



Supplement of

On thin glacial ice: New Austrian Glacier Inventory shows accelerating glacier shrinkage and 31 % area loss within two decades

Lea Hartl et al.

Correspondence to: Lea Hartl (lea.hartl@oeaw.ac.at)

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1 Data sources and meta data: Supplementary Tables

Table S1: Main data sources for the 20 subregions of AGIS

Region (Nr.)	Federal Province	Main data source	Additional data
Allgäu Alps (1)	Tyrol	Orthoimagery Province of Tyrol (2023) ¹	-
Ankogel –Hochalmspitze Group (2)	Salzburg, Carinthia	Lidar DEM Hillshade Province of Salzburg (2023) ³ ; Carinthia (2023) ⁴	DoD (Difference of DEMs) (2023-2010); Planet Scope Orthoimagery (2023), Orthoimagery Province of Salzburg ³ ; Carinthia ³ (2021; 2022)
Carnic Alps (3)	Carinthia	Lidar DEM Hillshade Province of Carinthia (2022) ⁴	Orthoimagery Province of Carinthia ⁴ (2021); Planet Scope Orthoimagery (2023)
Dachstein Group (4)	Salzburg, Upper Austria, Styria	Orthoimagery provided by BEV ² for Salzburg (2021); Upper Austria (2021); Styria (2021)	Orthoimagery provided by BEV ² for Salzburg; Upper Austria; Styria for 2022 and 2024; Lidar DEM Hillshade provided by BEV ² for Salzburg; Upper Austria; Styria
Deferegger Group (5)	Tyrol	Orthoimagery Province of Tyrol (2023) ¹	-
Glockner Group (6)	Salzburg, Tyrol, Carinthia	Orthoimagery provided by BEV ² for Tyrol (2022); Carinthia (2022); Orthoimagery Province of Salzburg (2022)	Pléiades Orthoimagery (2022), Planet Scope Orthoimagery (2023); DEM (2023) provided by BEV ² for Salzburg; Tyrol; Carinthia; Hillshade (2023); DoD (2023-2009)
Goldberg Group (Sonnblick Group, 7)	Salzburg, Carinthia	UAV Orthoimagery from Geosphere Austria (2023), Lidar DEM Hillshade Province of Salzburg (2022, 2023) ³ , Orthoimagery Province of Salzburg (2022, 2023) ³ ; Province of Carinthia(2022) ⁴	Lidar DEM Hillshade Province of Salzburg (2022, 2023) ³ ; UAV Orthoimagery and Hillshade from Geosphere Austria (2023); Orthoimagery Province of Salzburg (2022, 2023) ³ ; Province of Carinthia(2022) ⁴
Granatspitze Group (8)	Salzburg, Tyrol	DEM/ Hillshade Province of Salzburg (2023) ³ ; Tyrol (2023) ¹	Orthoimagery Province of Tyrol ¹ ; Salzburg ³ (2022)
Hochkönig Group (Salzburg Limestone Alps, 9)	Salzburg	Orthoimagery from Planet Labs: Satellite Imagery and Earth Data Analytics (2022)	Orthoimagery Province of Salzburg ³ (2022)
Lechtaler Alps (10)	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol (2023) ¹ ; Vorarlberg (2023) ⁵	Orthoimagery from 2009-2016; Lidar DEM and Hillshade Province of Tyrol ¹ ; Vorarlberg ⁵ ; DoD (2027-2023)
Ötztal Alps (11)	Tyrol	Orthoimagery Province of Tyrol (2023) ¹	In situ knowledge for individual glaciers; Orthoimagery Province of Tyrol ¹ for previous years; DEM Province of Tyrol ¹ ; Pleiades DoD (2017-2022 Berthier et al., 2024)

Rätikon (12)	Vorarlberg	Orthoimagery Province of Vorarlberg (2023) ⁵	Lidar DEM and Hillshade Province of Vorarlberg ⁵ ; DoD (2017-2023)
Rieserferner Group (13)	Tyrol	DEM Hillshade Province of Tyrol (2023) ¹	Orthoimagery Province of Tyrol ¹ (2021)
Samnaun Group (14)	Tyrol	Orthoimagery Province of Tyrol (2023) ¹	Hillshade Province of Tyrol ¹ (2018)
Schober Group (15)	Tyrol, Carinthia	DEM Hillshade Province of Tyrol (2022) ¹ , Province of Carinthia (2023) ⁴	Orthoimagery Province of Tyrol ¹ (2021)
Silvretta Group (16)	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol (2023) ¹ ; Vorarlberg (2023) ⁵	Lidar DEM and Hillshade Province of Vorarlberg ⁵ ; DoD (2017-2023) Orthoimagery Province of Tyrol ¹ for previous years; DEM Province of Tyrol ¹ (2018)
Stubai Alps (17)	Tyrol	Orthoimagery Province of Tyrol (2023) ¹	ALS DEM Province of Tyrol ¹ (2017/18); Orthoimagery Province of Tyrol ¹ for previous years; DoD (2006-2017/18)
Venediger Group (18)	Salzburg, Tyrol	Orthoimagery Province of Tyrol (2022) ¹ ; Salzburg (2022) ³	Planet Scope Orthoimagery (2024); DoD (2012-2023), Hillshade and DEM Province of Tyrol ¹ ; Salzburg ³ (2023)
Verwall Group (19)	Tyrol, Vorarlberg	Orthoimagery Province of Tyrol ¹ (2023); Vorarlberg (2023) ⁵	Lidar DEM and Hillshade Province of Vorarlberg ⁵ ; DoD (2017-2023); Orthoimagery Province of Tyrol ¹ for previous years
Zillertal Alps (20)	Tyrol, Salzburg	Orthoimagery Province of Tyrol ¹ (2022, 2023); Salzburg (2022) ³	Hillshade Province of Tyrol ¹ (2021)

¹ Land Tirol (data.tirol.gv.at)

² BEV (Federal Office of Metrology and Surveying, data.bev.gv.at)

³ Federal Province of Salzburg (salzburg.gv.at)

⁴ Federal Province of Carinthia (kagis.ktn.gv.at)

Table S2. Outline data attributes compiled for each AGI5 glacier.

Attribute	Description
id	Glacier ID number as per the Austrian glacier inventories
name	Glacier name as per the Austrian glacier inventories
year	Year of inventory (Typically: year of aerial survey, same year as src_date.)
data_type	Main type of imagery or data used for mapping.
src_date	Date of image/data acquisition.
image_ID1	id number to identify specific image tiles. Format depends on the provider. If there is more than one image id per glacier, the mode of the list of ids is given.
flightstr	id numbers of flight strips that overlap with each glacier, if available.
state	Name of Austrian federal province.
region	Name of mountain region (as per AGI3)
url	Link to data portal for source imagery if available
analyst	Name of analyst(s)
data_type2	Additional data used for mapping, if any.
src_date2	Date of image/data acquisition of data_type2.
source2	Further information for data_type2 as needed, e.g. image id, source, and survey date if not the same as for the main data_type.
img_qf	Image quality flag - categorical value indicating whether snow, shading, or image errors/artifacts affect outline mapping (further explanations in readme file).
outline_qf	Outline quality flag - categorical value indicating issues not related to the above (shading, snow cover, image errors) that affect outline mapping, typically related to debris cover and very small features (further explanations in readme file).
comment	Any relevant comments.
debris	Categorical value to approximately indicate the amount of debris cover (further explanations in readme file).
crevs	Categorical value to indicate whether there are visible crevasses (further explanations in readme file).
area	Glacier area in m ² , computed for the CRS of the file.
min_elevation	Minimum elevation of the glacier extracted from Digitales Geländemodell (DGM) Österreich (Geoland.at, 2015).
median_elevation	Median elevation of the glacier extracted from Digitales Geländemodell (DGM) Österreich (Geoland.at, 2015).
max_elevation	Maximum elevation of the glacier extracted from Digitales Geländemodell (DGM) Österreich (Geoland.at, 2015).
van_fragm	Number of glacier fragments (if any) classified as "vanishing", i.e., may still contain ice but cannot be mapped. These fragments were present in AGI3, flagged as "vanishing" in AGI5, and are no longer included in the AGI5 outlines.
nr_frag	Number of glacier fragments in AGI5.
ROGI	Indicates overlap of the feature with the rock glacier inventory (Wagner et al., 2020)

