

Supplement of

**Current glacier recession causes significant rockfall increase:
The immediate paraglacial response of deglaciating cirque walls**

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Table S1: Annual rockfall numbers/volumes, surface area and slope gradient classified by vertical distance between rockfall source area and glacier surface.

		Elevation above Glacier Surface (m)									
		0-10	10-20	20-30	30-40	40-50	50-100	100-150	150-200	200-250	Total
TOTAL	Nr. (n)	13.5	8.8	5.6	8.1	5.7	15.3	4.8	1.2	0.7	63.6
	%	21.2	13.8	8.8	12.7	8.9	24.1	7.6	1.8	1.0	100.0
	Vol. (m³)	262.7	68.3	12.3	19.2	4.2	63.2	3.1	4.5	0.1	437.7
	%	60.0	15.6	2.8	4.4	1.0	14.4	0.7	1.0	0.0	100.0
	Area (m²)	34,800	32,800	28,900	21,900	16,700	54,600	26,500	11,700	6,800	234,700
	%	14,8	14,0	12,3	9,3	7,1	23,3	11,3	5,0	2,9	100.0
	Slope (°)	60	55	51	51	48	47	41	42	41	50
KN	Nr. (n)	2.3	2.3	1.8	4.0	3.0	3.7	0.2	-	-	17.3
	%	13.5	13.5	10.6	23.1	17.3	21.2	1.0	-	-	100.0
	Vol. (m³)	190.3	26.3	4.4	17.6	1.6	2.2	0.0	-	-	242.6
	%	78.5	10.9	1.8	7.3	0.6	0.9	0.0	-	-	100.0
	Area (m²)	3,300	3,100	3,300	3,300	2,600	6,700	1,200	-	-	23,500
	%	14.1	13.1	14.1	13.8	11.0	28.6	5.3	-	-	100.0
	Slope (°)	56	51	45	44	44	49	47	-	-	47
KNW	Nr. (n)	2.3	2.3	2.5	2.7	2.3	11.2	4.7	1.2	0.7	29.8
	%	7.8	7.8	8.4	8.9	7.8	37.4	15.6	3.9	2.2	100.0
	Vol. (m³)	10.3	1.4	7.1	1.0	1.8	60.9	3.0	4.5	0.1	90.2
	%	11.5	1.6	7.8	1.1	2.0	67.5	3.4	5.0	0.1	100.0
	Area (m²)	10,000	10,200	9,600	8,800	8,500	42,500	25,300	11,700	6,800	133,400
	%	7.5	7.6	7.2	6.6	6.4	31.9	19.0	8.8	5.1	100.0
	Slope (°)	52	45	43	44	44	43	41	42	41	44
MKE	Nr. (n)	3.3	0.0	0.2	0.2	0.2	-	-	-	-	3.8
	%	87.0	0.0	4.3	4.3	4.3	-	-	-	-	100.0
	Vol. (m³)	45.7	0.0	0.0	0.0	0.8	-	-	-	-	46.6
	%	98.0	0.0	0.1	0.1	1.8	-	-	-	-	100.0
	Area (m²)	2,700	2,600	2,200	1,400	1,100	1,100	-	-	-	11,100
	%	24.3	23.4	19.8	12.6	9.9	9.9	-	-	-	100.0
	Slope (°)	77	69	66	75	75	63	-	-	-	71
MKW	Nr. (n)	1.5	1.8	0.3	0.3	-	-	-	-	-	3.8
	%	40.0	46.7	6.7	6.7	-	-	-	-	-	100.0
	Vol. (m³)	1.1	36.0	0.2	0.1	-	-	-	-	-	37.4
	%	3.0	96.2	0.7	0.1	-	-	-	-	-	100.0
	Area (m²)	3,000	2,300	900	100	-	-	-	-	-	6,300
	%	47.6	36.5	14.3	1.6	-	-	-	-	-	100.0
	Slope (°)	65	58	57	54	-	-	-	-	-	63
MGE	Nr. (n)	4.0	2.3	0.8	1.0	0.2	0.5	-	-	-	8.8
	%	45.3	26.4	9.4	11.3	1.9	5.7	-	-	-	100.0
	Vol. (m³)	15.2	4.6	0.5	0.5	0.0	0.1	-	-	-	20.9
	%	72.9	21.9	2.6	2.2	0.1	0.4	-	-	-	100.0
	Area (m²)	15,800	14,600	12,900	8,300	4,500	4,300	-	-	-	60,400
	%	26.2	24.2	21.4	13.7	7.5	7.1	-	-	-	100.0
	Slope (°)	62	59	56	57	52	76	-	-	-	61

Table S2: Key data acquisition parameters for each of the five monitored rockwalls.

