START-ZONE TERRAIN AND THE OCCURRENCE AND TIMING OF WET SLAB AVALANCHES IN COLORADO

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ABSTRACT: Wet slab avalanches (WSAs) release when liquid water reduces the strength of a buried weak layer or interface, and their timing is governed primarily by the snowpack energy balance and the movement of meltwater. We classified 717 WSAs from the Colorado Avalanche Information Center database (2011–2025) into five start-zone terrain categories and analysed the timing of naturally triggered, near- and above-treeline events using rank-based and Bayesian hierarchical methods. Start-zone terrain strongly governs the natural occurrence of WSAs: approximately 64% released in Rocky start zones (Cliffs/Rocks), while only ≈4% occurred on Open Slopes. After controlling for latitude and aspect, Rocky start zones released approximately five days before Open Slopes (90% CrI: 0.6–9.9 days). Latitude was the dominant timing predictor, shifting release by roughly 3–4 weeks from southern to northern Colorado. Cornice start zones concentrated WSA activity in early to mid-spring, with 40 of 41 releasing before mid-May. These findings support start-zone terrain classification as a low-cost addition to observation protocols for improving the spatial targeting of wet slab outlooks.

KEYWORDS: wet slab avalanche; start zone; terrain classification; release timing; Bayesian hierarchical model; Colorado

1. INTRODUCTION

Wet slab avalanches (WSAs) release when liquid water reduces the strength of a buried weak layer or interface; their timing is governed primarily by the snowpack energy balance and the movement of meltwater rather than by new loading (Conway and Raymond 1993; Baggi and Schweizer 2009; Mitterer and Schweizer 2013). In Colorado's continental snow climate (Mock and Birkeland 2000), WSAs occur predominantly in late winter and spring, as meltwater percolates through the snowpack, rather than from rain-on-snow. It is difficult to know when water reaches the layer of concern, and forecasting or mitigating WSAs is challenging (McClung and Schaerer 2006). Indeed, active mitigation often yields minimal results. Regional forecast centers have, at times, underpredicted wet avalanche cycles, given the difficulty of forecasting occurrence timing, especially during the first rapid spring warming cycle (Logan and Greene 2018; Logan and Greene 2023; Guy and Peitzsch 2023).

Forecasters traditionally anticipate WSA onset using weather variables, such as temperature, wind speed and direction, and incoming and outgoing radiation, to gauge meltwater production, a practice increasingly supported by physics-based snowpack models (Mitterer et al. 2011; Wever et al. 2016; Bellaire et al. 2017). However, weather variables indicate meltwater production, but not where it sits in the snowpack or whether it is near the layer of concern. Snow-cover models such as SNOWPACK can simulate the current and forecasted position of the wetting front (Wever et al. 2016; Bellaire et al. 2017), but this work is ongoing, and the model chains require tuning and verification. Aspect and elevation serve as proxies for the radiation and temperature regime, consistent with the strong spatial variability observed in wet-snow liquid-water content (Techel and Pielmeier 2011).

Current practice anticipates WSA onset through aspect and elevation, a pattern our data reproduce, and this works well for backcountry forecasting. Advising backcountry travelers to avoid sunnier aspects as a cycle begins, for example, is avoidance advice they can act on. Highway programs face a different challenge. Road locations are fixed, and closing roads for every warm spell is rarely practical. By the time field signs such as deep foot penetration indicate that a slope is wet, it is usually too late to mitigate. These programs need to know which slopes are likely to produce wet slabs, and roughly when, so they can time mitigation before a cycle starts. Ski patrols and backcountry travelers evaluating an individual slope share the same need.