2 Results: Additional figures and tables

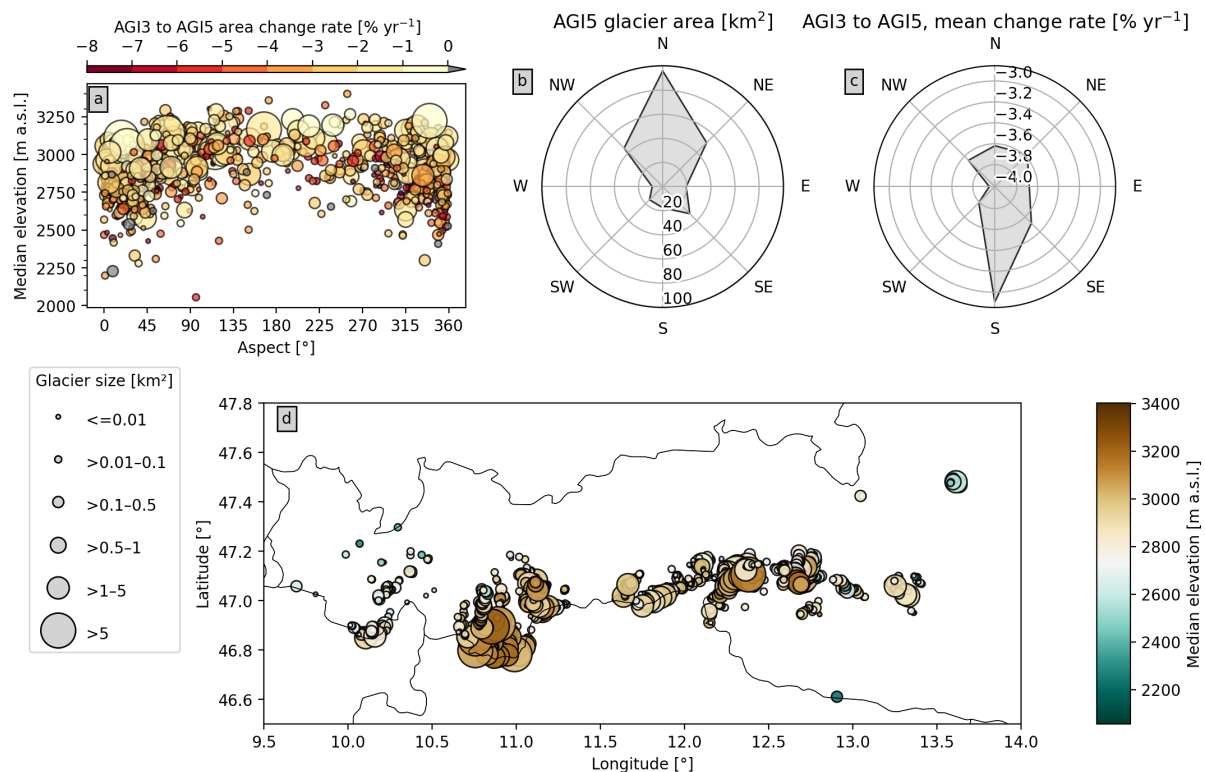
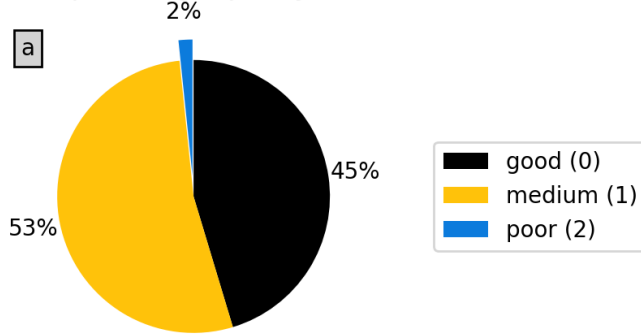
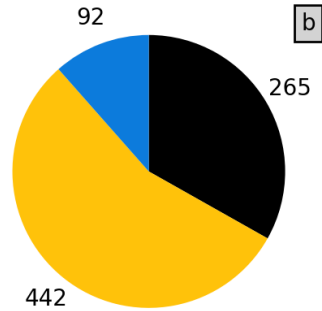


Figure S1. a: AGI5 median glacier elevation against mean aspect. Marker color indicates AGI3 to AGI5 area change rates, marker size indicates AGI5 glacier size. b: Polar plot of AGI5 glacier area in 45° aspect bins. c: Polar plot of mean change rates per aspect bin. d: Markers scaled to AGI5 glacier size and centered on the glaciers' centroid coordinates. Colors indicate median glacier elevation.

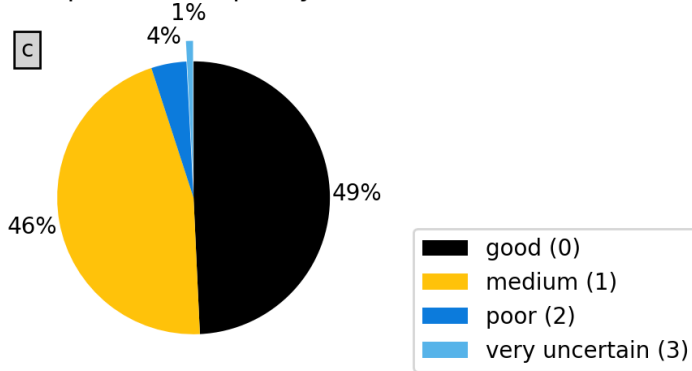
Area per image quality class



Number of glaciers per image quality class



Area per outline quality class



Number of glaciers per outline quality class

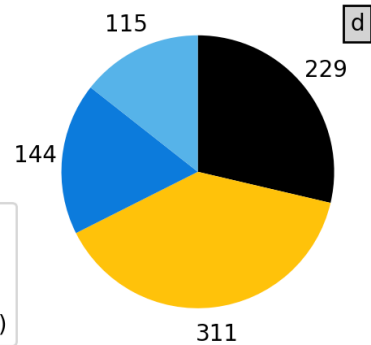


Figure S2. Pie charts showing the distribution of the image (a, b) and outline (c, d) quality flags as per table 2. Categories shown respectively for the fraction of total glacier area (a, c) and glacier count (b, d).

Table S3. Median elevation and area statistics for the AGI5 glaciers grouped by outline quality scores, debris cover, and crevasse categories.

Category	count	median elev. (m)	median area (km ²)	minimum area (km ²)	maximum area (km ²)	percentage of total area (%)
All	799	2882	0.0586	0.0002	14.6971	100
Outline quality						
Good	229	2967	0.1595	0.0029	14.6971	49.26
Medium	311	2866	0.0688	0.0006	14.6443	45.73
Uncertain	144	2812	0.0392	0.0017	0.9401	4.18
Very uncertain	115	2840	0.0128	0.0002	0.1650	0.83
Debris cover						
No debris cover	145	2929	0.0802	0.0014	14.6443	21.80
Partially debris-covered	396	2898	0.1030	0.0006	14.6971	72.22
Mostly debris-covered	158	2793	0.0373	0.0002	1.5842	4.40
Fully debris-covered	82	2899	0.0204	0.0004	0.4733	1.22
Crevasses						
Crevasses	404	2931	0.1880	0.0034	14.6971	92.71
No crevasses	363	2828	0.0225	0.0002	2.3515	6.95

Table S4. AGI3 to AGI5 median area change rates and glacier counts grouped by size bins. Vanished glaciers are included in the computation of median change rates assuming a 2023 area of zero. Glacier counts do not include vanished glaciers.

