

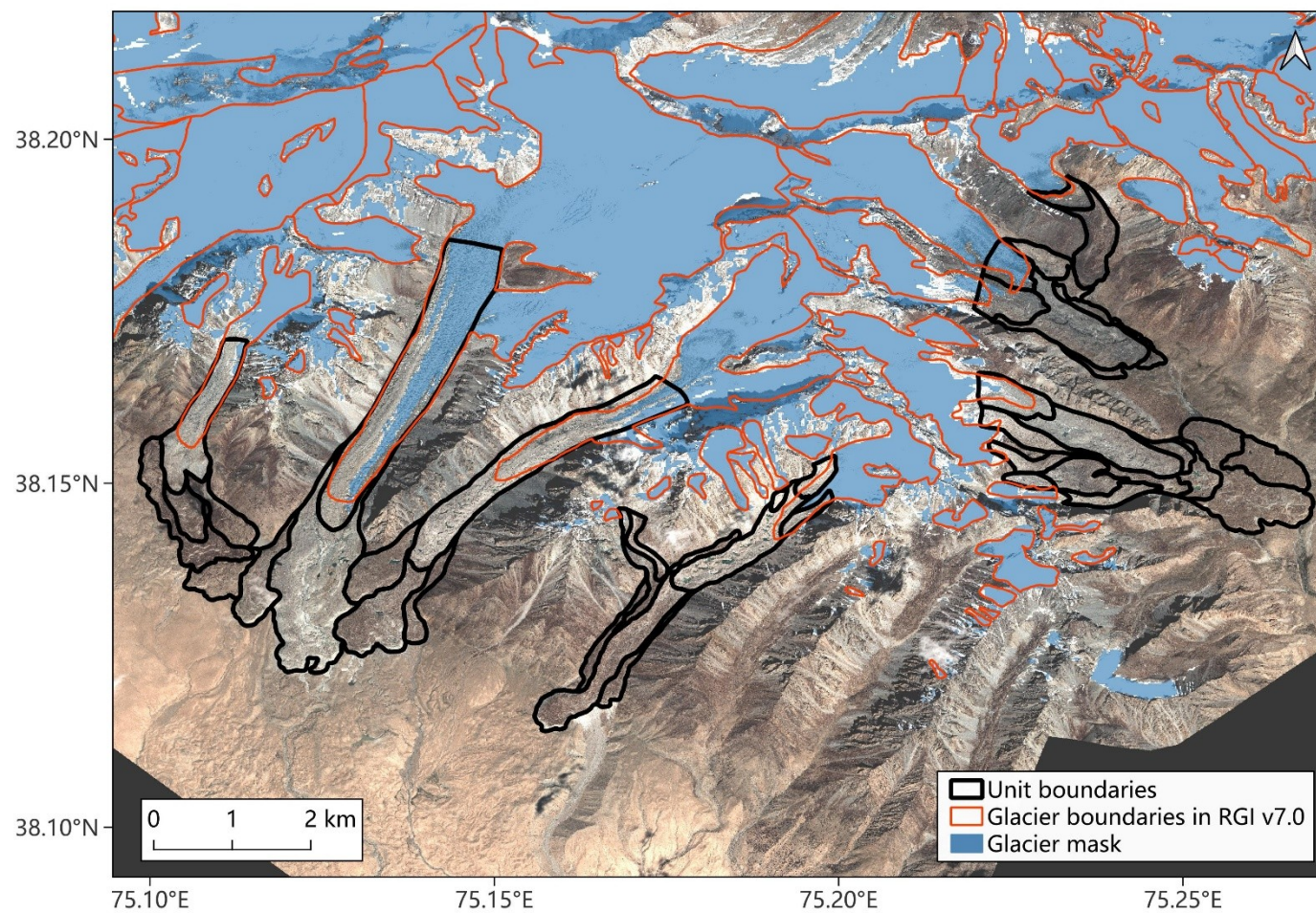


Figure S1: Debris-free glacier extents derived from Sentinel-2 imagery and the extents of analyzed ice-debris complexes.