One slope-scale variable related to WSA occurrence has been largely overlooked: the physical character of the start zone itself. Practitioners realize that wet slabs frequently initiate around exposed rocks and cliff bands. This may be because rock absorbs shortwave radiation and conducts heat into the adjacent snowpack, locally increasing meltwater production and instability ahead of surrounding slopes devoid of those dark objects (i.e., cliffs or rocks). However, start-zone terrain characteristics such as Cliffs/Rocks, Couloirs, Cornices, Trees, and Open Slopes are rarely recorded or explicitly analyzed. We classified more than 700 start zones of wet slab avalanches and

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asked three questions: 1) Which start-zone features are most associated with wet slabs? 2) Once latitude and aspect are accounted for, do certain start-zone characteristics produce wet slabs first? 3) When other variables are controlled, do certain aspects or locations in Colorado produce wet slab avalanches first? Our subsequent analysis and answers can help highway and ski-area programs as well as backcountry travelers take action.

2. METHODS

2.1. Data and start-zone classification

We compiled 717 WSAs from the Colorado Avalanche Information Center (CAIC) database (2011–2025) that included start-zone oblique imagery. Because the dataset requires oblique imagery, it favors visible and accessible terrain. Two forecasters independently reviewed the images and manually classified each avalanche start zone into one of five terrain categories (Figure 1). Start zones showing more than one feature were assigned to the dominant one. For each avalanche, we recorded the location, start-zone terrain category, trigger (natural or human-triggered), aspect, elevation band, date (or estimated if precise date is unknown), and time of occurrence. For avalanches with unknown occurrence times, we assigned a default time of 12:00 PM (Greene et al. 2016).

2.2. Analysis population

We used naturally triggered WSAs at or above the treeline (commonly near 3500 m in Colorado) to analyze the timing of WSA release. We excluded events without a recorded trigger, leaving 255 avalanches. We grouped the five field categories into three analysis classes: Rocky (Cliffs/Rocks), Open (Open Slopes and slopes under Cornices), and Couloir (couloirs within cliff bands). Above the treeline, there is no forest canopy, so dark bodies (rocks and cliffs) in the start zone are likely the primary local controls on energy absorption into the snowpack. We focused on natural releases because they carry timing information; they occur when the snowpack becomes unstable, whereas human-triggered avalanches occur when someone reaches and loads the slope. We expressed timing as day-of-season (days since 1 October), treated aspects as eight cardinal classes and as a binary variable for sunny (E/SE/S/SW) or shady (N/NE/W/NW), and used latitude as a continuous covariate.

2.3. Statistical analysis

Release dates in our database are skewed, with most avalanches clustered together and a long tail of late-season events. Rather than assume a bell-shaped distribution, we used rank-based and Bayesian methods throughout, computed in Python with SciPy (Virtanen et al. 2020), statsmodels (Seabold and Perktold 2010), scikit-posthocs, and PyMC, Bambi, and ArviZ for the Bayesian models (Abril-Pla et al. 2023; Capretto et al. 2022; Kumar et al. 2019). The analysis proceeds in three stages: we first ask whether release timing (by date) differs by terrain, then check whether that difference, if present, survives after accounting for latitude and aspect, and finally test a specific forecasting hypothesis about late-season avalanches in rocky start zones.

