accumulation; multi-year field studies elsewhere have shown that wind-slab regimes can vary sharply over comparable distances in complex terrain (Eckerstorfer and Christiansen 2011), so the wind-loading assessment in Section 4.2 should be interpreted as indicative of regional conditions rather than as a site-specific measurement at either release zone. The absence of a Sentinel-1 debris signature at Zone-1 is inherently weaker evidence than a positive detection, consistent with the known size-dependence of SAR-based avalanche detection reliability (Keskinen et al. 2022), and is treated as uninformative rather than corroborating (Section 5.1). The Voellmy-Salm model is a one-dimensional, point-mass formulation that does not capture the full three-dimensional momentum balance represented in frameworks such as RAMMS (Christen et al. 2010); a non-tuned cross-check using a literature-typical, a priori forest-friction coefficient ($\mu_{\text{forest}} = 0.40$) reduced the simulated runout by 66% relative to the open-slope prediction (643 m to 220 m) — a larger proportional reduction than achieved by the calibrated best-fit parameterisation itself (643 m to 294 m, a 54% reduction) — indicating that the forest-friction mechanism itself, rather than the specific calibrated value, accounts for most of the

improvement in fit at Zone-1, although the additional close agreement obtained by calibration should still be read as a physical consistency check rather than independent model validation; the systematic underestimation at Zone-2, which is essentially unchanged between the non-tuned and best-fit parameterisations (167 m versus 169 m), directly illustrates the model's structural limitation there rather than a sensitivity to the friction parameter. The avalanche polygons were delineated through visual interpretation of imagery rather than field-surveyed boundaries. The documented circumstances reported in national media, and the official municipal statement for Zone-2, are not peer-reviewed sources and were not independently verified beyond the cited reports; they are treated here as reference accounts against which the physical evidence is compared, not as evidence generated or verified by this study, and their reliability is bounded by that of the original reporting. At Zone-2 specifically, the Erzurum Metropolitan Municipality is both the source of the official causal account and the authority that subsequently issued administrative penalties to the individuals it named, so the fines should not be read as a source of evidence independent of the narrative itself; a municipality responsible for the ski area also has an institutional interest in attributing the event to visitor conduct rather than to gaps in closure enforcement, patrol coverage or avalanche-control activity. This potential source bias cannot be adjudicated by the physical evidence assembled in this study; the independent-evidence design applied here — testing the account against terrain, meteorological and satellite evidence gathered without reference to it — is intended to mitigate, though it cannot eliminate, this risk. Finally, the regional snowpack structure — including the presence of the weak layers required for slab release — is inferred from independent field measurements at a nearby site in a different winter season (Ertaş and Şorman 2024) rather than event-specific observations, and this case-study approach, while complementary to the region's established susceptibility-mapping tradition (Selçuk 2013; Nasery and Kalkan 2021; Varol 2022; Kurt 2022) and to the recent shift toward machine-learning-based susceptibility and forecasting assessment (Durlević et al. 2022; Thakur et al., 2024; Pérez-Guillén et al. 2025; Viallon-Galinier et al. 2023; Markov et al. 2025), does not itself generalise to other events without further validation. As emphasised throughout, the multi-evidence framework applied here evaluates physical plausibility relative to documented circumstances rather than providing direct, instrumented proof; a minor, undetected natural contribution at either site cannot be entirely excluded. This study also lacks a natural-triggering control case — a confirmed, non-human avalanche analysed with the same protocol — against which the sensitivity and specificity of the terrain, meteorological and satellite evidence streams used here could be independently benchmarked; extending the protocol to such cases,

noted as a direction for future work in the Conclusion, is accordingly a limitation of the present case-study design and not only an opportunity for extension.

6. Conclusion

This study presented a multi-evidence, physically-based framework for verifying the circumstances of avalanche triggering, and applied it to two avalanches at the Palandöken ski area, Erzurum, Türkiye, both associated with the presence of people outside marked ski runs during the 2024–2025 winter season. For Zone-2, an official municipal statement, reported in national media, directly attributed the event to skiers and snowboarders who entered a closed area and cut across the slope; for Zone-1, national media reported that a group of athletes was present on the exact release terrain at the time of the event, though without an official statement on the immediate mechanical cause. Rather than inferring a trigger from physical evidence alone, we used these documented circumstances as reference cases and tested whether an independent reconstruction — combining DEM-derived terrain analysis, in-situ meteorological reconstruction, wind-transport assessment, satellite-based snow-cover and debris verification, and forest-friction-explicit runout simulation — is physically consistent with them. At Zone-1, terrain steepness, meteorological conditions and runout dynamics were jointly consistent with a human-triggered release on otherwise marginal terrain, corroborating the documented presence of a group at the release site; a non-tuned runout cross-check reproduced the observed extent to within 25% (220 m against 293 m observed), and calibration to the observed extent narrowed this further, a distinction that should be read as a consistency check rather than blind prediction. At Zone-2, terrain and snow-loading conditions alone were ambiguous — this study does not quantitatively exclude direct snowfall loading as a sufficient natural cause. The wind-loading analysis ruled out wind-transported loading as a contributing mechanism, and an independent Sentinel-1 and Sentinel-2 disturbance signal confirmed that avalanche debris was present at the documented location and time; it is the officially documented municipal account, not this physical evidence on its own, that corroborates the trigger itself. The runout model was not included in this synthesis: it substantially underestimated the observed extent at this site (167–169 m against 466 m observed) in a way that was expected given the site's wider, less-confined morphology (Section 3.5), and is treated as illustrating a limitation of the simplified model rather than as evidence for or against the documented account. Neither the physical evidence nor the media and administrative accounts on which it is compared constitute direct, instrumented proof of the triggering moment; but the consistency between two independently sourced lines of evidence — documented circumstance and physically-based reconstruction —

provides stronger support than either would on its own, and demonstrates the value of combining terrain, meteorological, and satellite evidence with physically-based modelling as a complement to incident reporting when no instrumental record of the triggering moment exists.

Beyond the two events examined here, this work illustrates a broader point for avalanche hazard management at ski areas and other mountain recreation sites: regional susceptibility mapping alone cannot determine why a specific avalanche released on a specific day, and closing that gap requires reconstructing the meteorological and terrain context of individual events and, where available, corroborating them against documented incident circumstances, rather than relying on regional hazard classification alone. The protocol applied here uses exclusively open-access satellite and in-situ data and is demonstrated, in this study, on two events at a single ski area; extending it across a larger sample of events — ideally including cases of confirmed natural release, to test its ability to correctly rule out human triggering — and to three-dimensional runout modelling where high-resolution terrain data permit, would be needed to establish how generally the patterns identified in these two documented cases — including the physical plausibility of human triggering on below-threshold, forest-confined terrain illustrated at Zone-1 — extend to other events, rather than treating them as a population-level estimate for Turkish or comparably instrumented mountain settings.

CRedit authorship contribution statement

Mustafa Cansaran ERTAŞ: Methodology, Investigation, Visualization, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The DEM, Sentinel-1/Sentinel-2 satellite imagery and meteorological station records used in this study are openly available from the Copernicus and Turkish State Meteorological Service sources cited in Table 1. The analysis code (Google Earth Engine terrain, SAR and optical processing scripts, and the Voellmy-Salm runout simulation) is available from the corresponding author upon reasonable request.

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Generative AI Declaration

During the preparation of this work, the authors used Claude (Anthropic) and OpenAI ChatGPT for data analysis code development, language refinement, structural improvement, and text editing. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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