Supplement of Earth Surf. Dynam., 8, 729–751, 2020
https://doi.org/10.5194/esurf-8-729-2020-supplement
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Earth Surface Dynamics
Open Access

Supplement of

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

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Table S1: Selected morphometric parameters for all five investigated rockwalls.

	Area	Altitude (min/max)	Avg. Height	Avg. Slope	Avg. Aspect
	(m²)	*(m a.s.l.)*	*(m)*	*(°)*	*(°)*
Kitzsteinhorn north-face (KN)	23,500	2,921 / 3,060	~ 70	47	(N) 357
Kitzsteinhorn northwest-face (KNW)	133,400	2,768 / 3,203	~ 200	44	(NW) 322
Magnetkoepfl east-face (MKE)	11,100	2,853 / 2,953	~ 55	71	(E) 110
Magnetkoepfl west-face (MKW)	6,300	2,876 / 2,944	~ 35	63	(W) 268
Maurergrat east-face (MGE)	60,400	2,742 / 2,994	~ 55	61	(E) 86

Table S2: Glacier surface elevation changes (ice surface lowering) adjacent to monitored rockwalls reconstructed from 1953 air photos (Land Salzburg, 1953) and from acquired terrestrial laserscans (2011, 2017).

	KN	KNW	MKE	*MKW	MGE	OVERALL MEAN
	(m)	*(m)*	*(m)*	*(m)*	*(m)*	*(m)*
1953-2017						
Total	-20	-23	-15	-18	-14	-17
Annual	-0.3	-0.4	-0.2	-0.3	-0.2	-0.3
2011-2017 (LiDAR monitoring period)						
Total	-3.7	-5.7	-5.6	-2.6	-3.1	4.1
Annual	-0.6	-1.0	-0.9	-0.7	-0.5	-0.7

*Reference periods for MKW: 1953-2016 and 2012-2016.

Table S3: Key data acquisition parameters for each of the five monitored rockwalls. Data acquisition was performed with a Riegl LMS-Z620i laserscanner (accuracy ± 10 mm (1σ @ 100 m)).

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	Magnetkoepfl	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	Magnetkoepfl	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	0.025	4.8/6.1/7.9
	MKW11	25.08.2016	Glacier 2	130/160/200	0.025	5.7/7.0/8.7
MGE	MGE1	18.08.2011	Magnetkoepfl	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 S4: Number, volume and failure depth of registered rockfalls, classified by rockwall and volume class.

		Rockfalls		Rockfall Volume				Mean Failure Depth
		(n)	*(%)*	(m^3)	*(%)*	Error (± m^3)	*Error (± %)*	(m)
TOTAL	**< 0.1 m³**	258	*40.8*	12.8	*0.5*	5.1	*40.0*	0.24
	0.1 – 1 m³	299	*47.3*	94.7	*3.7*	25.4	*26.8*	0.39
	1 – 10 m³	50	*7.9*	151.8	*5.9*	21.3	*14.0*	0.81
	10 – 100 m³	20	*3.2*	547.8	*21.4*	51.2	*9.3*	1.56
	100 – 1,000 m³	5	*0.8*	1,757.0	*68.5*	38.9	*2.2*	3.97
	Total	**632**	***100.0***	**2,564.3**	***100.0***	**141.9**	***5.5***	**0.43**
KN	**< 0.1 m³**	119	*53.4*	5.7	*0.4*	2.2	*37.8*	0.21
	0.1 – 1 m³	83	*37.2*	24.5	*1.7*	5.2	*21.3*	0.38
	1 – 10 m³	13	*5.8*	48.3	*3.3*	3.8	*7.9*	0.95
	10 – 100 m³	5	*2.2*	104.6	*7.2*	5.5	*5.2*	1.41
	100 – 1,000 m³	3	*1.3*	1,278.0	*87.5*	15.9	*1.2*	4.55
	Total	**223**	***100.0***	**1,461.1**	***100.0***	**32.6**	***2.2***	**0.40**
KNW	**< 0.1 m³**	77	*30.1*	4.7	*0.9*	1.9	*40.7*	0.27
	0.1 – 1 m³	150	*58.6*	45.9	*8.4*	13.8	*30.0*	0.36
	1 – 10 m³	21	*8.2*	65.9	*12.1*	11.7	*17.8*	0.64
	10 – 100 m³	7	*2.7*	156.7	*28.7*	21.2	*13.6*	1.06
	100 – 1,000 m³	1	*0.4*	272.7	*50.0*	11.4	*4.2*	2.45
	Total	**256**	***100.0***	**545.9**	***100.0***	**60.0**	***11.0***	**0.38**
MKE	**< 0.1 m³**	22	*48.9*	1.0	*0.3*	0.4	*39.6*	0.22
	0.1 – 1 m³	15	*33.3*	6.7	*2.4*	1.4	*21.2*	0.51
	1 – 10 m³	4	*8.9*	12.6	*4.5*	1.6	*12.3*	1.15
	10 – 100 m³	3	*6.7*	54.0	*19.3*	4.9	*9.0*	1.72
	100 – 1,000 m³	1	*2.2*	206.3	*73.5*	11.6	*5.6*	3.75
	Total	**45**	***100.0***	**280.6**	***100.0***	**19.8**	***7.1***	**0.58**
MKW	**< 0.1 m³**	1	*6.3*	0.1	*0.1*	0.0	*22.6*	0.28
	0.1 – 1 m³	8	*50.0*	2.8	*1.9*	1.0	*35.9*	0.44
	1 – 10 m³	5	*31.3*	10.7	*7.2*	1.7	*16.1*	0.97
	10 – 100 m³	2	*12.5*	136.2	*90.9*	11.6	*8.5*	2.69
	100 – 1,000 m³	-	-	-	-	-	-	-
	Total	**16**	***100.0***	**149.8**	***100.0***	**14.3**	***9.6***	**0.88**
MGE	**< 0.1 m³**	39	*42.4*	1.3	*1.1*	0.7	*48.5*	0.26
	0.1 – 1 m³	43	*46.7*	14.8	*11.7*	4.0	*27.0*	0.48
	1 – 10 m³	7	*7.6*	14.4	*11.3*	2.5	*17.2*	0.78
	10 – 100 m³	3	*3.3*	96.4	*76.0*	8.0	*8.3*	2.10
	100 – 1,000 m³	-	-	-	-	-	-	-
	Total	**92**	***100.0***	**126.9**	***100.0***	**15.2**	***11.9***	**0.46**

