# Complexities of Using Satellite Imagery for Defining Snowline Altitudes

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## 1. Introduction

End-of-season snowlines (ESS) on glaciers may be mapped remotely from satellite imagery to find their snowline altitudes (SLA), to be used as proxies for the glacier equilibrium-line altitudes (ELA)[1]. When using this approach a number of potential limitations must be considered.

## 2. Methodology

2.1 Glaciers with long-term ELA records selected from World Glacier Monitoring Service (WGMS) database[2].

2.2 Two LANDSAT images selected per year for each glacier:
1. *Closest Date* - acquisition date closest to in-situ ELA measurement,
2. *Highest Snowline* - snow cover visibly at its least.

2.3 Snowline mapped manually for each image (Figure 1).

2.4 Snowline elevation extracted from ASTERGDEM V3. $\overline{\text{SLA}}$, $M$(SLA), and associated uncertainties calculated (Table 1).

2.5 Snowline metrics compared with corresponding in-situ ELA measurements.

Table 1. Common notations.

| Notation | Definition |
|---|---|
| ELA | Equilibrium line altitude from WGMS. |
| $\text{SLA}_i$ | Elevation of the snowline at point $i$. |
| $\overline{\text{SLA}}$ | Mean elevation of the snowline. |
| $M$(SLA) | Median elevation of the snowline. |
| $\Delta E_{\overline{\text{SLA}}}$ | $\overline{\text{SLA}}$ – ELA |
| $\Delta E_{M(\text{SLA})}$ | $M$(SLA) – ELA |
| $\varepsilon_{\overline{\text{SLA}}}$ | Measurement uncertainty for $\overline{\text{SLA}}$ |
| $\varepsilon_{M(\text{SLA})}$ | Measurement uncertainty for $M$(SLA) |

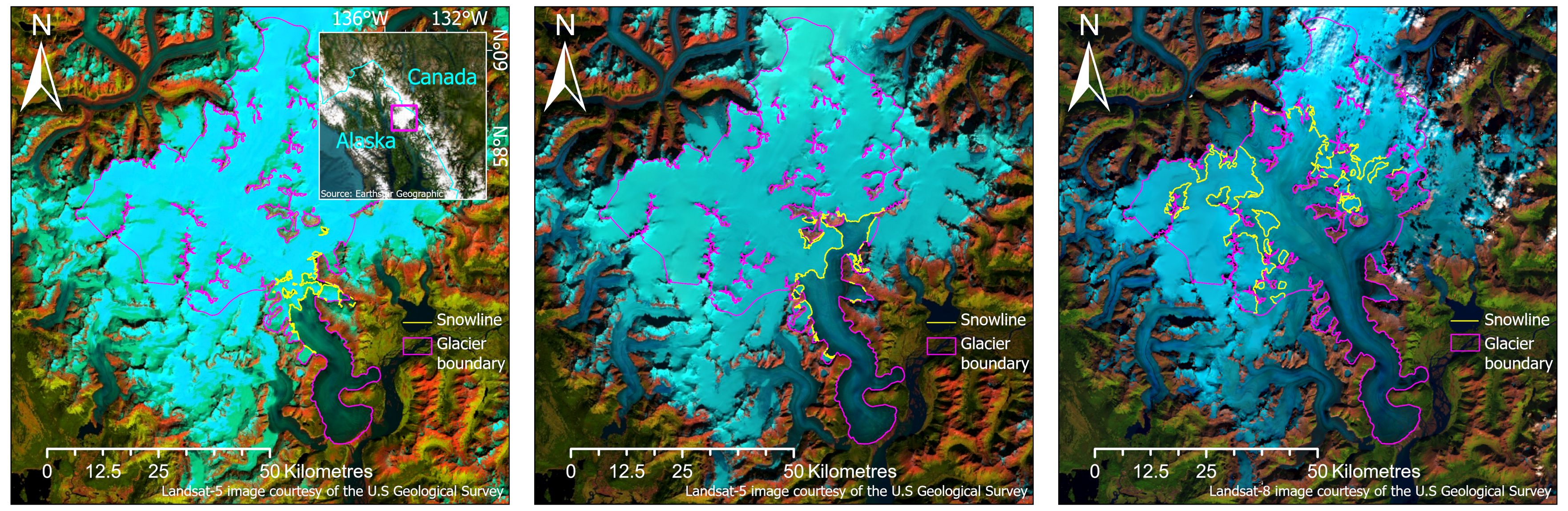

Figure 1. Taku Glacier, Juneau Icefield, Alaska, USA, on 02/08/1999 (left), 14/09/2009 (centre), and 10/09/2019 (right). Dates represent the imagery from which the least snow cover was visible. SWIR, NIR, and red false colour composites. The glacier boundary is shown in magenta, and the snowline is shown in yellow. Landsat-5 and Landsat-8 images courtesy of U.S. Geological Survey[3].