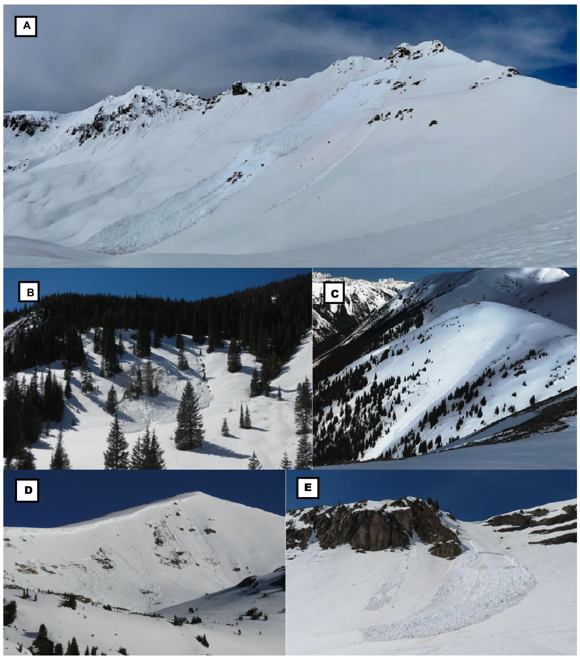

Figure 1: Start zone classification into five types from images. A) Cliffs/Rocks—WSA beneath a band of exposed, vertical rock, or among scattered exposed rocks (Image: Ben Pritchett). B) Trees—WSA releasing from or among a stand of trees (Image: Scott Toepfer). C) Open Slope—WSA on a slope bearing only snowpack (Image: Brian Lazar). D) Cornice—WSA beneath a cornice (Image: Brandon Levy). E) Couloir—WSA on a snow-filled chute or couloir bounded by rock (Image: Crested Butte Avalanche Center).

Do terrain types release at different days throughout the year? We compared release timing across the three terrain classes using the Kruskal–Wallis test (Kruskal and Wallis 1952), then used Dunn's Holm-adjusted post hoc test (Dunn 1964; Holm 1979) to identify which specific pairs of terrain types differed. For simple two-group comparisons, we used the Mann–Whitney U test (Mann and Whitney 1947). All three tests compare the rank order of release dates rather than their raw values, which suits our skewed data.

Is that difference really about terrain, or about latitude and aspect? Latitude and aspect both shift melt timing, so before crediting terrain with an effect, we needed to rule them out. We summarized the latitude effect with a Spearman rank correlation (Spearman 1904) and by splitting sites into southern and northern halves at the median latitude. To isolate terrain from aspect, we median-centered day-of-season within each aspect and retested terrain on the residual, asking, in effect, whether terrain still matters once we account for a slope's orientation. We then controlled for latitude and aspect jointly in two complementary ways: an ordinary least-squares regression (`day_of_season` $\sim$ `latitude + aspect + terrain`) with a Type II ANOVA to partial out each effect, and a Bayesian hierarchical Student-t model (`day_of_season` $\sim$ `terrain + latitude + (1|aspect) + (1|season)`) in which terrain is a population-level effect (reference = Rocky) while aspect and season are partial-pooled random effects that absorb warm- versus cold-spring variation (Gelman and Hill 2007). We drew four chains and confirmed convergence with the Gelman–Rubin statistic ($\hat{R} \leq 1.01$). To visualize the model's implied timing (Figures 3 and 7), we generated posterior-predictive draws of day-of-season with aspect and season random effects marginalized out: varying terrain at mean latitude (Figure 5), and varying latitude (± 1 SD) with terrain fixed at Rocky (Figure 4); curves show the empirical cumulative distribution of these draws. We added a further terrain and sunny/shady interaction model to test whether the terrain effect depends on sun exposure.

2.4. Rocky terrain and melt-out timing

Some practitioners suggest that certain slopes do not produce wet slab avalanches until ablation exposes rocks in the start zones (Figure 2). The result would be late-season avalanches around rocks and cliffs that could skew the timing data.

Testing this is harder than simply counting late-season avalanches because we only observe slopes that released, not the full population of slopes that could have released. That "at-risk" population shrinks throughout the season as slopes avalanche and drop out of the pool, a survivor bias that thins late-season counts for every terrain type, not just rocky start zones. To work around this, we relied on measures that are robust to this bias: the survivor-robust composition of activity (each terrain's share of events by half-month) and the trend in rocky terrain's share of rocky-plus-open-slope events over the season, estimated using logistic regression. We also characterized each terrain's tail shape relative to its own peak (kernel-density mode), so that "late" means past the bulk of that group's own activity, summarizing with the mean−median gap, skew, and the post-peak versus pre-peak share of events. We compared a Normal, a skew-normal, and a two-component Gaussian mixture fit to the rock release dates using leave-one-out cross-validation (LOO; Vehtari et al. 2017). We lack the slopes-at-risk denominator (the full population of slopes that could produce wet slab avalanches); therefore, our timing models describe when avalanches tend to occur and not an absolute hazard of release.