25

Table S5: Number and volume of mass movements from unconsolidated sediments, classified by rockwall and volume class.

		Mass Movements		Sediment Volume			
		(n)	*(%)*	(m^3)	*(%)*	Error (± m^3)	*Error (± %)*
TOTAL	**< 0.1 m³**	25	*22.1*	1.6	*0.5*	0.8	*49.0*
	0.1 – 1 m³	48	*42.5*	19.1	*6.6*	7.0	*36.7*
	1 – 10 m³	31	*27.4*	107.1	*36.7*	28.3	*26.5*
	10 – 100 m³	9	*8.0*	164.2	*56.2*	36.2	*22.0*
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**113**	***100.0***	**292.0**	***100.0***	**72.3**	***24.8***
KN	**< 0.1 m³**	15	*39.5*	0.9	*4.0*	0.5	*51.1*
	0.1 – 1 m³	18	*47.4*	5.5	*23.4*	1.9	*33.3*
	1 – 10 m³	5	*13.2*	17.2	*72.6*	2.9	*16.9*
	10 – 100 m³	-	-	-	-	-	-
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**38**	***38***	**23.7**	***100.0***	**5.2**	***22.1***
KNW	**< 0.1 m³**	2	*3.1*	0.2	*0.1*	0.1	*47.4*
	0.1 – 1 m³	27	*42.2*	12.1	*4.5*	4.6	*37.7*
	1 – 10 m³	26	*40.6*	89.9	*33.8*	25.4	*28.3*
	10 – 100 m³	9	*14.1*	164.2	*61.6*	36.2	*22.0*
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**64**	***100.0***	**266.4**	***100.0***	**66.3**	***24.9***
MKE	**< 0.1 m³**	2	*100.0*	0.1	*100.0*	0.0	*35.4*
	0.1 – 1 m³	-	-	-	-	-	-
	1 – 10 m³	-	-	-	-	-	-
	10 – 100 m³	-	-	-	-	-	-
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**2**	***100.0***	**0.1**	***100.0***	**0.0**	***35.4***
MKW	**< 0.1 m³**	-	-	-	-	-	-
	0.1 – 1 m³	1	*100.0*	1.0	*100.0*	0.4	*42.2*
	1 – 10 m³	-	-	-	-	-	-
	10 – 100 m³	-	-	-	-	-	-
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**1**	***100.0***	**1.0**	***100.0***	**0.4**	***42.2***
MGE	**< 0.1 m³**	6	*75.0*	0.3	*41.3*	0.2	*48.7*
	0.1 – 1 m³	2	*25.0*	0.5	*58.7*	0.2	*37.3*
	1 – 10 m³	-	-	-	-	-	-
	10 – 100 m³	-	-	-	-	-	-
	100 – 1,000 m³	-	-	-	-	-	-
	Total	**8**	***100.0***	**0.8**	***100.0***	**0.4**	***42.0***

30

Table S6: Number of rockfalls per year, rockfall volume per year, and size of investigated rockwall surface area, classified by elevation.