## 3. Results

For all glaciers:

*Closest Date* $\overline{\text{SLA}}$
- Median $\Delta E_{\overline{\text{SLA}}}$ = -221.3 m,
- $0.0 \lesssim R^2 \lesssim 0.5$.

*Highest Snowline* $\overline{\text{SLA}}$
- Median $\Delta E_{\overline{\text{SLA}}}$ = -84.7 m,
- $0.1 \lesssim R^2 \lesssim 0.7$.

*Highest Snowline M(SLA)*
- Median $\Delta E_{M(\text{SLA})}$ = -80.8 m,
- $0.1 \lesssim R^2 \lesssim 0.7$.

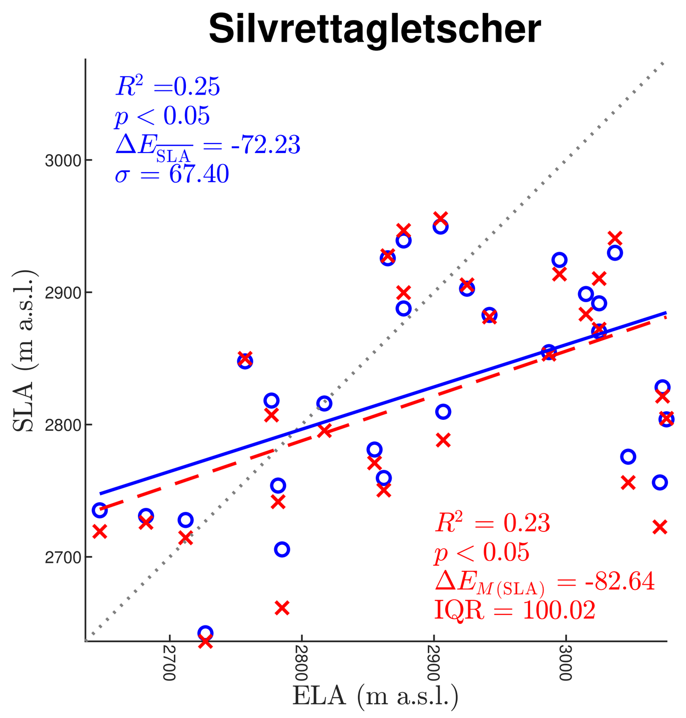


Figure 2. ELAs vs SLAs and for Silvrettagletscher, Switzerland. 1:1 reference line is shown in dotted grey. ELA vs. $\overline{\text{SLA}}$ points shown by blue circles, with regression line in solid blue. ELA vs. $M$(SLA) points shown by red crosses, with regression line in dashed red. Each point represents a year of measurement. $R^2$, $p$-value, median $\Delta E_{\overline{\text{SLA}}}$, and standard deviation ($\sigma$) are given in the top left for ELA vs. $\overline{\text{SLA}}$. $R^2$, $p$-value, median $\Delta E_{M(\text{SLA})}$, and Interquratile range (IQR) are given in the bootom right for ELA vs. $\overline{\text{SLA}}$.

$M$(SLA) performs better than $\overline{\text{SLA}}$ overall, but not in every case (e.g. Figure 2), suggesting a potential oversampling bias.

## 4. limitations

4.1 **Satellite revisit times** Landsat revisit times are 16 days (8 days where 2 satellites are in orbit simultaneously)[4].

4.2 **Cloud cover** The most extreme case was 86 days between the ELA measurement date and the collection date of a cloud-free image (Figure 3).