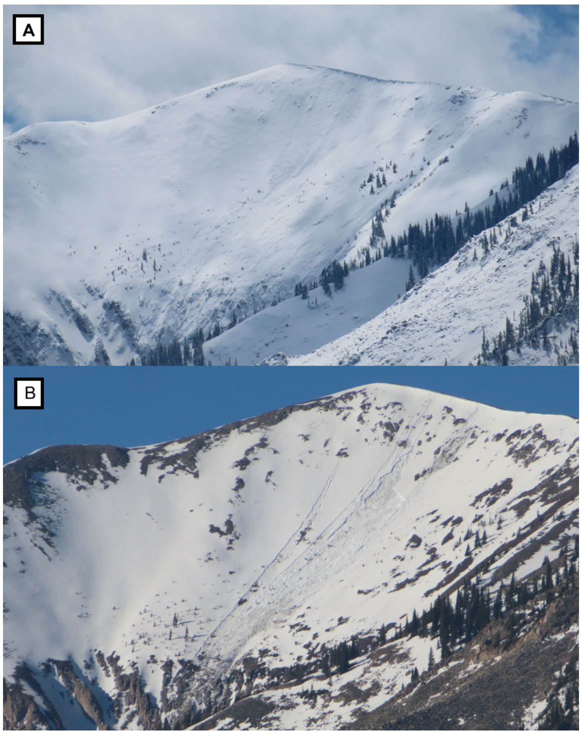

Figure 2: A) Whetstone Mountain with a small (D1) dry snow avalanche on April 2, 2026. The slope is largely devoid of exposed rocks at this point. B) Whetstone Mountain with a large (D2) wet slab avalanche on May 13, 2026. The slope has many exposed rocks in the start zone (images: Zach Guy).

3. RESULTS

3.1. Terrain type and WSA occurrence

Natural wet slab avalanches occur most often around cliffs and rocks. Among natural, near- and above-treeline events, 64% released from Cliffs/Rocks, 16% from Cornices, 9% in Couloirs, 7% in Trees, and 4% in Open Slopes. The terrain distribution differed significantly between natural and human triggers ($p < 0.001$): human-triggered WSAs spread far more evenly across start-zone types, with Open Slopes approaching the frequency of Rocky terrain. The distinction between natural releases associated with Rocky terrain and human releases distributed across terrain types is the strongest terrain signal in the dataset. This result suggests start-zone terrain as a control on the natural occurrence of WSA rather than human-triggered WSAs.

3.2. Latitude and aspect

Wet slab avalanche release began in southern Colorado and continued northward as the season progressed. Latitude of WSA occurrence correlated with day-of-season ($r_s = 0.33$, $p < 0.001$); southern-Colorado events released a median of 25 days earlier than northern ones ($p < 0.001$), and the hierarchical model estimated $+8.7$ days per degree of latitude (Figures 3 and 4). Aspect also influenced timing (Kruskal–Wallis across eight aspects $H = 16.4$, $p = 0.02$): north aspects released latest, by roughly three weeks after the earliest, and sunny aspects released ≈ 10 days before shady aspects (one-sided $p < 0.001$; Figure 3).

3.3. Comparing like-for-like: terrain shifts release timing

Terrain signals are masked when comparing release dates across the entire dataset due to the impacts of aspect and latitude. When we control those two variables and compare like-for-like among slopes at similar latitude and aspect, Rocky start zones release on the order of five days before Open Slopes (Figure 5), while Couloirs are indistinguishable from Rocky start zones in their central timing.