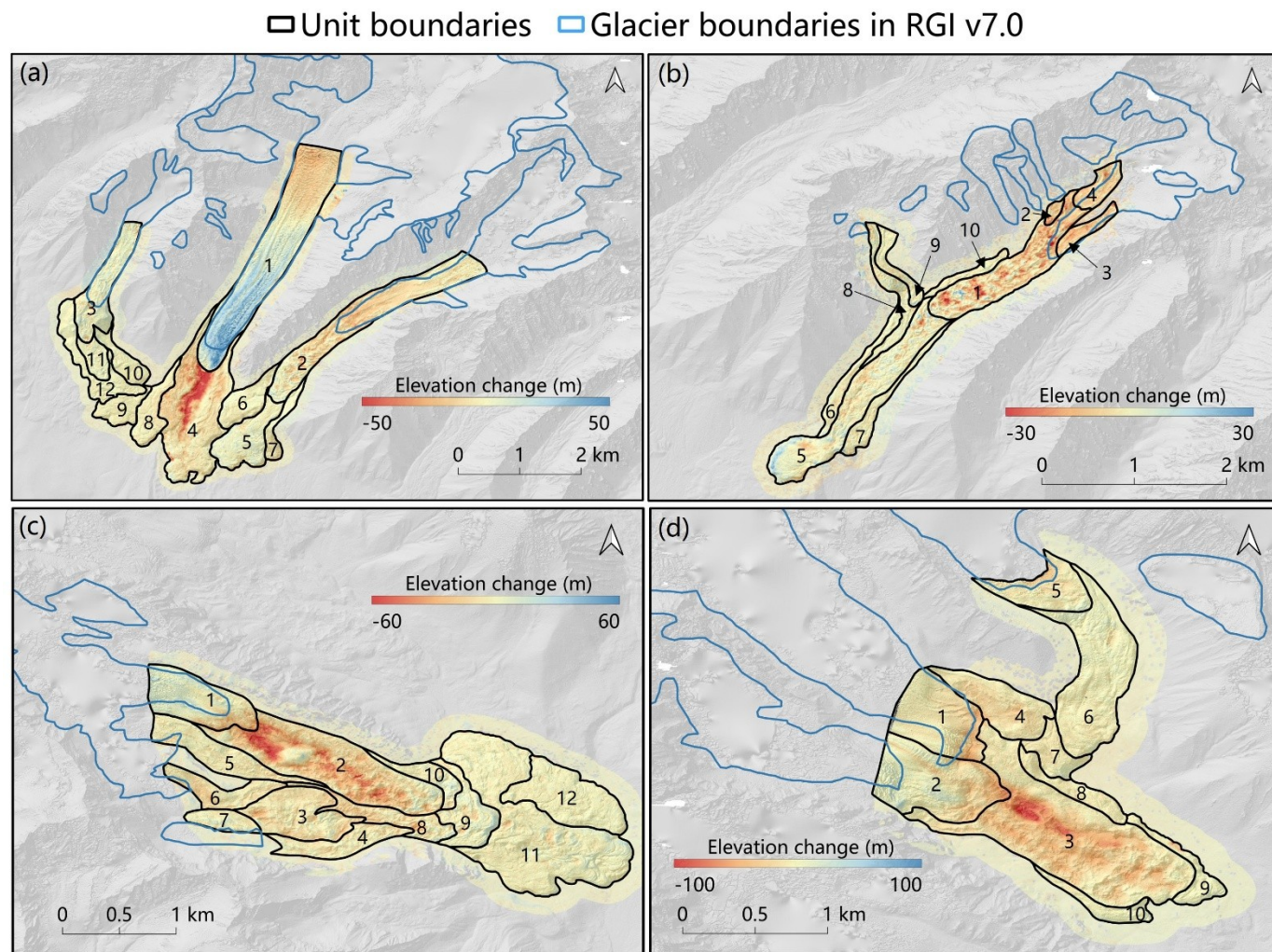


Figure S2: Elevation changes for the period of 1967–2013 of ice-debris complex (a) I, (b) II, (c) III, (d) IV.