Size category (km ²)	median change rate (% yr ⁻¹)	glacier count
=< 0.01	-5.44	105
>0.01 - 0.05	-3.86	272
>0.05 - 0.1	-2.80	106
>0.01 - 0.1	-3.53	378
>0.1 - 0.5	-2.52	209
>0.5 - 1.0	-1.89	40
>1.0 - 5.0	-1.64	58
>5	-1.31	9

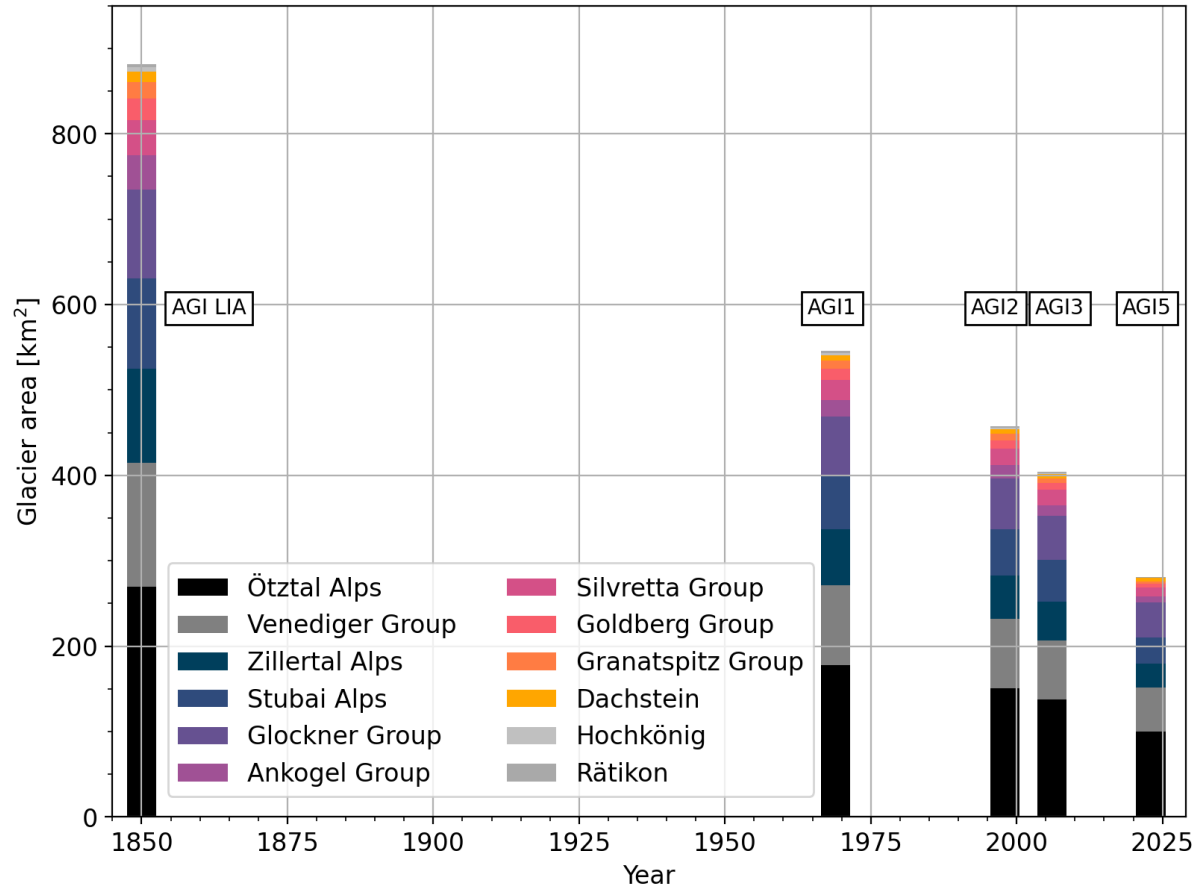


Figure S3. Regional area for AGI LIA, 1, 2, 3, and 5 for the subregions included in all AGI (AGI LIA and AGI 1 did not include all 20 subregions).

3 Round Robin experiment - detailed comments

The following sections provide additional commentary on the outline mapping carried out for the RR-experiment. In addition to the inter-analyst comparison, the variability in results produced by one analyst repeatedly mapping the same glacier ("digitization uncertainty") was determined for three of the RR glaciers in smaller experiment. One analyst mapped three glaciers (NN, Arvental Kees, Wurten Kees) three times on different days. The "digitization uncertainty" was considerably lower than the uncertainty derived from the RR-comparison for all three cases (NN: 1.9%, Arvental Kees: 0.2%, Wurten Kees: 0.3%). We therefore omit a more detailed assessment of this source of uncertainty and assume that the "digitization uncertainty" is covered by our more general uncertainty estimates.

3.1 Madlein Ferner

Madlein Ferner (Fig. S4) was classified as vanished or vanishing by all but one of the analysts. The feature is completely debris-covered in the AGI5 imagery, although some snow patches remain within the AGI3 area. The AGI3 outline overlaps with a substantially larger rock glacier that was inventorized in the rock glacier inventory (Wagner et al., 2020). One analyst remarked on this, further noting that a small pool of water within the AGI3 outlines in combination with a possibly creeping or otherwise advancing debris front suggests that there is subsurface ice in this area, but that it is not possible to say if the distinct "front" formation in the debris is related to permafrost creep or a glacial process such as debris gradually sliding over remaining glacial ice. This analyst deemed the "vanishing" category appropriate here since there is likely still ice but it was 1) not possible to delineate the margin under the debris cover and 2) unclear whether the feature should be considered a (former) glacier bordering a rock glacier, or part of the rock glacier complex.

Other analysts did not remark on the rock glacier but similarly mentioned surface structures and snow patches as indicative of remaining ice, which could not be delineated in the imagery. The analyst who did map an outline for Madlein Ferner based their approach on surface structures and subtle color differences that they interpreted as indicative of buried ice and ice melt, respectively.

3.2 NN

The nameless glacier (NN, Fig. S5) in the RR experiment was classified as vanishing by two analysts. They did not give specific reasons other than noting the very small size of the feature. The AGI5 imagery shows visible ice within the AGI3 boundaries. The analysts outlined variations of the visible ice margin with considerable differences in interpretations of debris cover. As in other cases, analysts pointed out surface structures and supraglacial water features as evidence of remaining ice under debris cover. Outlines are well-aligned along the border of a small lake on the northeastern margin of the glacier and deviate most noticeably in the southern and northwestern sections of the margin.

3.3 Arvental Kees

At Arvental Kees (Fig. S6, also known as Affental Kees), most (9/15) analysts partially extended the AGI5 outlines beyond those of AGI3. Their reasoning was related to their interpretation of surface structures and the surrounding terrain. The analysts who stayed within the AGI3 outlines mentioned giving more weight to the older outline in the delineation of ambiguous, debris-covered sectors, as well as assumptions about processes and debris cover extent that differed from those of the other group. The analyst who classified Arvental Kees as vanishing indicated considerable uncertainty around this choice and mentioned an inclination to revise the decision after discussion with other analysts.

3.4 Seekarles Ferner

At Seekarles Ferner (Fig. S7), the largest discrepancies are in the debris-covered lower section. Two analysts excluded this section entirely and one placed a "vanishing fragment" marker in this area to indicate that it may still contain ice but cannot be mapped with confidence. The remaining 12 analysts included the debris-covered section and mapped it as connected to the