Elevation	Surface Area		Rockfall Volume				Rockfall Number			
m (a.s.l.)	*[m²]*	*[%]*	*[m³ a⁻¹]*	*[%]*	*[m³ a⁻¹ 10,000 m⁻²]*	*[%]*	*[n a⁻¹]*	*[%]*	*[n a⁻¹ 10,000 m⁻²]*	*[%]*
2,700-2,750	300	*0.1*	0.0	*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	*4.4*
2,800-2,850	21,100	*9.0*	5.1	*1.2*	2.4	*2.5*	3.0	*4.7*	1.4	*7.7*
2,850-2,900	38,200	*16.3*	76.2	*17.4*	19.9	*20.4*	7.8	*12.3*	2.1	*11.5*
2,900-2,950	63,400	*27.0*	238.1	*54.4*	37.6	*38.6*	20.1	*31.6*	3.2	*17.5*
2,950-3,000	44,300	*18.9*	62.3	*14.2*	14.1	*14.5*	20.5	*32.2*	4.6	*25.1*
3,000-3,050	25,800	*11.0*	49.4	*11.3*	19.2	*19.7*	7.0	*11.0*	2.7	*14.8*
3,050-3,100	17,000	*7.2*	5.9	*1.4*	3.5	*3.6*	3.3	*5.2*	2.0	*10.9*
3,100-3,150	11,600	*4.9*	0.2	*0.1*	0.2	*0.2*	0.8	*1.3*	0.7	*3.8*
3,150-3,200	6,400	*2.7*	0.1	*0.0*	0.2	*0.2*	0.5	*0.8*	0.8	*4.4*
3,200-3,250	100	*0.0*	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**	***100.0***

Table S7: Annual rockfall numbers/volumes, surface area, and slope gradient classified by vertical distance between rockfall source area and glacier surface.

		Height 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 S8: Number of rockfalls classified by failure depth.

		Failure Depth (m)							
		< 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
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*