Rockwall	Scan ID	Date	Scan Position	Object Distance (min/mean/max) (m)	Acquisition Resolution (°)	Resulting Resolution (min/mean/max) (cm)
KN	KN1	18.08.2011	Magnetkoepl	155/270/370	0.008	2.1/3.8/5.2
	KN2	21.08.2012			0.01 – 0.02	2.7/4.7/6.5 - 5.4/9.4/12.9
	KN3	11.08.2015			0.01	2.7/4.7/6.5
	KN4	26.08.2016			0.01	2.7/4.7/6.5
	KN5	24.08.2017			0.01	2.7/4.7/6.5
KNW	KNW1	08.07.2011	Magnetkoepl	250/370/570	0.025	10.9/16.1/24.9
	KNW2	16.08.2011			0.03	13.1/19.4/29.8
	KNW3	21.08.2012			0.02	8.7/12.9/19.9
	KNW4	11.08.2015			0.01	4.4/6.5/9.9
	KNW5	26.08.2016			0.01 – 0.02	4.4/6.5/9.9 – 8.7/12.9/19.9
	KNW6	24.08.2017			0.01 – 0.016	4.4/6.5/9.9 – 7.0/10.3/15.9
MKE	MKE1	17.08.2011	Summit Station	260/300/380	0.05	22.7/26.2/33.2
	MKE2	07.07.2012			0.02	9.1/10.5/13.3
	MKE3	10.09.2012			0.05	22.7/26.2/33.2
	MKE4	31.07.2013			0.05	22.7/26.2/33.2
	MKE5	07.10.2013			0.02	9.1/10.5/13.3
	MKE6	18.07.2014			0.025	11.3/13.1/16.6
	MKE7	28.08.2014			0.025	11.3/13.1/16.6
	MKE8	15.10.2014			0.017	7.7/8.9/11.3
	MKE9	17.07.2015			0.015	6.8/7.9/9.9
	MKE10	11.08.2015			0.007	3.2/3.7/4.6
	MKE11	25.08.2016			0.008	3.6/4.2/5.3
	MKE12	24.08.2017			0.008	3.6/4.2/5.3
MKW	MKW1	07.07.2012	Maurergrat	580/640/690	0.04	40.5/44.7/48.2
	MKW2	11.09.2012			0.03	30.4/33.5/36.1
	MKW3	17.06.2013			0.03	30.4/33.5/36.1
	MKW4	30.07.2013			0.05	50.6/55.9/60.2
	MKW5	08.10.2013			0.03	30.4/33.5/36.1
	MKW6	18.07.2014			0.025	25.3/27.9/30.1
	MKW7	29.08.2014			0.025	25.3/27.9/30.1
	MKW8	18.07.2015			0.01	10.1/11.2/12.0
	MKW9	12.08.2015			0.008	8.1/8.9/9.6
	MKW10	25.08.2016			Glacier 1	110/140/180
	MKW11	25.08.2016	Glacier 2	130/160/200	0.025	5.7/7.0/8.7
MGE	MGE1	18.08.2011	Magnetkoepl	520/650/860	0.025	22.7/28.4/37.5
	MGE2	21.08.2012			0.03	27.2/34.0/45.0
	MGE3	11.09.2012			0.03	27.2/34.0/45.0
	MGE4	30.07.2013			0.03	27.2/34.0/45.0
	MGE5	08.10.2013			0.025	22.7/28.4/37.5
	MGE6	18.07.2014			0.025	22.7/28.4/37.5
	MGE7	29.08.2014			0.025	22.7/28.4/37.5
	MGE8	15.10.2014			0.025	22.7/28.4/37.5
	MGE9	17.07.2015			0.025	22.7/28.4/37.5
	MGE10	11.08.2015			0.025	22.7/28.4/37.5
	MGE11	26.08.2016			0.01	9.1/11.3/15.0
	MGE12	24.08.2017			0.01	9.1/11.3/15.0

Table S3: Number, volume and failure depth of registered rockfalls, classified by rockwall and volume class.