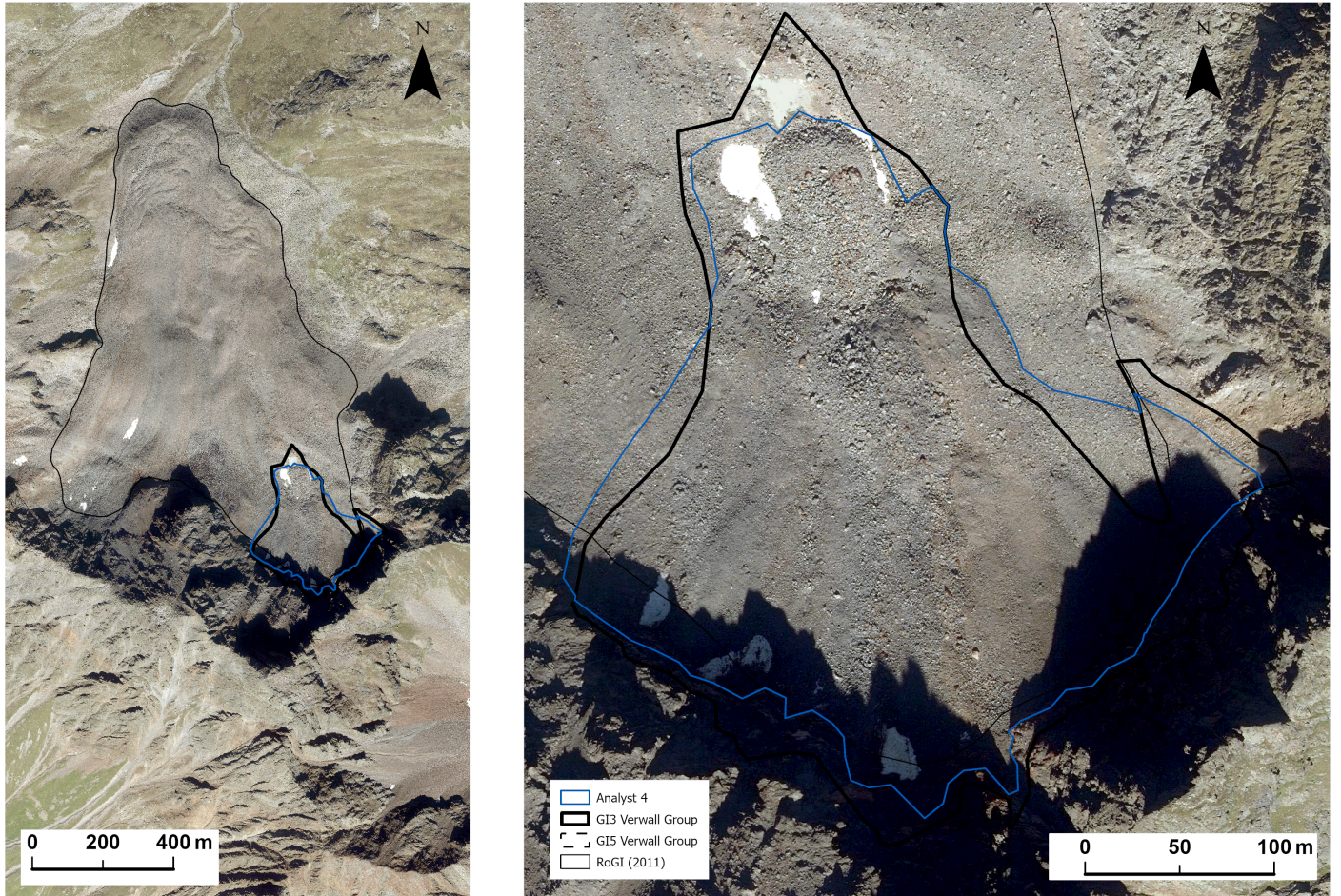


Figure S4. Round Robin outlines for Madleinferner, shown over a 2023 orthophoto. The left panel shows a zoomed out view of the rock glacier in the vicinity, the right shows a zoomed in view of the AGI3 Madlein Ferner outline and the outline produced by analyst 4 in the RR experiment. Rock glacier outline: Wagner et al. (2020), outline year for the rock glacier in the figure: 2011. Orthophoto data © Province of Tyrol, CC BY 4.0 AT (2023).

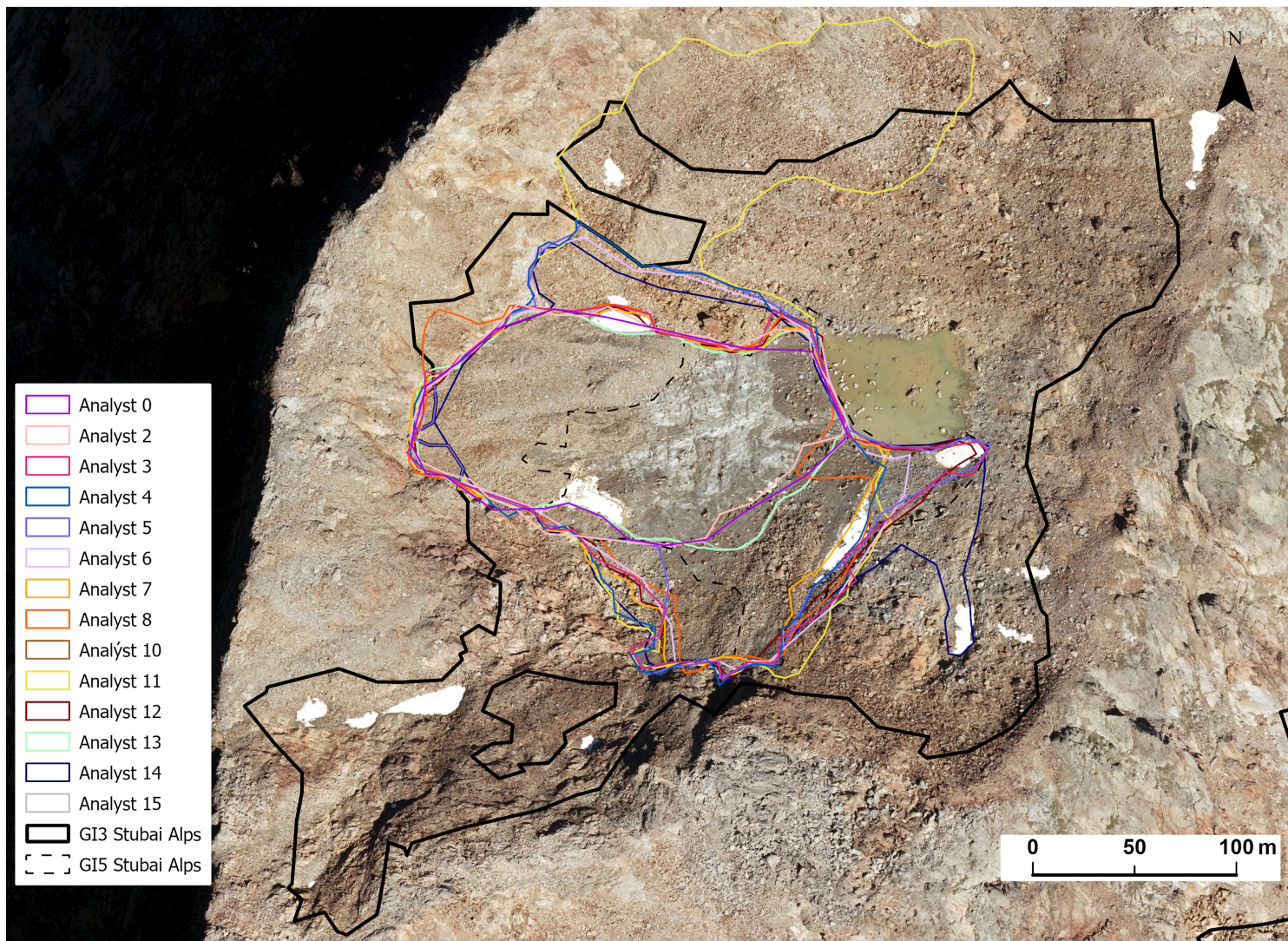


Figure S5. Round Robin outlines for a nameless glacier (“NN”), shown over a 2023 orthophoto. Orthophoto data © Province of Tyrol, CC BY 4.0 AT (2023)).