- **Aspect-centered timing:** Kruskal–Wallis across terrain $H = 6.8$, $p = 0.03$; Rocky earlier than Open Slope one-sided $p = 0.06$; Rock earlier than Couloir $p = 0.01$.
- **Joint control (Type II ANOVA):** latitude $F = 16.7$ ($p < 0.001$), aspect $F = 2.4$ ($p = 0.02$), and terrain $F = 2.7$ ($p = 0.07$)—marginal after the other two; the residualized one-sided rank test gave Rocky earlier than Open Slope, $p = 0.04$.
- **Bayesian model** (reference = Rocky): Open Slope $+5.3$ days (90% CrI 0.6–9.9), Couloir $+1.2$ days (90% CrI -5.0–7.3), latitude $+8.7$ days/°N (Figure 6).

All three estimates control for latitude and aspect jointly, and the two are not confounded: Rocky and Open Slope avalanches occurred at statistically indistinguishable latitudes (median $39.0°$ vs. $38.9°$, Mann–Whitney $p = 0.45$). Controlling for latitude therefore sharpens the terrain estimate by removing latitude noise rather than removing a bias; the Rocky-vs-Open Slope contrast is one-sided $p = 0.21$ with no controls, 0.05 controlling for aspect, and 0.04 controlling for both latitude and aspect. The interaction model showed the rocky head-start was not amplified on sunny aspects (sunny Open Slope − Rocky $= +5.3$ days; shady $= +8.5$ days; interaction $+3.2$ days, 90% CrI -6.9–13.3; Figure 7): terrain and aspect act largely additively rather than synergistically.

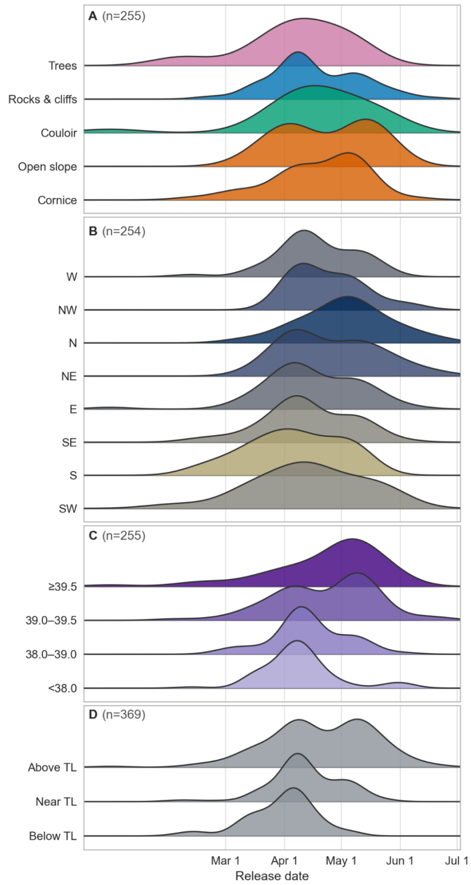

Figure 3: Observed release timing (day-of-season) by (A) start-zone terrain (blue = Rock, vermillion = Open, green = Couloir, pink = Trees), (B) aspect, clockwise from W and shaded by sun exposure (light = sun-facing, dark = shaded; aspects mirrored about the S–N axis, such as E and W, share a step), (C) latitude band (darker = farther north; $n = 72, 54, 74, 55$ from south to north; Spearman $\rho = 0.30$, $p = 8 \times 10^{-7}$ on raw latitude, not the binned bands), and (D) position relative to treeline. All panels are stacked kernel-density ridges on one shared date axis, each normalized to equal peak height, with each panel's sample size shown in its upper-left corner; panels (A)–(C) are natural, near/above-treeline events, (D) includes all natural events.