	Rockfalls		Rockfall Volume				Mean Failure Depth	
	(n)	(%)	(m ³)	(%)	Error (\pm m ³)	Error (\pm %)	(m)	
TOTAL	< 0.1 m ³	258	40.8	12.8	0.5	0.22	1.72	0.24
	0.1 – 1 m ³	299	47.3	94.7	3.7	0.63	0.66	0.39
	1 – 10 m ³	50	7.9	151.8	5.9	0.26	0.17	0.81
	10 – 100 m ³	20	3.2	547.8	21.4	0.31	0.06	1.56
	100 – 1,000 m ³	5	0.8	1,757.0	68.5	0.11	0.01	3.97
	Total	632	100.0	2,564.3	100.0	1.53	0.06	0.43
KN	< 0.1 m ³	119	53.4	5.7	0.4	0.08	1.32	0.21
	0.1 – 1 m ³	83	37.2	24.5	1.7	0.12	0.48	0.38
	1 – 10 m ³	13	5.8	48.3	3.3	0.04	0.08	0.95
	10 – 100 m ³	5	2.2	104.6	7.2	0.03	0.02	1.41
	100 – 1,000 m ³	3	1.3	1,278.0	87.5	0.04	0.00	4.55
	Total	223	100.0	1,461.1	100.0	0.29	0.02	0.40
KNW	< 0.1 m ³	77	30.1	4.7	0.9	0.10	2.11	0.27
	0.1 – 1 m ³	150	58.6	45.9	8.4	0.35	0.76	0.36
	1 – 10 m ³	21	8.2	65.9	12.1	0.14	0.21	0.64
	10 – 100 m ³	7	2.7	156.7	28.7	0.09	0.06	1.06
	100 – 1,000 m ³	1	0.4	272.7	50.0	0.03	0.01	2.45
	Total	256	100.0	545.9	100.0	0.71	0.13	0.38
MKE	< 0.1 m ³	22	48.9	1.0	0.3	0.01	1.35	0.22
	0.1 – 1 m ³	15	33.3	6.7	2.4	0.03	0.50	0.51
	1 – 10 m ³	4	8.9	12.6	4.5	0.02	0.15	1.15
	10 – 100 m ³	3	6.7	54.0	19.3	0.04	0.07	1.72
	100 – 1,000 m ³	1	2.2	206.3	73.5	0.04	0.02	3.75
	Total	45	100.0	280.6	100.0	0.15	0.05	0.58
MKW	< 0.1 m ³	1	6.3	0.1	0.1	0.00	1.25	0.28
	0.1 – 1 m ³	8	50.0	2.8	1.9	0.02	0.75	0.44
	1 – 10 m ³	5	31.3	10.7	7.2	0.03	0.25	0.97
	10 – 100 m ³	2	12.5	136.2	90.9	0.07	0.05	2.69
	100 – 1,000 m ³	-	-	-	-	-	-	-
	Total	16	100.0	149.8	100.0	0.12	0.08	0.88
MGE	< 0.1 m ³	39	42.4	1.3	1.1	0.03	2.31	0.26
	0.1 – 1 m ³	43	46.7	14.8	11.7	0.11	0.72	0.48
	1 – 10 m ³	7	7.6	14.4	11.3	0.04	0.27	0.78
	10 – 100 m ³	3	3.3	96.4	76.0	0.08	0.08	2.10
	100 – 1,000 m ³	-	-	-	-	-	-	-
	Total	92	100.0	126.9	100.0	0.25	0.20	0.46