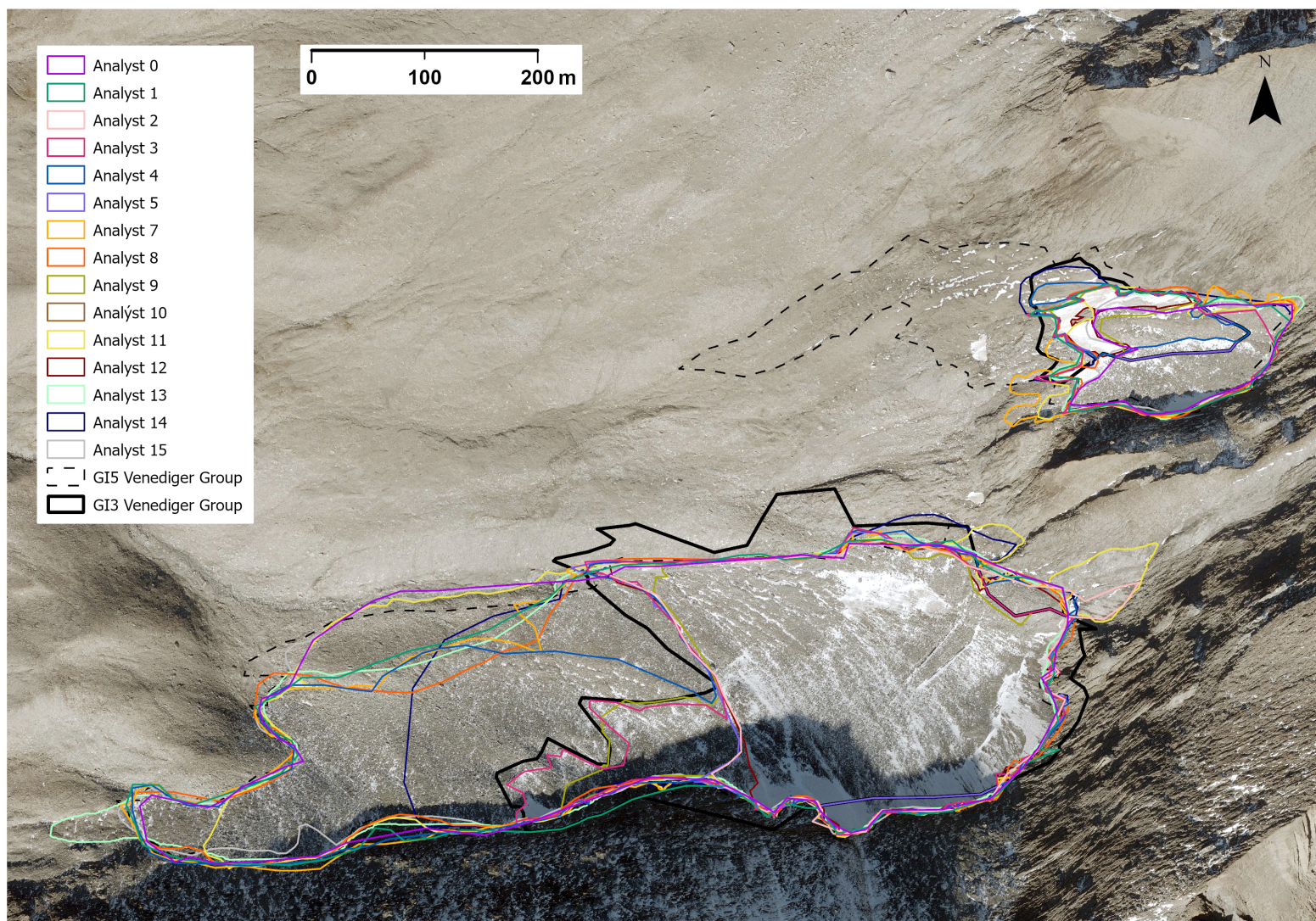


Figure S6. Round Robin outlines for Arvental Kees, shown over a 2022 orthophoto. Orthophoto data © Province of Tyrol, CC BY 4.0 AT (2022).

main glacier. Here, the poor visibility in the shaded sections was mentioned as a main cause of uncertainties in addition to the debris cover.

45 Extensive local terrain knowledge is available for this glacier due to frequent site visits by an analyst as part of the mass balance monitoring program. The AGI5 outline of Seekarles Ferner reflects this and is on the upper end of the RR area results due to the inclusion of debris-covered areas.

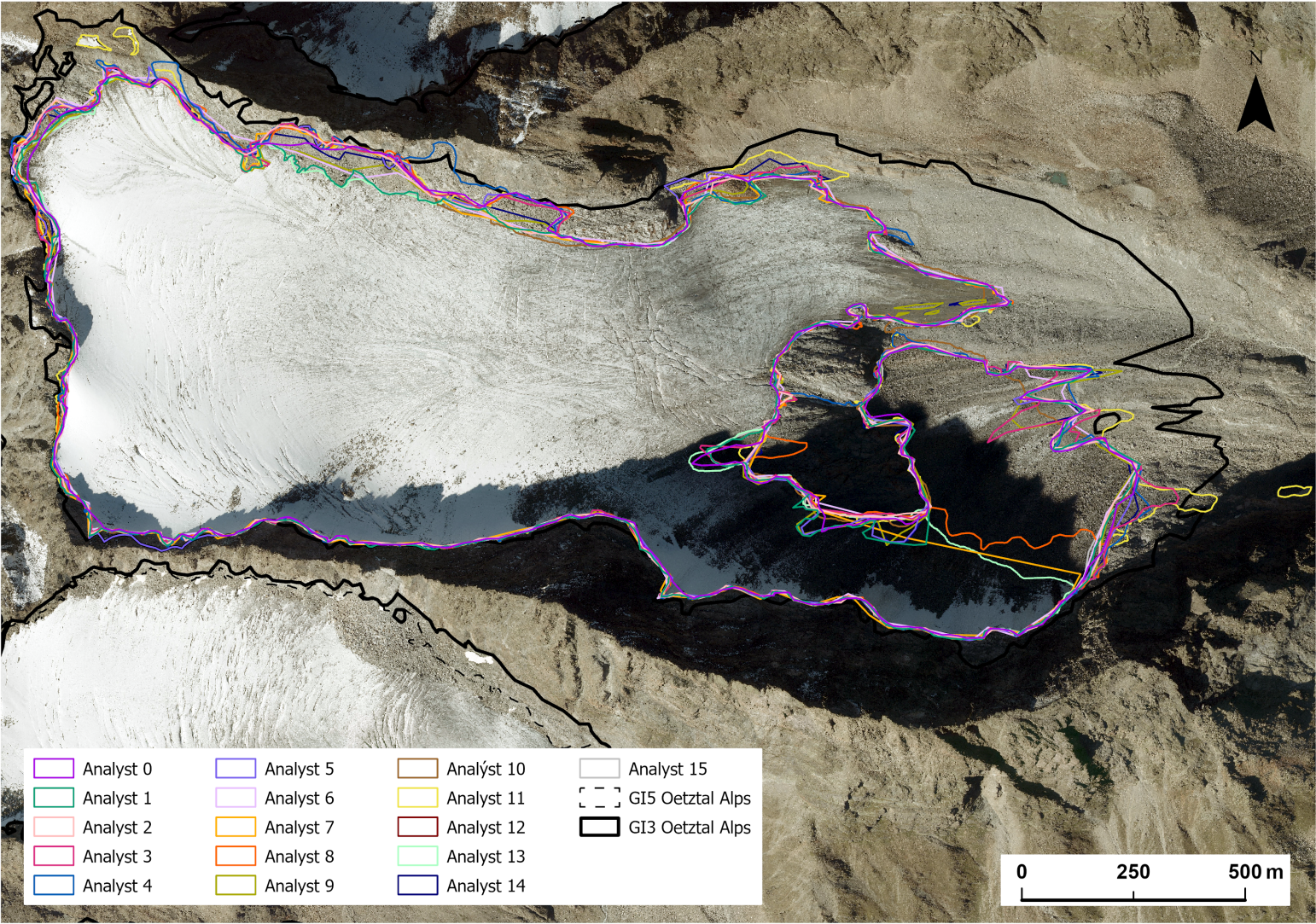


Figure S7. Round Robin outlines for Seekarles Ferner, shown over a 2023 orthophoto. Orthophoto data © Province of Tyrol, CC BY 4.0 AT (2023).

3.5 Wurtenkees

At Wurten Kees (Fig. S8), analysts reported using differences in surface structure apparent in the hillshade to determine the margins especially of the western fragments. The high outlier in this case deviates from the other outlines mainly around these fragments and in the lower sections of the larger, eastern fragments. An orthophoto is available for the eastern fragments (Fig. S9).