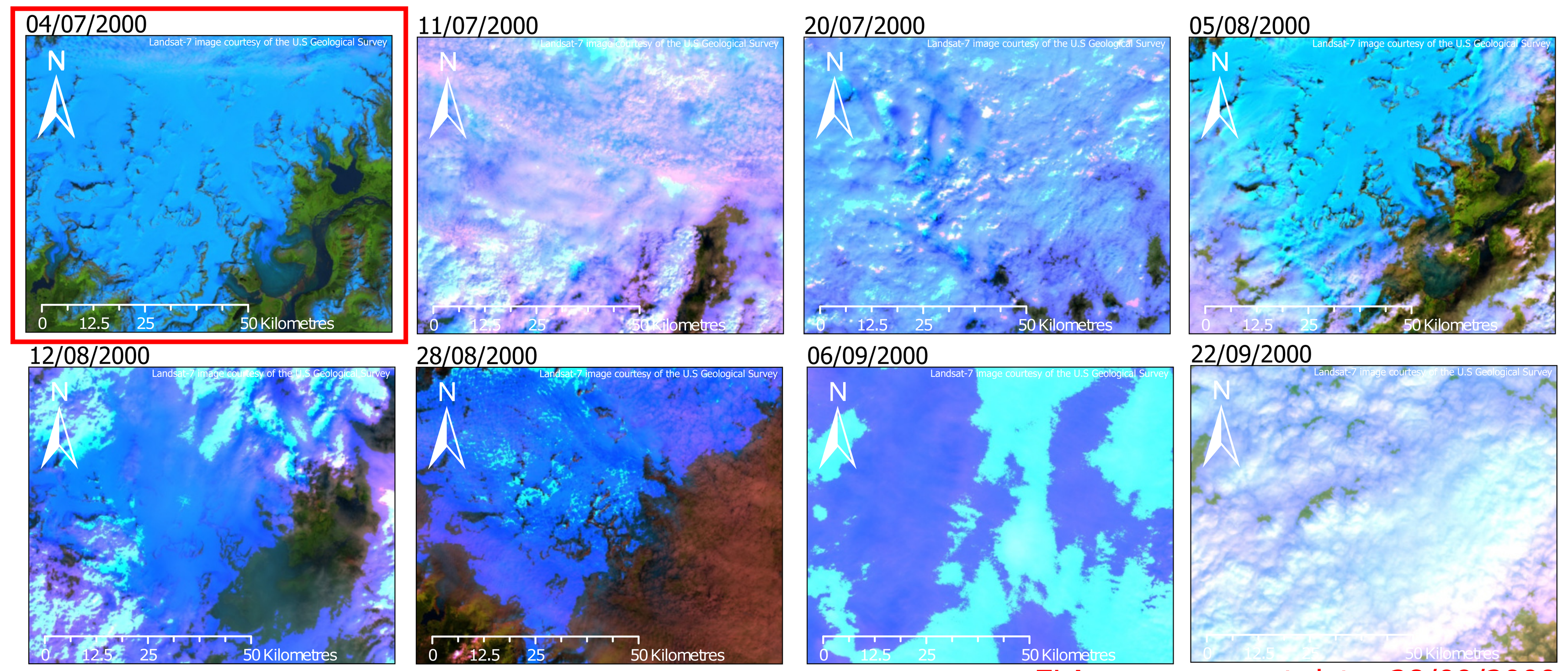


Figure 3. Taku Glacier, Juneau Icefield, Alaska, USA, 04/07/2000 - 22/09/2000. SWIR, NIR, and red false colour composites. Landsat-7 images courtesy of U.S. Geological Survey[3].

4.3 **Snowfall events** Early snowfall events may occur close to the date of the highest snowline (Figure 4).