□ Unit boundaries □ Glacier boundaries in RGI v7.0

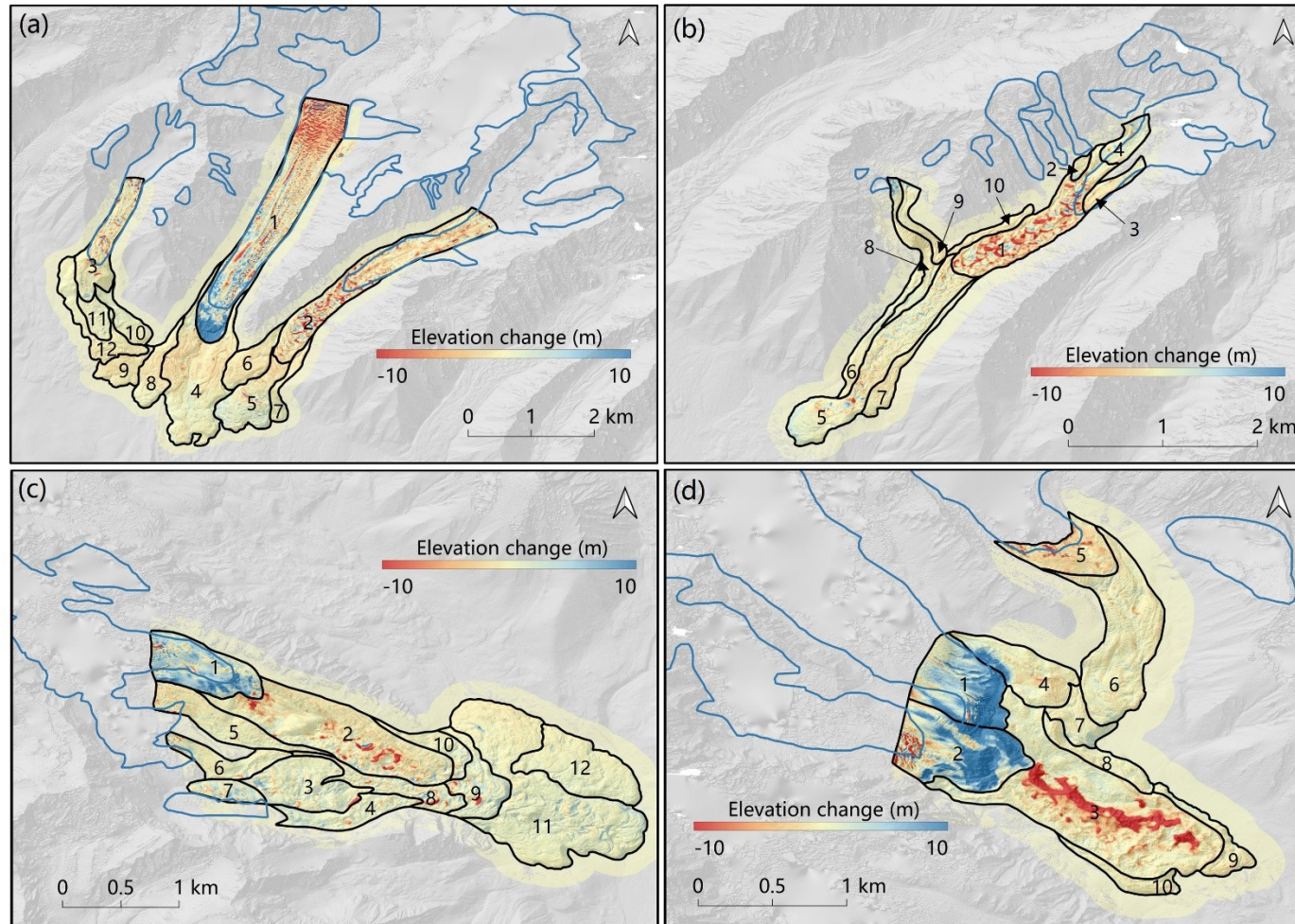


Figure S3: Elevation changes for the period of 2013–2019 of ice-debris complex (a) I, (b) II, (c) III, (d) IV.