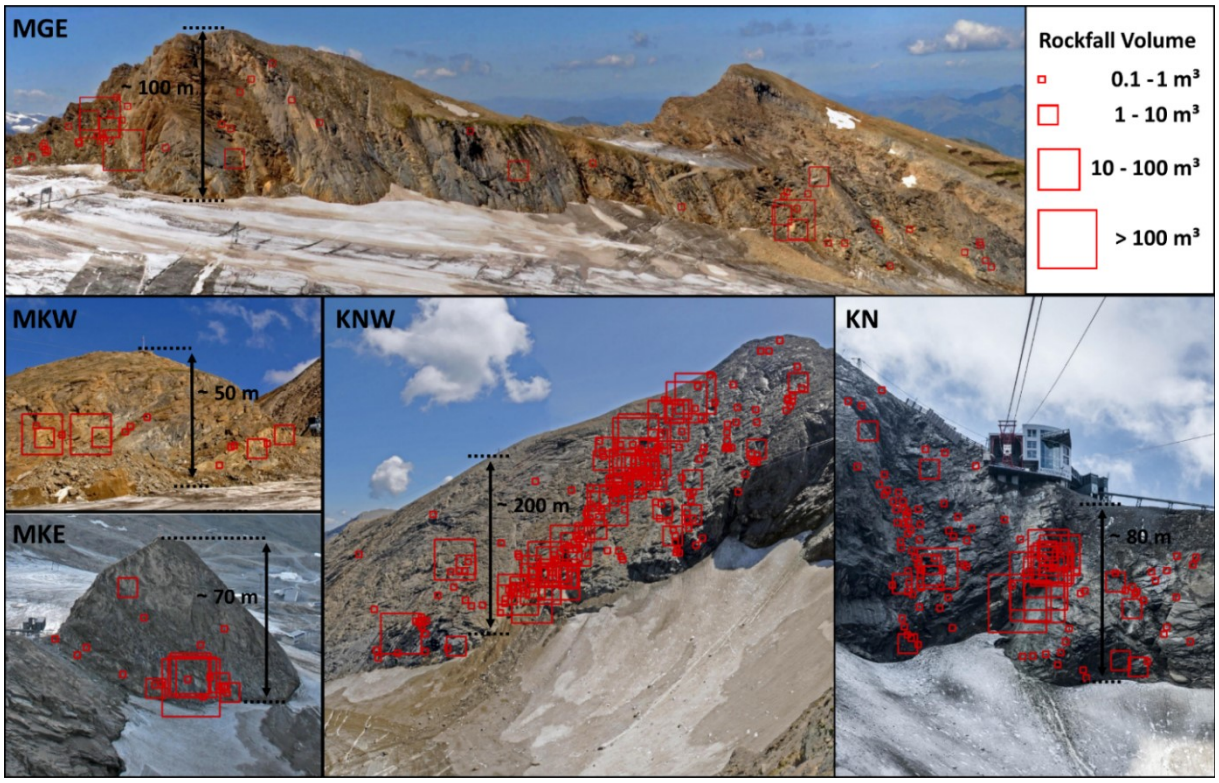

Figure S1: Rockfall source areas and volumes for all five monitored rockwalls (Photos: Robert Delleske).

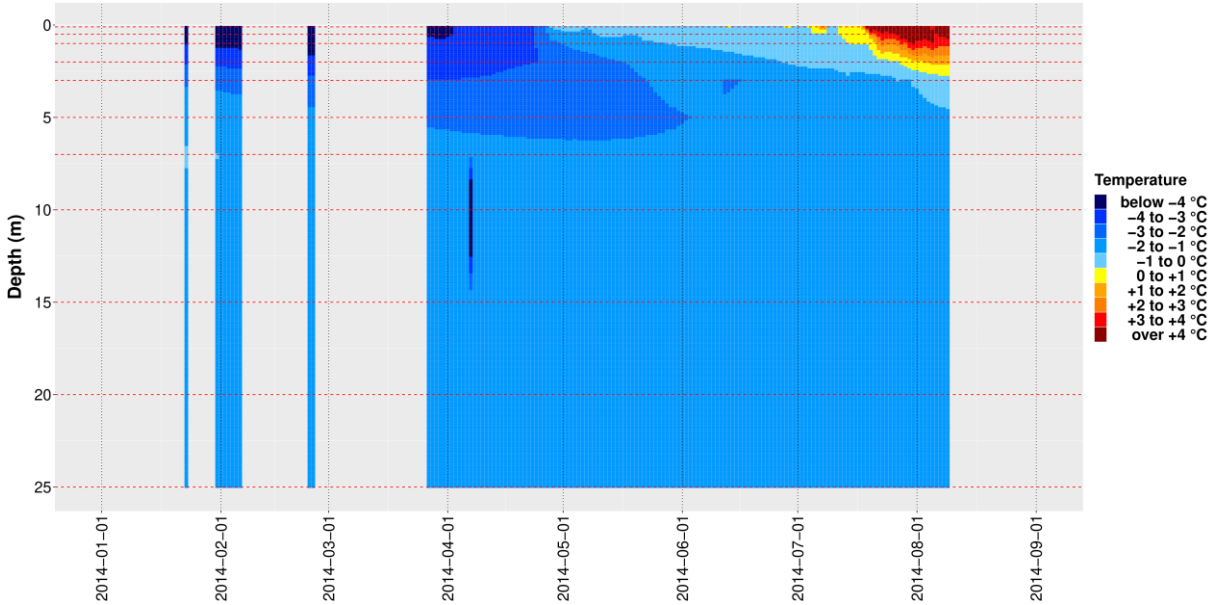

Figure S2: Temperature record from 25 m deep borehole T-BW (2,975 m a.s.l., Kitzsteinhorn W-face). Temperature at 25 m depth ranged between -1.1 and -1.2 °C during the observation period. Repeated lightning strike damage caused fragmentary data availability.

Figure S3: Images from the investigated Randkluft below the Kitzsteinhorn north-face (KN). A: Picture was taken at ~ 10 m depth, permanently ice-covered headwall is on the left, glacier is on the right (Photo: I. Hartmeyer, 09.10.2015). B: Randkluft is narrowing with depth. Picture was taken at ~ 15 m depth, T-RK3 is visible in the background (headwall is on the right, glacier on the left) (Photo: I. Hartmeyer, 13.09.2019). C: Melt- and rainwater entering the Randkluft contributes to the formation of thick ice coatings and icicles on the rockwall (Photo: I. Hartmeyer, 16.10.2018).