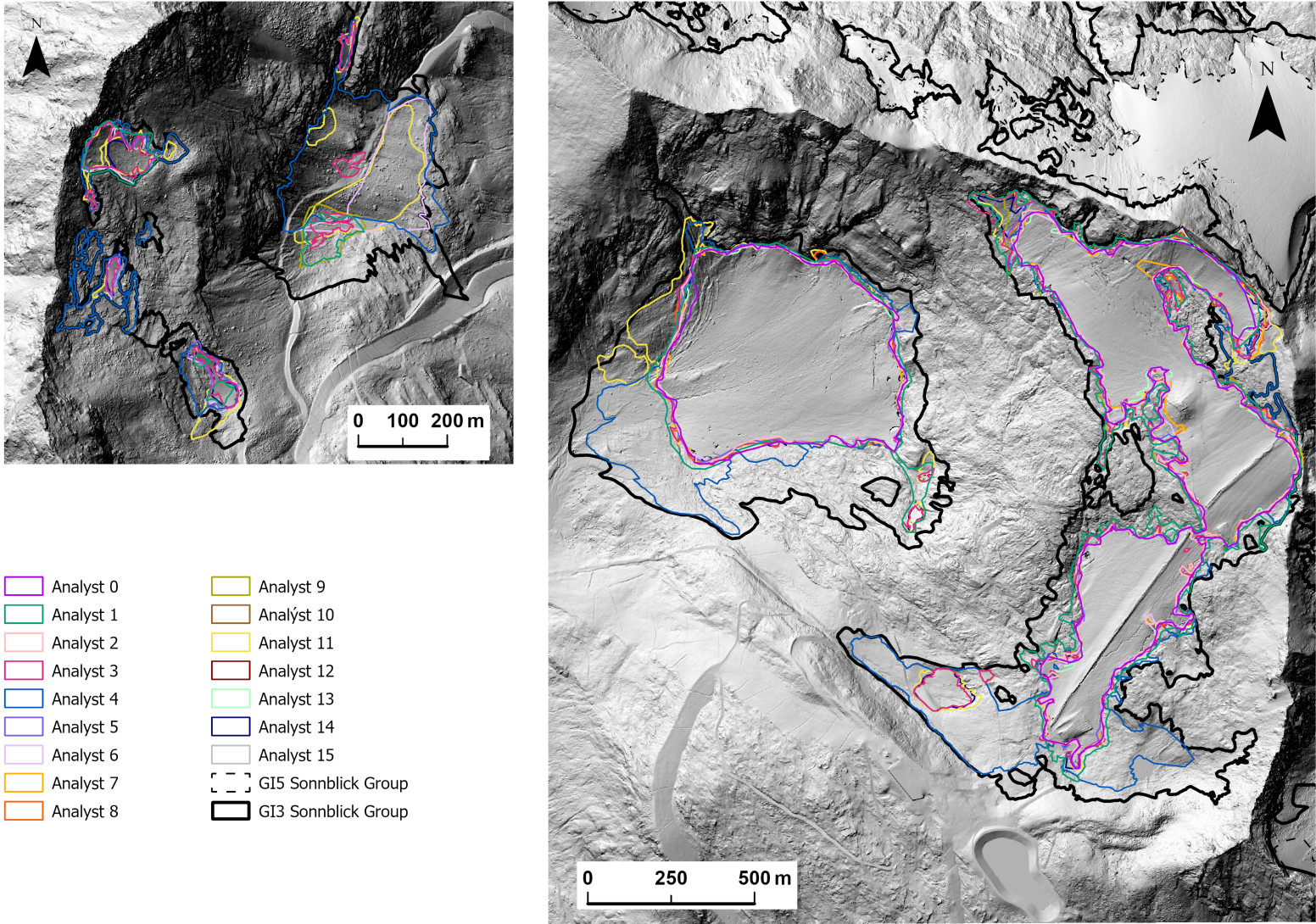


Figure S8. Round Robin outlines for Wurten Kees, shown over a hillshade derived from the 2023 DEM. DEM data © Province of Carinthia, CC BY 4.0 (2023).

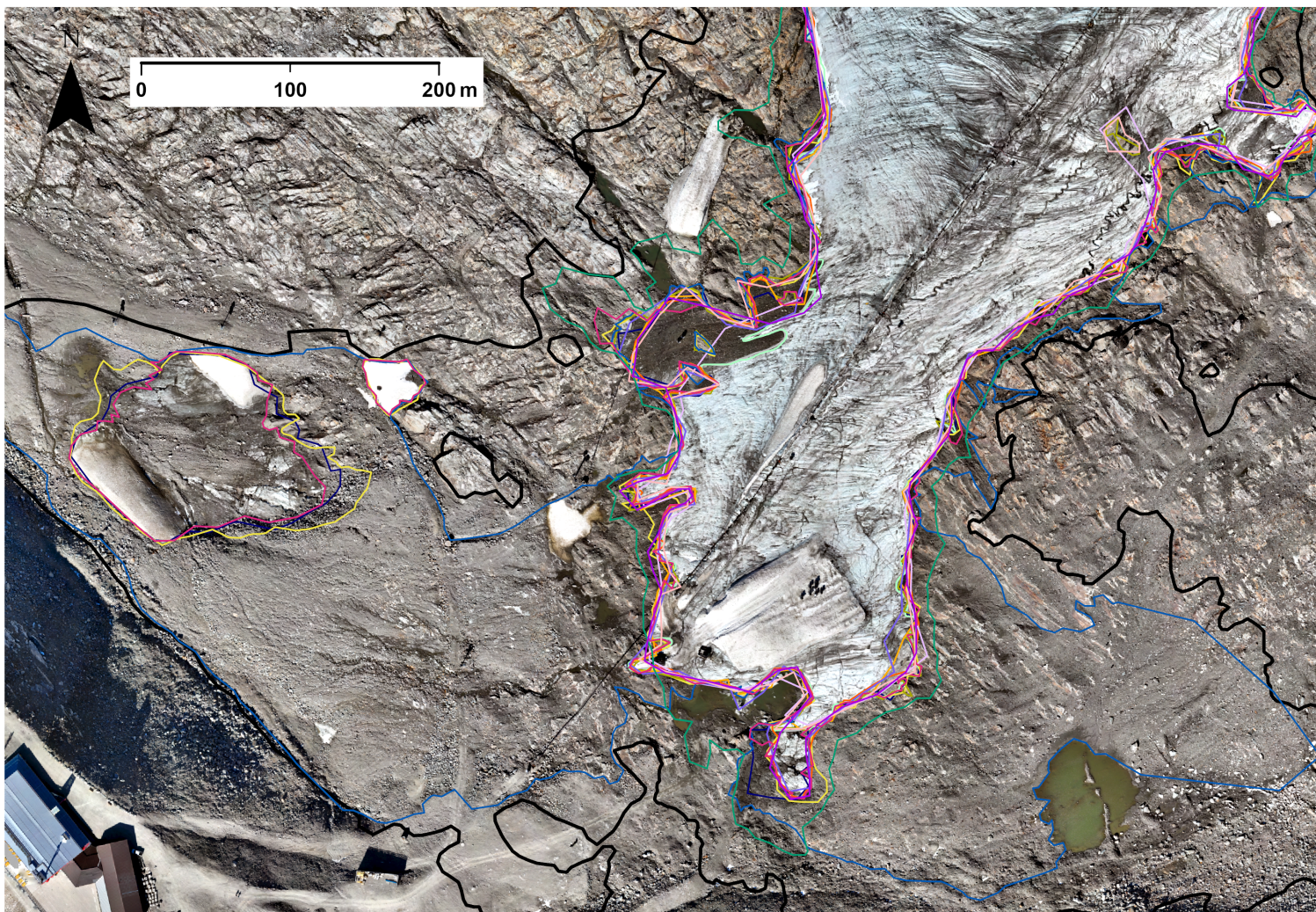


Figure S9. Close-up view of Round Robin outlines for the terminus of the main fragment of Wurten Kees, shown over a 2023 UAV orthophoto provided by Geosphere Austria.

3.6 Pasterze

Pasterzen Kees (Fig. S10) is the largest RR glacier (and the largest glacier in AGI5) and had the largest spread between minimum and maximum area in the RR experiment. The highest and lowest values are outliers compared to the more closely aligned range produced by the majority of analysts (12 of 14). The low outlier excludes a substantial section of the debris-covered terminus, which is known to contain ice but can appear visually ambiguous in aerial imagery. It can reasonably be speculated that familiarity with this particular glacier leads to inclusion of larger sections of the debris-covered tongue. The high outlier generally included more debris-covered areas along the margins of the glacier, both in the area of the terminus as well as elsewhere along the glacier margins, citing familiarity with the terrain.