Table S1: Details about the investigated ice-debris complexes.

Ice-debris complex ID	Location	Aspect	Size	Origin	Upslope connected glacier ID
I	38.14° N, 75.12° E	Southwestern	Width more than 4 km and area more than 10 km ²	Moraines originating from three glaciers in different valleys, which merge into a complex and eventually terminate in multiple rock glacier like lobes	RGI2000-v7.0-G-13-18539; RGI2000-v7.0-G-13-13861 (surge-type); RGI2000-v7.0-G-13-13860 (CN5Y656I0027)
II	38.13° N, 75.18° E	Southwestern	Width more than 500 m and area more than 3 km ²	Moraine in front of a glacier	RGI2000-v7.0-G-13-13847
III	38.15° N, 75.25° E	Eastern	Length up to 4 km, width above 1 km, and area more than 4 km ²	Moraines originating from upslope glaciers merge and form this complex	RGI2000-v7.0-G-13-13863; RGI2000-v7.0-G-13-13842
IV	38.18° N, 75.23° E	Southeastern	Length up to 2 km, width up to 1 km, and area more than 2 km ²	Moraines in front of glaciers	RGI2000-v7.0-G-13-13864 (CN5Y656I0036); RGI2000-v7.0-G-13-13845; RGI2000-v7.0-G-13-18611 (CN5Y656I0038)

Table S2: Statistics of elevation differences over stable terrain (buffer areas). STD: Standard Deviation, NMAD: Normalized Median Absolute Deviation.

Period	Ice-debris complex ID	Mean (m)	STD (m)	Median (m)	NMAD (m)
1967–2013	I	0.00	6.49	−0.34	5.25
	II	0.00	5.33	−0.12	4.56
	III	0.00	5.42	−0.46	4.03
	IV	0.00	5.32	0.17	5.35
2013–2019	I	0.00	0.81	0.01	0.85
	II	0.00	0.84	0.00	0.90
	III	0.00	0.84	0.01	0.89
	IV	0.00	0.73	0.05	0.70

Table S3: Statistics of surface velocities over stable terrain (buffer areas). Clearly and non-clearly detectable velocity threshold equals to median plus NMAD.

Ice-debris complex ID	Mean (m/yr)	STD (m/yr)	Median (m/yr)	NMAD (m/yr)	Threshold (m/yr)
I	0.33	0.45	0.22	0.10	0.52
II	0.49	0.31	0.44	0.17	0.95
III	0.41	0.35	0.30	0.13	0.69
IV	0.29	0.25	0.23	0.07	0.44

Table S4: Elevation changes of ice-debris complex units.