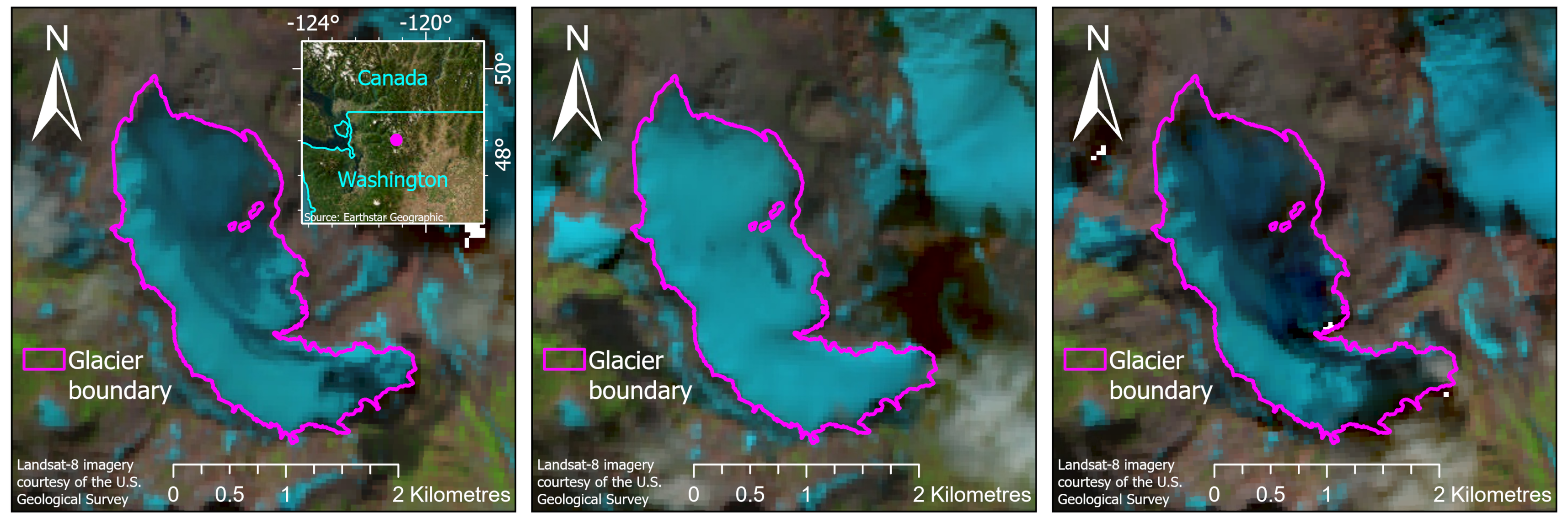


Figure 4. South Cascade glacier, Washington, USA, on 03/09/2018 (left), 12/09/2018 (centre left), 19/09/2018 (centre right), and 28/09/2018 (right). SWIR, NIR, and red false colour composites. Glacier boundary shown in magenta. Landsat-8 images courtesy of U.S. Geological Survey[3].

4.4 **4.4. Firn Exposure** In years where the snowline is higher than the previous year, firn may be exposed. It can be difficult to distinguish the snowline and firnline from satellite imagery in this case[5][6].

4.5 **Superimposed Ice** Meltwater from snowfall percolates down into pore spaces within the snow-pack and refreezes. Where lots of meltwater is produced, the refrozen ice layers merge into a continuous mass, superimposed ice, forming part of the accumulation zone. If the image is taken as the snowline is at its maximum elevation and superimposed ice has formed below the snowline, the SLA measurement will overestimate the ELA[5]

4.6 **ASTERGDEM V3 uncertainty** ASTERGDEM V3 is based on data from 2000 to 2013. Elevation uncertainties are likely increased outside these years due to glacier thinning rates[7].

## 4.7. Snowline irregularity

Patchy/irregular snowcover → greater length of snowline required to trace "zig-zags" → over-sampling from patchy/irregular snowcover.

Figure 5 shows an example for Silvrettagletscher, Switzerland, on 03/09/2015. Patch A contributes a longer length of snowline than patch B, despite being smaller in area.

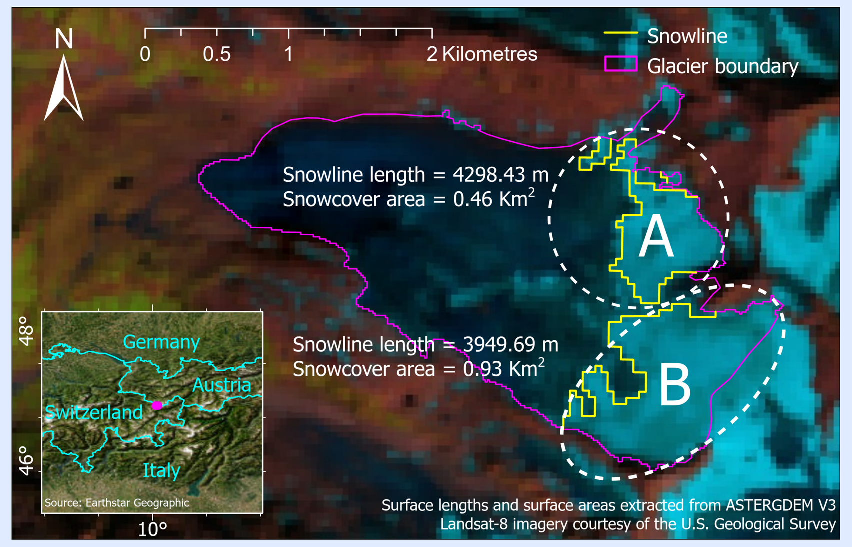


Figure 5. Silvrettagletscher, Switzerland, on 03/09/2015, SWIR, NIR, and red false colour composite. Snowline shown in yellow, glacier boundary shown in magenta. Landsat-8 images courtesy of U.S. Geological Survey[3].