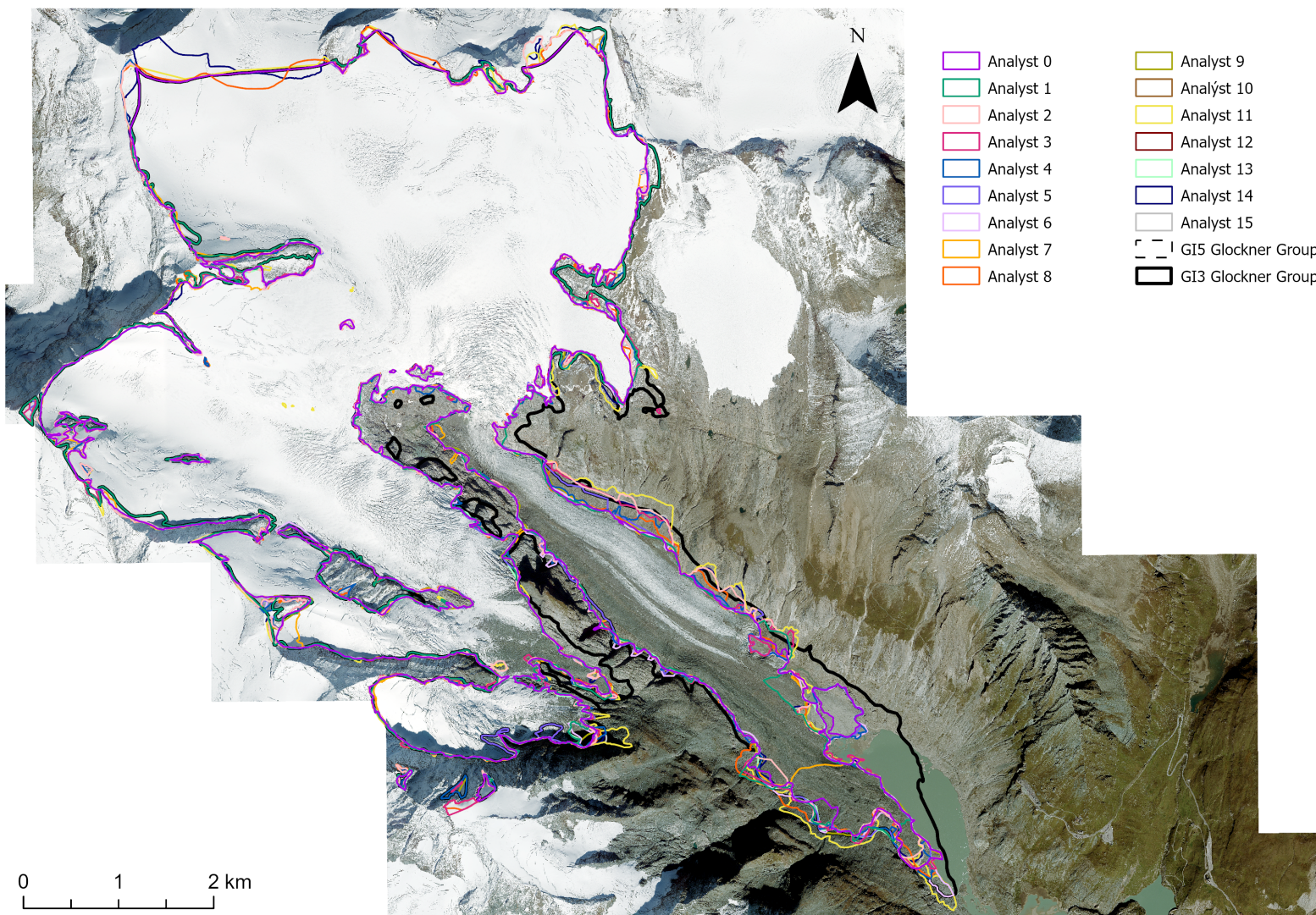


Figure S10. Round Robin outlines Pasterze, shown over a 2022 orthophoto. Orthophoto data © Province of Carinthia, CC BY 4.0 (2022).

4 Round Robin uncertainty estimation - buffer approach

For each RR glacier except Madlein ferner ("vanishing"), we determined the fraction of RR outlines that lie within a certain distance of the AGI5 outline. That is, we checked the distance by which the RR outlines deviate from each other and the main AGI5 outline. Only the largest fragment of each glacier was used for this analysis to avoid complications introduced by very small fragments that were mapped by some but not all analysts in the RR experiment.

Table S5. Percentage of RR outlines located within a given distance of the main AGI5 outline. The percentage is calculated as the length of all outlines within a given buffer compared to the total length of the outlines. See Fig. S11 for a cumulative version of these data.

Glacier (ID)	±0-2 m	±2-5 m	±5-10 m	±10-20 m	±20-40 m	±40-100 m	>100 m	AGI5 size (km ²)
NN (3028)	20.41	14.36	11.07	13.35	31.26	9.33	0.22	0.008
Arvental (6013)	45.06	26.07	11.45	6.37	6.29	4.77	0.00	0.089
Wurten K. (4038)	58.50	18.00	10.54	6.77	3.82	1.14	1.25	0.417
Seekarles F. (14033)	57.02	17.94	9.70	6.60	5.70	2.87	0.17	0.849
Pasterzen K. (4027)	45.93	20.98	12.04	8.56	5.63	4.62	2.29	14.697

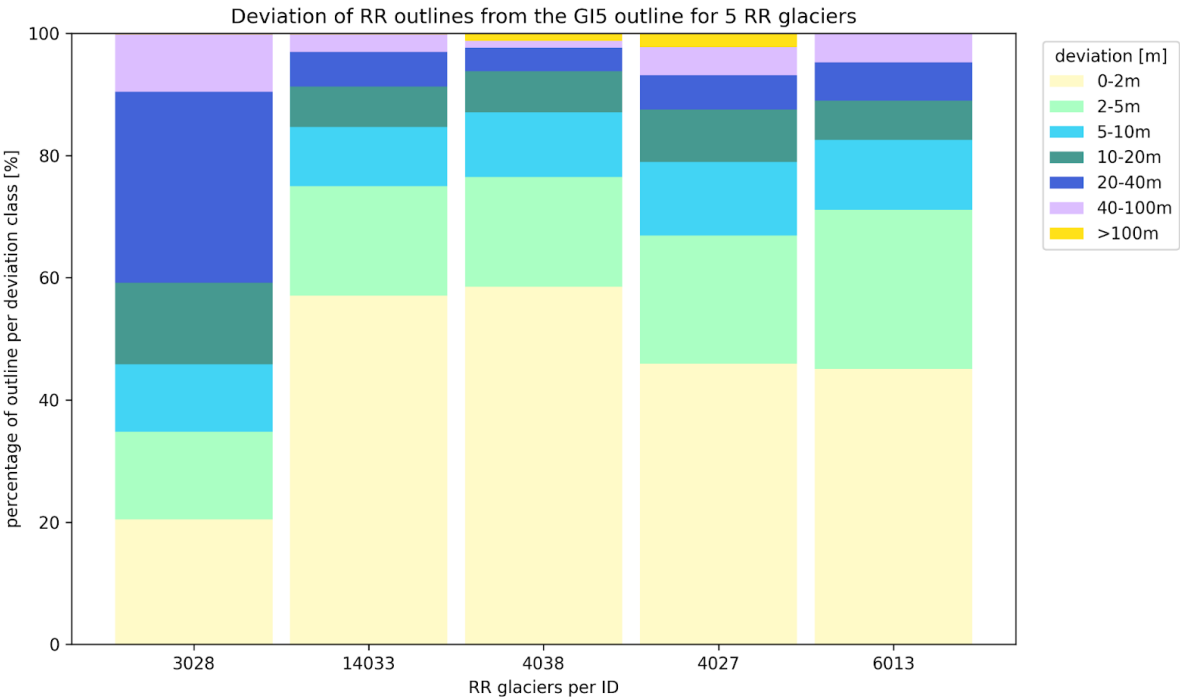


Figure S11. The same data as in Tab. S5 shown as a cumulative bar plot.

5 Mapping of debris-covered ice including local knowledge/field experience vs. aerial imagery only

For a subset of 61 glaciers in the Ötztal Alps (median area: 0.13 km², 31 glaciers categorized as mostly or fully debris-covered), outline mapping was performed using local terrain knowledge of the analyst in addition to aerial imagery and DEM

data (analyst A). An alternative set of outlines was produced using only aerial imagery and DEM data by an analyst without detailed knowledge of local terrain (analyst B). Fig. S12 shows the results for an example glacier. At 59 of 61 glaciers, the outlines by analyst A yield a larger glacier area than those by analyst B (differences are near zero in the other two cases). In 38 cases, the difference is larger than the assumed uncertainty (Fig. S13a). The area differences between analyst A and B range from near zero to 88% (Fig. S13a). In addition, four completely debris-covered glaciers included by analyst A were classified as vanishing by analyst B (100 % difference). Discrepancies between the two sets of outlines tend to increase with decreasing glacier size and increasing debris cover (Fig. S13a). Differences in glacier area are greater than the assumed uncertainty in 62% of the test cases.