Ice-debris complex ID	Unit ID	1967–2013				2013–2019			
		Mean (m)	Median (m)	Minimum (m)	Maximum (m)	Mean (m)	Median (m)	Minimum (m)	Maximum (m)
I	1	5.6	5.03	−48.32	56.61	0.58	−0.68	−31.7	69.24
	2	−7.71	−8.24	−40.3	56.78	−1.91	−1.58	−65.99	17.47
	3	2.14	2.66	−43.19	39.15	−0.69	−0.39	−58.62	30.18
	4	−12.72	−8.86	−70.32	32.26	−0.48	−0.48	−18.69	25.22
	5	1.19	1.33	−24.6	41.11	0.16	0.23	−10.81	12.14
	6	−1.56	−1.46	−21.83	24.87	−1.02	−1.11	−7.27	4.49
	7	−1.75	−1.17	−19.28	12.49	−0.36	−0.38	−4.28	5.55
	8	−3.66	−3.44	−23.23	20.86	−0.61	−0.66	−4.58	4.6
	9	−2.38	−2.15	−22.55	12.89	−0.89	−0.98	−3.75	3.92
	10	−0.33	−0.53	−14.05	15.29	0.41	0.32	−4.64	5.07
	11	1.19	1.27	−23.53	17.75	0.41	0.35	−4.31	4.71
	12	−0.02	0	−14.09	13.86	−0.28	−0.25	−4.63	8.99
II	1	−8.49	−8.54	−43.17	30.03	−2.8	−2.05	−34.26	12.87
	2	−10.47	−10.39	−29.63	6.16	0.06	−0.07	−8.99	8.4
	3	−10.33	−10.29	−29.06	9.83	−0.85	−0.95	−10.32	21.66
	4	−7.86	−8.05	−25.99	9.9	0.8	0.78	−9.27	9.46
	5	−0.15	−0.34	−27.34	28.69	0.09	0.11	−13.81	12.02
	6	−0.72	−0.77	−20.04	18.11	0.3	0.12	−8.9	101.37
	7	−0.99	−0.86	−20.59	19.38	−0.42	−0.53	−7.51	5.33
	8	−0.25	−0.1	−21.55	20.8	0.54	0.17	−12.63	24.91
	9	−0.66	−0.74	−16.57	14.4	−0.08	−0.17	−7.24	10.06
	10	−1.77	−1.73	−18.52	8.42	−0.92	−0.91	−5.16	4.61
III	1	0.3	2.79	−44.89	49.01	3.54	3.57	−50.82	24.74

	2	-18.42	-16.78	-93.98	23.83	-1.06	-0.6	-48.47	67.16
	3	-8	-7.55	-35.75	21.05	0.62	0.76	-15.72	10.04
	4	-5.2	-4.82	-29.64	12.06	0.86	1.03	-13.66	11.51
	5	-3.95	-3.95	-20.6	14.39	-0.3	-0.16	-17.74	12.05
	6	-7.46	-7.14	-31.93	11.63	0.12	0.23	-13.58	12.81
	7	-1.22	-1.6	-16.37	14.35	1.2	1.3	-7.07	9.98
	8	-9.45	-9.45	-35.49	18.78	0.12	0.4	-25.18	7.71
	9	-0.03	-0.3	-24.12	29.45	0.69	0.95	-16.27	7.58
	10	-0.8	-1.33	-25.39	24.01	0.33	0.22	-7.1	6.09
	11	-1.24	-1.73	-25.92	27.56	0.55	0.47	-4.2	11.41
	12	-1.12	-1.11	-38.59	17.41	0.41	0.38	-2.89	4.89
IV	1	-13.49	-10.13	-56.13	8.73	8.25	5.37	-16.33	51.39
	2	-8.21	-4.96	-67.7	40.89	7.58	4.86	-29.12	50.48
	3	-25.37	-22.12	-107.23	14.66	-2.65	-0.63	-37.29	6.16
	4	-13.7	-11.99	-46.04	4.45	1.04	0.1	-8.61	24.92
	5	-8.7	-8.07	-37.07	20.75	-2.19	-1.81	-18.33	8.34
	6	-1.66	-1.58	-22.7	19	-0.09	-0.13	-7.94	5.94
	7	-6.79	-8.28	-17.43	18.91	0.38	0.21	-3.11	5.09
	8	-7.49	-7.35	-26.36	7.92	0.07	0.1	-3.67	4.32
	9	-1.73	-0.57	-72.55	17.22	-0.25	-0.3	-4.93	3.68
	10	0.01	0.14	-16.62	22.36	-0.17	-0.25	-3.4	4.48

Table S5: Elevation change rates, surface velocities, geomorphological characteristics and classification of ice-debris complex units. The no velocity values are due to the incomplete velocity fields (less than 50%).