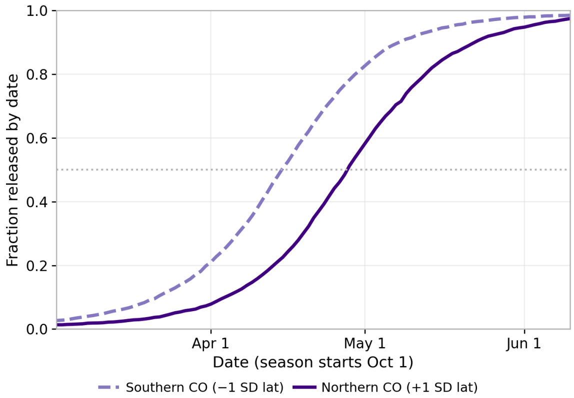

Figure 4: Predicted WSA release timing for rocky terrain, south vs. north: posterior predictive cumulative release curves (fraction of rock-terrain WSAs released by date) for southern (-1 SD latitude) vs. northern ($+1$ SD latitude) Colorado; the whole season shifts about three to four weeks earlier in the south.

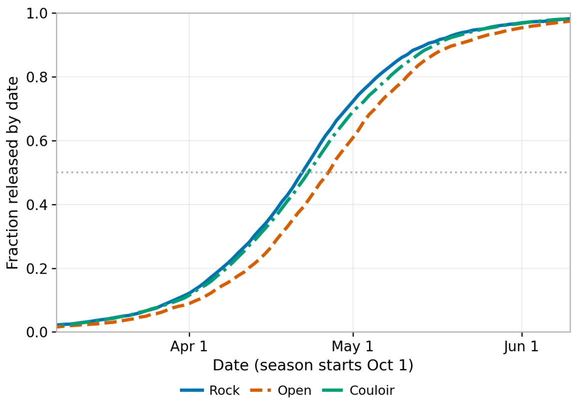

Figure 5: Predicted WSA release timing by terrain (mean latitude/aspect): posterior-predictive cumulative release curves by terrain at mean latitude and aspect; Rocky reaches 50% released roughly five days before open terrain.

Using the survivor-robust composition of activity (Figure 8), Rocky-terrain start zones accounted for approximately 75–80% of natural WSAs across all periods from March to late May, while Open Slopes were rare throughout the season. In contrast, WSAs in Cornice terrain types occurred more commonly in early- to mid-spring, with 40 of 41 releasing before mid-May. The within-season timing of WSAs in Cornice terrain confounds a naive Rocky-versus-"Open Slope" share comparison. In other words, the proportion of WSAs in rocky terrain appeared to rise after mid-May ($75\% \rightarrow 83\%$) only because the number of WSAs in corniced terrain decreased to zero, and the clean Rocky-versus-Open-Slope contrast rested on just 10 open-slope events. Whether the proportion of WSAs releasing in Rocky terrain rises specifically

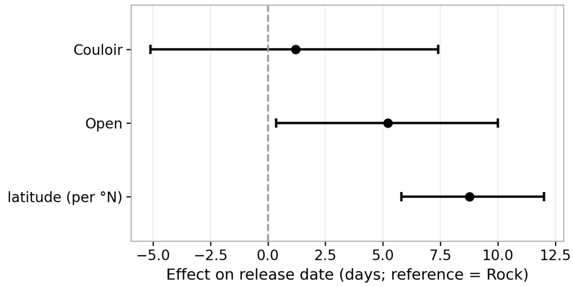

Figure 6: Posterior terrain and latitude effects on release day-of-season (90% credible intervals; reference = Rocky).

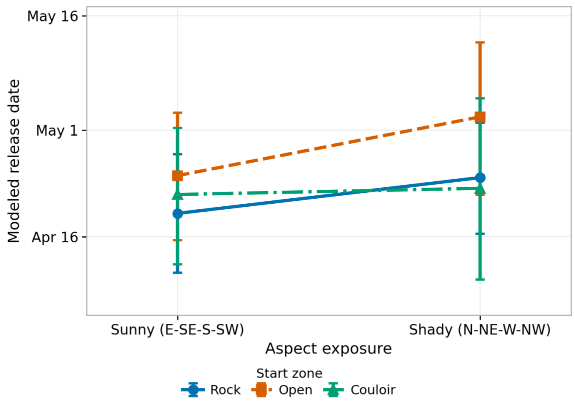

Figure 7: Aspect $\times$ terrain interaction in WSA release timing: modeled release date by aspect exposure for each terrain group (90% credible intervals). The terrain lines are essentially parallel; thus, the rock head-start does not depend on sun exposure.