Grouping the glaciers by the categorical debris cover scores assigned by the analysts shows that the median area difference between outlines rises from 10% for "partially debris-covered" to 21% for "mostly debris-covered" and to 38% for "fully debris-covered" glaciers (Fig. S13b). Of the 17 instances of positive area change between AGI3 and AGI5 (Tab. 4, main manuscript), 7 are associated with glaciers for which previously unmapped debris-covered areas were included in AGI5 based on local knowledge. Generally, glacier area is underestimated in case B compared to case A due to greater inclusion of debris-covered areas in A. We found only one instance (Vernagt Ferner, Ötztal Alps) where the analyst unfamiliar with local conditions (B) noticeably included a debris-covered sector where the analyst with local knowledge (A) did not. The overall glacier area in this case is still larger in the outline by A due to omissions of debris cover by B elsewhere.

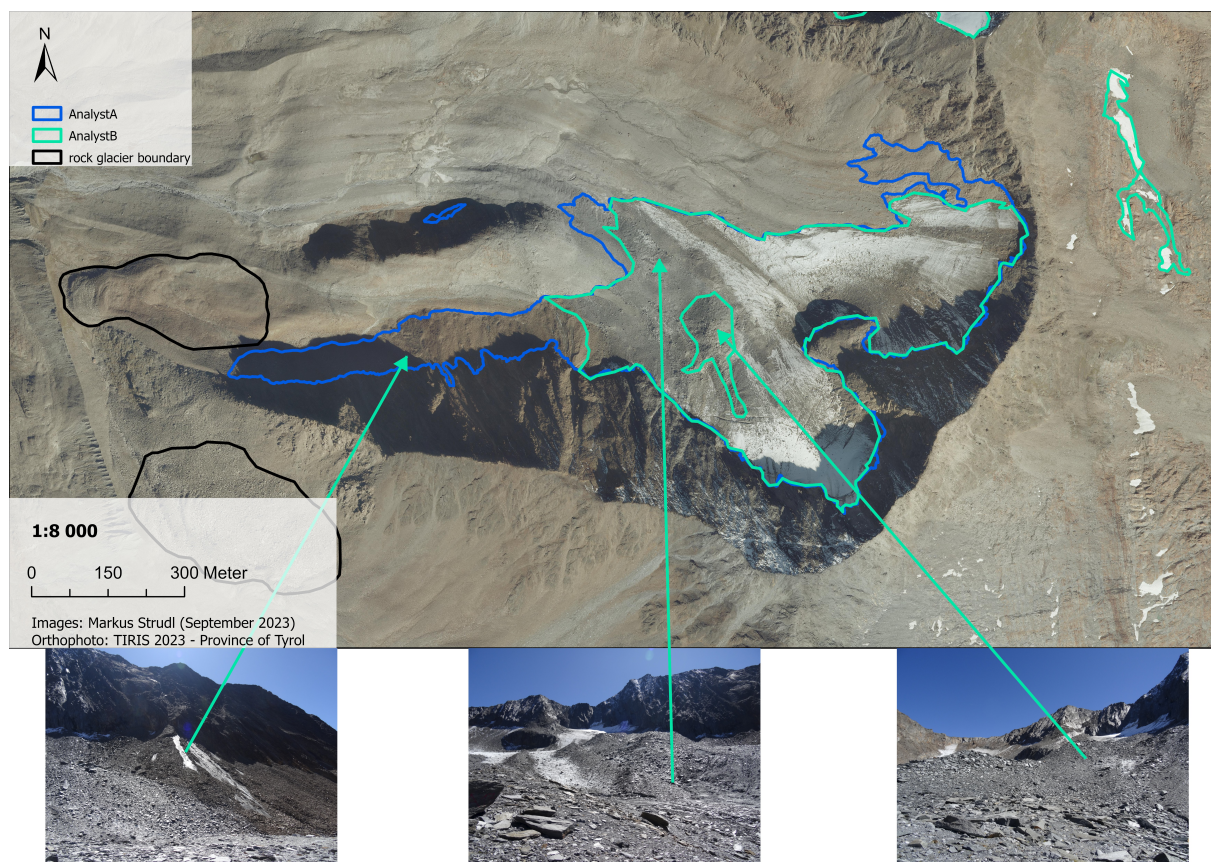


Figure S12. Top image: Glacier boundaries of Firmisan Ferner mapped based on aerial images (Analyst B) and taking into account local knowledge in addition to the imagery (Analyst A). The arrows indicate the locations shown in the photos below, where debris-covered ice was observed during site visits by Analyst A. Orthophoto data © Province of Tyrol (TIRIS), CC BY 4.0 AT (2023).

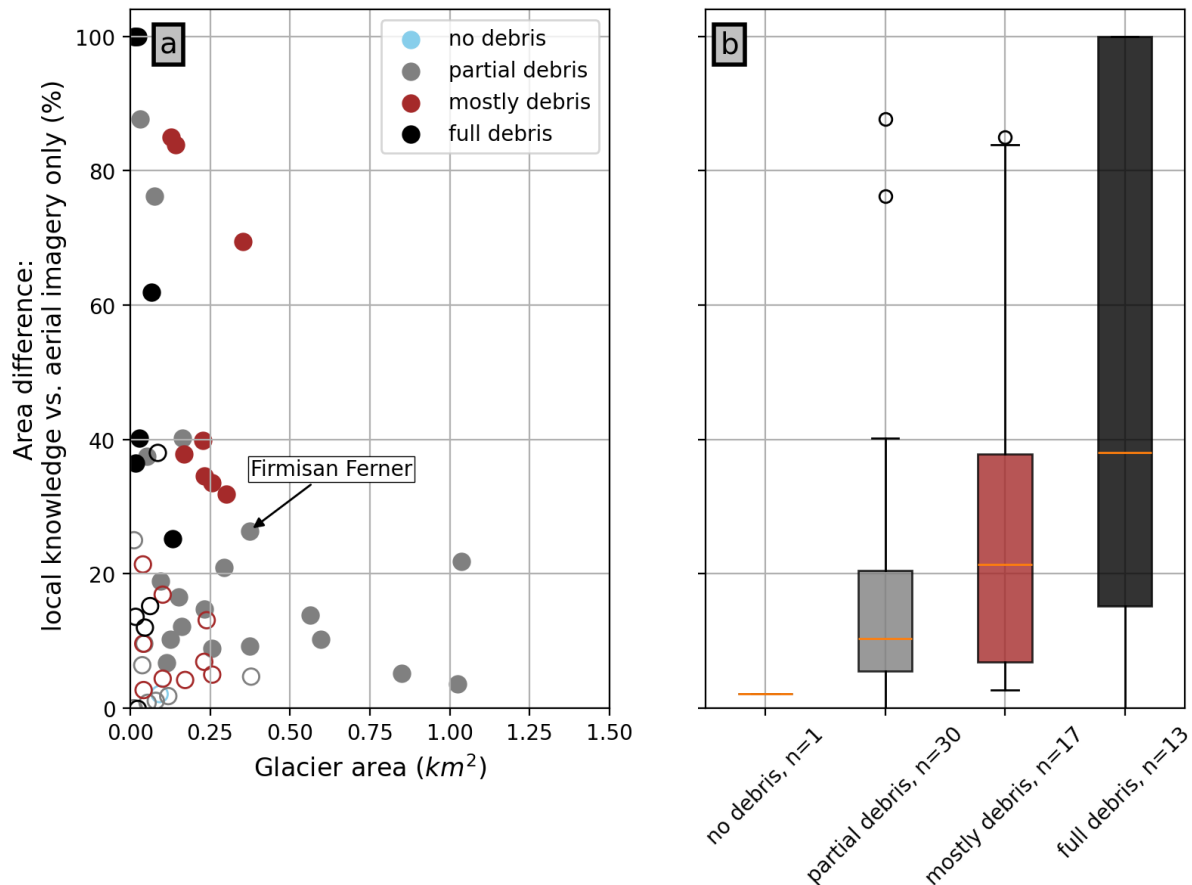


Figure S13. a: Difference between glacier area derived from local knowledge and aerial imagery and from aerial imagery only, expressed as a percentage of the former, plotted against glacier area. Colors indicate debris-cover scores. Filled markers indicate that the difference is larger than the estimated uncertainty. The data point for Firmisan Ferner, shown in Fig. S12, is annotated. b: The same data as boxplots grouped by debris cover scores.

85 References

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