Ice-debris complex ID	Unit ID	Elevation change rates (m/yr)		Velocities (m/yr)	Geomorphological characteristics	Classification
		1967–2013	2013–2019	Median [25th, 75th]		
		Median [25th, 75th]	Median [25th, 75th]			
I	1	0.11 [−0.21, 0.41]	−0.11 [−0.67, 0.47]	-	Abundant crevasses, supraglacial ponds, and ice cliffs	Debris-covered glacier
	2	−0.18 [−0.29, −0.05]	−0.26 [−0.59, 0.04]	-	Abundant crevasses, supraglacial ponds, and ice cliffs	Debris-covered glacier
	3	0.06 [−0.02, 0.13]	−0.06 [−0.28, 0.10]	-	Abundant crevasses, supraglacial ponds, and ice cliffs	Debris-covered glacier
	4	−0.19 [−0.36, −0.09]	−0.08 [−0.23, 0.06]	0.29 [0.19, 0.52]	Supraglacial lakes and streams	Debris-covered dead ice body
	5	0.03 [−0.05, 0.10]	0.04 [−0.20, 0.25]	2.27 [1.28, 3.06]	Coherent viscous flow pattern, steep front	Rock glacier with clearly detectable velocities
	6	−0.03 [−0.07, 0.01]	−0.19 [−0.26, −0.10]	0.18 [0.13, 0.28]	Coherent viscous flow pattern, few lakes	Rock glacier without clearly detectable velocities
	7	−0.03 [−0.10, 0.03]	−0.06 [−0.18, 0.06]	0.19 [0.15, 0.26]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	8	−0.07 [−0.12, −0.03]	−0.11 [−0.23, 0.02]	0.20 [0.13, 0.32]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	9	−0.05 [−0.07, −0.02]	−0.16 [−0.23, −0.08]	0.16 [0.12, 0.22]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	10	−0.01 [−0.04, 0.02]	0.05 [−0.02, 0.14]	0.22 [0.18, 0.28]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	11	0.03 [−0.01, 0.07]	0.06 [−0.03, 0.15]	0.28 [0.18, 0.41]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities

	12	0.00 [−0.03, 0.03]	−0.04 [−0.14, 0.05]	0.18 [0.14, 0.24]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
II	1	−0.19 [−0.29, −0.07]	−0.34 [−0.77, −0.03]	-	Substantial ice-related features, including crevasses, thermokarst depression, supraglacial ponds, and ice cliffs	Debris-covered glacier
	2	−0.23 [−0.30, −0.14]	−0.01 [−0.18, 0.20]	-	Thermokarst depression	Debris-covered glacier
	3	−0.22 [−0.29, −0.16]	−0.16 [−0.33, 0.01]	-	Thermokarst depression	Debris-covered glacier
	4	−0.17 [−0.23, −0.12]	0.13 [−0.06, 0.32]	-	Thermokarst depression	Debris-covered glacier
	5	−0.01 [−0.07, 0.06]	0.02 [−0.17, 0.21]	1.77 [1.15, 2.34]	Coherent viscous flow pattern, steep front	Rock glacier with clearly detectable velocities
	6	−0.02 [−0.06, 0.03]	0.02 [−0.09, 0.15]	0.37 [0.28, 0.51]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	7	−0.02 [−0.06, 0.02]	−0.09 [−0.18, 0.02]	0.35 [0.23, 0.50]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	8	0.00 [−0.05, 0.05]	0.03 [−0.12, 0.20]	0.64 [0.44, 1.01]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	9	−0.02 [−0.05, 0.02]	−0.03 [−0.17, 0.11]	0.68 [0.45, 1.02]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	10	−0.04 [−0.07, 0.00]	−0.15 [−0.25, −0.06]	0.24 [0.20, 0.29]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
III	1	0.06 [−0.11, 0.18]	0.59 [0.27, 0.91]	-	Abundant crevasses, supraglacial ponds, and ice cliffs	Debris-covered glacier
	2	−0.36 [−0.59, −0.17]	−0.10 [−0.29, 0.05]	0.53 [0.29, 1.00]	Abundant thermokarst depression, lakes, crevasses and supraglacial streams	Debris-covered dead ice body