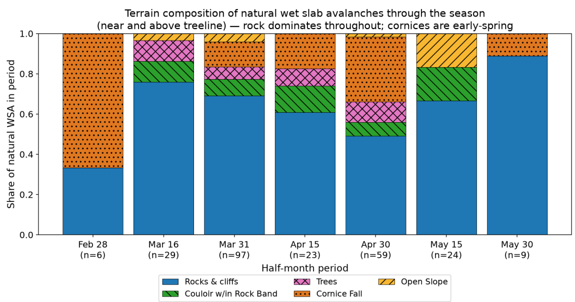

Figure 8: Terrain composition of natural near- and above-treeline WSA by half-month (proportion within each period; n per period shown). WSAs in rocky terrain (shades of blue) represent the majority of occurrences over time; WSAs in corniced terrain are an early-spring phenomenon, and those on open slopes are rare. The x-axis is the bin's start date.

late in the season remains unresolved (slope -0.005/day, $p = 0.46$).

The distribution of WSAs in Rocky terrain was right-skewed (Figure 9), with an early peak and a longer late-season tail. The peak frequency of WSA release is April 10, with median and mean release dates of April 14 and April 17, respectively. The three weeks beyond the distribution peak contained about three times as many occurrences as the early side of the distribution ($\approx 25\%$ vs. 9%; Figure 9). The distribution of WSAs in open terrain showed the opposite: left-skewed (mean earlier than median). This confirms that the late tail is a genuine rocky feature, not a season-wide artifact.

4. DISCUSSION

The clearest result is that start-zone terrain governs where natural wet slabs release: roughly two-thirds occurred near Cliffs and Rocks, only a few percent on Open Slopes, and the terrain distribution for natural releases differed sharply from that for human-triggered wet slabs. This is consistent with a local radiative and conductive mechanism: exposed dark rock absorbs shortwave energy and warms the adjacent snowpack, advancing the liquid-water and energy-balance thresholds for wet-snow instability (Conway and Raymond 1993; Mitterer and Schweizer 2013). These avalanches occur ahead of wet slab avalanches on Open Slopes at the same latitude and aspect.

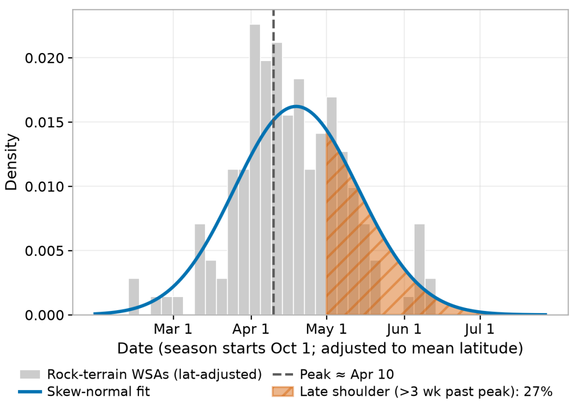

Figure 9: Latitude-adjusted rock-terrain release dates with the skew-normal fit, anchored on the distribution's own peak (≈Apr 10, dashed). The late shoulder, beyond three weeks past the peak (shaded), accounts for $\approx 27\%$ of events, about three times the matching early shoulder; the distribution is right-skewed (an early peak and a longer late tail) but unimodal, with no distinct second mode.