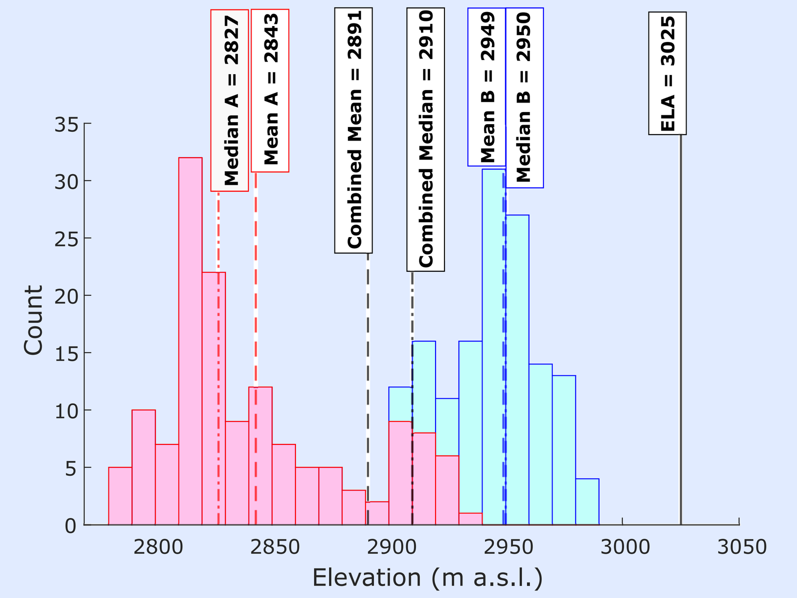


Figure 6. Distribution of elevation points along the snowline (taken at 30 m intervals) in 10 m bins for Silvrettagletscher, Switzerland, on 03/09/2015.

As satellite imagery resolution improves, the snowline can be mapped more precisely, improving vertical uncertainty but potentially exacerbating oversampling bias, as in Figure 7[8].

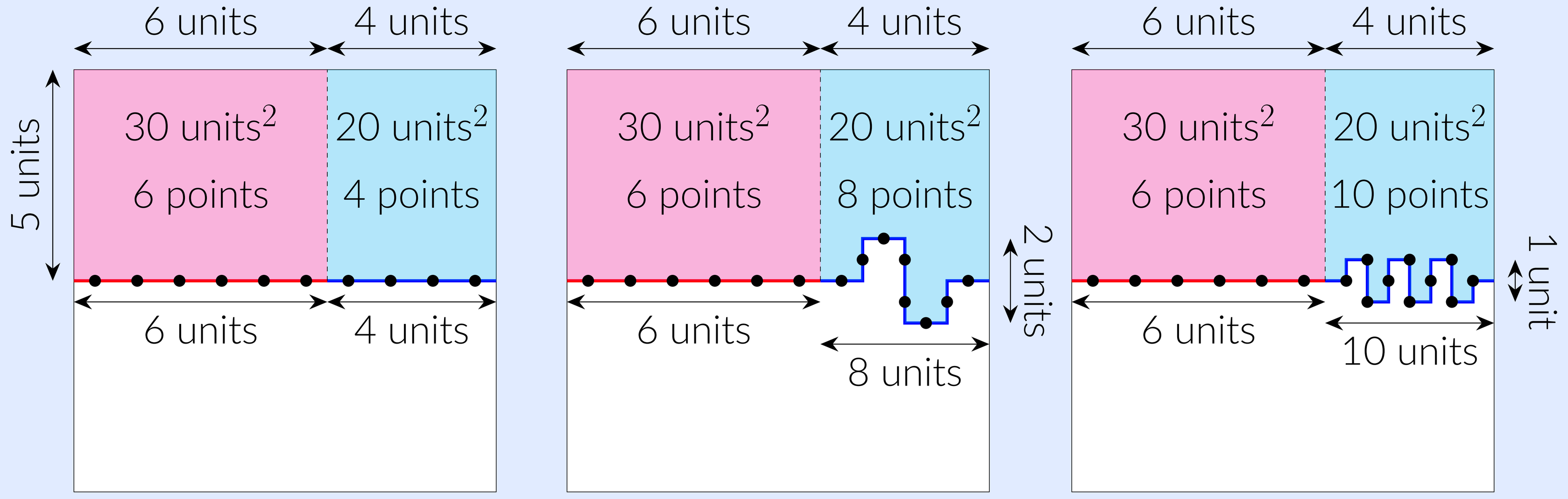


Figure 7. Larger 'snowcover' regions shown in pink and smaller 'snowcover' regions shown in blue, with corresponding red and blue 'snowlines', respectively.

## 5. Conclusions

- Seeking out the image with the least visible snow cover gives a better proxy for the ELA than simply selecting the image closest to the expected end of melt season.
- Snowline mapping is highly susceptible to influence from summer snowfall events.
- The median elevation of the snowline is generally a better proxy for ELA than the mean elevation of the snowline, but not in all cases.
- The oversampling bias arising from snowline irregularity highlights the requirement for an alternative method of calculating the SLA.

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