	3	−0.16 [−0.25, −0.09]	0.13 [−0.03, 0.28]	-	Thermokarst depression and lakes	Ice-cored moraine
	4	−0.10 [−0.18, −0.04]	0.17 [0.00, 0.32]	-	Thermokarst depression and lakes	Ice-cored moraine
	5	−0.09 [−0.14, −0.03]	−0.03 [−0.16, 0.09]	-	Thermokarst depression	Ice-cored moraine
	6	−0.16 [−0.24, −0.08]	0.04 [−0.09, 0.17]	-	Thermokarst depression	Ice-cored moraine
	7	−0.03 [−0.11, 0.04]	0.22 [−0.02, 0.43]	-	Thermokarst depression	Ice-cored moraine
	8	−0.21 [−0.33, −0.10]	0.07 [−0.14, 0.27]	1.51 [1.30, 1.69]	Coherent viscous flow pattern, few lakes, steep front	Rock glacier with clearly detectable velocities
	9	−0.01 [−0.09, 0.09]	0.16 [−0.02, 0.33]	0.84 [0.59, 1.08]	Coherent viscous flow pattern, few lakes	Rock glacier with clearly detectable velocities
	10	−0.03 [−0.09, 0.04]	0.04 [−0.06, 0.16]	0.54 [0.33, 1.14]	Coherent viscous flow pattern, few lakes	Rock glacier without clearly detectable velocities
	11	−0.04 [−0.08, 0.02]	0.08 [−0.04, 0.20]	0.47 [0.32, 0.79]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	12	−0.02 [−0.06, 0.02]	0.06 [−0.02, 0.15]	0.33 [0.27, 0.43]	Coherent viscous flow pattern, few lakes	Rock glacier without clearly detectable velocities
IV	1	−0.22 [−0.37, −0.12]	0.90 [0.38, 1.67]	-	Glacier characteristics with seracs and moraines	Debris-free glacier
	2	−0.11 [−0.38, 0.09]	0.81 [0.09, 2.04]	-	Abundant crevasses, supraglacial ponds, and ice cliffs	Debris-covered glacier
	3	−0.48 [−0.80, −0.21]	−0.10 [−0.49, 0.08]	0.29 [0.21, 0.44]	Abundant thermokarst depression, small lakes, many crevasses and supraglacial streams	Debris-covered dead ice body
	4	−0.26	0.02	0.28	Thermokarst depression and lakes	Ice-cored moraine

		[-0.41, -0.17]	[-0.13, 0.19]	[0.22, 0.34]		
	5	-0.18 [-0.29, -0.06]	-0.30 [-0.50, -0.15]	-	Thermokarst depression	Ice-cored moraine
	6	-0.03 [-0.11, 0.04]	-0.02 [-0.13, 0.09]	0.80 [0.49, 1.08]	Coherent viscous flow pattern	Rock glacier with clearly detectable velocities
	7	-0.18 [-0.23, -0.10]	0.04 [-0.08, 0.18]	0.85 [0.39, 1.20]	Coherent viscous flow pattern	Rock glacier with clearly detectable velocities
	8	-0.16 [-0.21, -0.12]	0.02 [-0.10, 0.12]	0.25 [0.19, 0.34]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	9	-0.01 [-0.08, 0.06]	-0.05 [-0.18, 0.09]	0.34 [0.28, 0.42]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities
	10	0.00 [-0.08, 0.08]	-0.04 [-0.15, 0.08]	0.35 [0.29, 0.41]	Coherent viscous flow pattern	Rock glacier without clearly detectable velocities