We emphasize that this is an association, not demonstrated causation. The link is observational, though it survives tests controlling for latitude, aspect, and season, and a coherence argument weighs against pure reporting bias. Natural WSA occur most often in Rocky terrain. Meanwhile, human-triggered WSAs are evenly distributed across all of the start-zone categories (Figure 1, Section 3.1.). Unmeasured confounders such as slope angle and radiative exposure (e.g., "super-northerly" slopes, which receive direct sun later), snowpack, microclimate, and wind speed and direction remain. Furthermore, the radiative mechanism is a physically plausible explanation, not a proven cause; establishing causation would require slope-angle control or direct measurement of snow warming beside exposed rock.

We set out to test the late-season melt-out idea directly, but the data left this hypothesis unresolved. Rocky start zones kept producing wet slabs long after Open Slopes stopped. This is consistent with wet slab avalanches occurring once melt exposes rock at the surface (Figure 2). The evidence is circumstantial and timing-based, so the survivor-bias caveat applies, and other explanations remain possible.

Several limitations apply, and results are specific to our dataset and Colorado's avalanche climate. We record compass aspect but not slope angle, so our sunny/shady proxy only partially captures true radiative exposure (consider, for example, "super-northerly" slopes). Additionally, trigger labels are missing for a substantial share of events, making our natural-versus-human-triggered counts provisional. The data are observation-only, with no denominator of slopes at risk; therefore, our timing models describe when avalanches tend to occur rather than an absolute release probability, including whether the melt-out pattern reflects a real process or differing at-risk pool sizes between terrain types.

Operationally, terrain's clearest value is spatial, not temporal: it flags where natural wet slabs concentrate far more reliably than it predicts when they'll release. This question—When will WSAs release?—is critical for highway and ski-area programs, since their terrain is fixed and field signs of wetting often appear too late to act. Cornice start zones are the one exception with a strong temporal signal: wet slabs below Cornices are an early- to mid-spring phenomenon that effectively ends by mid-May, so that risk can be front-loaded when planning action steps. Meanwhile, Rocky terrain produces wet slab avalanches into early summer.

5. CONCLUSIONS

- Natural wet slab avalanches (WSAs) near and above the treeline in Colorado are concentrated in start zones with Rocks and Cliffs ($\approx 64\%$) and are rare on Open Slopes ($\approx 4\%$); terrain strongly governs their occurrence.

- Release timing is controlled first by latitude ($\sim$3–4 weeks south to north) and aspect (north latest; sunny aspects earlier), with start-zone terrain a modest, secondary modifier.
- After controlling for latitude and aspect, Rocky start zones release ~ 5 days before open terrain; the effect is marginal and not amplified on sunny aspects. In practical terms, for our dataset, this means that within a given drainage or latitude band, start-zone terrain has a real effect on release order: Rock and Cliff terrain tends to avalanche first, followed by Couloirs, with Open Slopes releasing last.
- WSAs in Rocky terrain peak in early April, with roughly three times as many occurrences post-peak as pre-peak.
- Wet slabs from Cornice start zones happen in early and mid-spring, then stop almost entirely; 40 of 41 released before mid-May.
- Although human-triggered wet slabs are spread more evenly across terrain types, understanding that Rocky terrain typically avalanches naturally earlier and more frequently can improve travel strategies, particularly for managing overhead hazards.

Operationally, this spatial signal is most actionable for highway and ski-area programs, whose terrain is fixed and must be mitigated rather than avoided. A start-zone terrain tag flags which paths warrant the most observation and active mitigation at the slope scale. The timing signal is weaker and should be treated accordingly, as Rocky start zones keep producing wet slabs into late spring/early summer, and, following the melt-out hypothesis proposed in Section 2.4., a path that has visibly melted out enough to expose dark rock at the snow surface may warrant increased attention after the main wet-slab cycle has passed. We flag this as a hypothesis for operational testing, not an established trigger. Ultimately, recording start-zone terrain type is a low-cost addition to existing observation protocols that could improve the spatial targeting of WSA outlooks.

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