30 Table S4: Number and volume of mass movements from unconsolidated sediments, classified by rockwall and volume class.

	Mass Movements		Sediment Volume				
	(n)	(%)	(m ³)	(%)	Error (\pm m ³)	Error (\pm %)	
TOTAL	< 0.1 m ³	25	22.1	1.6	0.5	0.02	1.22
	0.1 – 1 m ³	48	42.5	19.1	6.6	0.12	0.63
	1 – 10 m ³	31	27.4	107.1	36.7	0.17	0.16
	10 – 100 m ³	9	8.0	164.2	56.2	0.12	0.07
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	113	100.0	292.0	100.0	0.44	0.15
KN	< 0.1 m ³	15	39.5	0.9	4.0	0.01	1.23
	0.1 – 1 m ³	18	47.4	5.5	23.4	0.03	0.57
	1 – 10 m ³	5	13.2	17.2	72.6	0.02	0.13
	10 – 100 m ³	-	-	-	-	-	-
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	38	38	23.7	100.0	0.07	0.28
KNW	< 0.1 m ³	2	3.1	0.2	0.1	0.00	1.32
	0.1 – 1 m ³	27	42.2	12.1	4.5	0.08	0.65
	1 – 10 m ³	26	40.6	89.9	33.8	0.15	0.17
	10 – 100 m ³	9	14.1	164.2	61.6	0.12	0.07
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	64	100.0	266.4	100.0	0.35	0.13
MKE	< 0.1 m ³	2	100.0	0.1	100.0	0.00	0.70
	0.1 – 1 m ³	-	-	-	-	-	-
	1 – 10 m ³	-	-	-	-	-	-
	10 – 100 m ³	-	-	-	-	-	-
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	2	100.0	0.1	100.0	0.00	0.70
MKW	< 0.1 m ³	-	-	-	-	-	-
	0.1 – 1 m ³	1	100.0	1.0	100.0	0.3	32.9
	1 – 10 m ³	-	-	-	-	-	-
	10 – 100 m ³	-	-	-	-	-	-
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	1	100.0	1.0	100.0	0.3	32.9
MGE	< 0.1 m ³	6	75.0	0.3	41.3	0.00	1.33
	0.1 – 1 m ³	2	25.0	0.5	58.7	0.00	0.62
	1 – 10 m ³	-	-	-	-	-	-
	10 – 100 m ³	-	-	-	-	-	-
	100 – 1,000 m ³	-	-	-	-	-	-
	Total	8	100.0	0.8	100.0	0.01	0.91

Table S5: Number of rockfalls per year, rockfall volume per year and size of investigated rockwall surface area, classified by elevation above sea level.

Elevation	Surface Area		Rockfall Volume				Rockfall Number			
	<i>m (a.s.l.)</i>	<i>[m²]</i> <i>[%]</i>	<i>[m³ a⁻¹]</i> <i>[%]</i>	<i>[m³ a⁻¹ 10,000 m²]</i> <i>[%]</i>	<i>[n a⁻¹]</i> <i>[%]</i>	<i>[n a⁻¹ 10,000 m²]</i> <i>[%]</i>	<i>[n a⁻¹]</i> <i>[%]</i>	<i>[n a⁻¹ 10,000 m²]</i> <i>[%]</i>		
2,700-2,750	300	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
2,750-2,800	6,500	2.8	0.2	0.1	0.4	0.4	0.5	0.8	0.8	
2,800-2,850	21,100	9.0	5.1	1.2	2.4	2.5	3.0	4.7	1.4	
2,850-2,900	38,200	16.3	76.2	17.4	19.9	20.4	7.8	12.3	2.1	
2,900-2,950	63,400	27.0	238.1	54.4	37.6	38.6	20.1	31.6	3.2	
2,950-3,000	44,300	18.9	62.3	14.2	14.1	14.5	20.5	32.2	4.6	
3,000-3,050	25,800	11.0	49.4	11.3	19.2	19.7	7.0	11.0	2.7	
3,050-3,100	17,000	7.2	5.9	1.4	3.5	3.6	3.3	5.2	2.0	
3,100-3,150	11,600	4.9	0.2	0.1	0.2	0.2	0.8	1.3	0.7	
3,150-3,200	6,400	2.7	0.1	0.0	0.2	0.2	0.5	0.8	0.8	
3,200-3,250	100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
	234,700	100.0	437.7	100.0	18.6	100.0	63.6	100.0	2.7	

40 **Table S6: Number of rockfalls classified by failure depth.**

		Failure Depth (m)							Total
		< 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	2.0 – 2.5	2.5 – 3.0	> 3.0	
TOTAL	Nr. (n)	258	83	20	2	5	1	5	374
	%	69.0	22.2	5.3	0.5	1.3	0.3	1.3	100.0
KN	Nr. (n)	73	17	9	2	-	-	3	104
	%	70.2	16.3	9.7	1.9	-	-	2.9	100.0
KNW	Nr. (n)	145	29	3	-	2	-	-	179
	%	81.0	16.2	1.7	-	1.1	-	-	100.0
MKE	Nr. (n)	9	7	5	-	1	-	1	23
	%	39.1	30.4	21.7	-	4.3	-	4.3	100.0
MKW	Nr. (n)	6	5	2	-	1	1	-	15
	%	40.0	33.3	13.3	-	6.7	6.7	-	100.0
MGE	Nr. (n)	25	25	1	-	1	-	1	53
	%	47.2	47.2	1.9	-	1.9	-	1.9	100.0