

SUPPLEMENT

Moraines in the Austrian Alps record repeated phases of glacier stabilization through the Late Glacial and the Early Holocene

AUTHORS

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1 QUARTZ CONTENT IN ROCK SAMPLES

Table S 1: Quartz yields of rock samples collected from Jamtal (JAM) and Fimbatal (FMB); values range between 1.1 and 11.3% with a median of 5.2%.

Sample ID	Start weight [g]	Quartz yield [g]	Quartz yield [%]
JAM-18-11	481	9.01	1.9%
JAM-18-13	685	16.74	2.4%
JAM-19-19	412	40.13	9.7%
JAM-19-20	363	18.97	5.2%
JAM-20-23	436	26.90	6.2%
JAM-20-24	465	7.02	1.5%
JAM-20-25	440	11.20	2.5%
JAM-20-26	317	35.70	11.3%
JAM-20-27	462	25.05	5.4%
FMB-18-04	419	42.93	10.2%
FMB-18-05	409	4.59	1.1%
FMB-18-08	420	25.79	6.1%
FMB-18-09	356	23.85	6.7%
FMB-19-12	476	19.16	4.0%
FMB-19-13	647	16.41	2.5%
		Maximum	11.3%
		Minimum	1.1%
		Median	5.2%

2 ORGANIZATION OF ^{10}Be SAMPLE BATCHES INCLUDING PROCEDURAL BLANKS

Table S 2: A total of 15 rock samples was processed according to the LDEO protocol ^{1,2}. Samples were processed in four batches, each of them including one to two procedural blanks (in blue font). The numbers of atoms counted in blanks that were processed with each batch were subtracted from the total number of atoms in each sample of the same batch. If two blanks were available (batches 3 and 4), the average of both blanks was used for blank correction. Blank correction ranged from 0.1% to 0.3% depending on the total number of ^{10}Be atoms in the samples. Concentrations of the LDEO ^9Be carriers are corrected for evaporation.

Batch #	Sample ID	$^{10}\text{Be}/^9\text{Be}$ AMS ratio	1 σ anal. unc. $^{10}\text{Be}/^9\text{Be}$ AMS ratio	1 σ anal. unc. $^{10}\text{Be}/^9\text{Be}$ AMS ratio [%]	Counted ^{10}Be atoms [atoms/sample]	1 σ anal. unc. $^{10}\text{Be}/^9\text{Be}$ [atoms/sample]	Blank correction [%]	Carrier & Concentration [ppm]
3	Blk1_2019May23	8.36E-16	2.09E-16	25.0%	10266	2566	-	Carrier 7 1028
	Blk2_2019May23	6.18E-16	1.72E-16	27.8%	7694	2135	-	
	FMB-18-04	7.91E-13	1.68E-14	2.1%	9716105	205863	0.1%	
	FMB-18-08	4.90E-13	9.08E-15	1.9%	6008892	111455	0.1%	
	FMB-18-09	3.43E-13	6.44E-15	1.9%	4215324	79209	0.2%	
4	BLK1-2019June6	4.32E-16	1.44E-16	33.4%	5355	1786	-	Carrier 7 1028
	BLK2-2019June6	2.81E-16	9.95E-17	35.4%	3492	1236	-	
	JAM-18-11	3.05E-13	5.65E-15	1.9%	3778652	70081	0.1%	
	JAM-18-13	4.46E-13	8.30E-15	1.9%	5532868	103026	0.1%	
	FMB-18-05	1.03E-13	2.02E-15	2.0%	1283934	25261	0.3%	
6	BLK3-2020Jan31	5.05E-16	1.46E-16	28.9%	6243	1804	-	Carrier 7 1032
	JAM-19-19	3.40E-13	6.36E-15	1.9%	4214518	78808	0.1%	
	JAM-19-20	2.70E-13	5.04E-15	1.9%	3347499	62609	0.2%	
	FMB-19-12	1.98E-13	3.70E-15	1.9%	2440545	45594	0.3%	
	FMB-19-13	1.86E-13	3.48E-15	1.9%	2254712	42127	0.3%	
7	BLK-2021Nov17	2.29E-16	8.09E-17	35.4%	2846	1008	-	Carrier 7 1035
	JAM-20-23	3.51E-13	7.10E-15	2.0%	4383259	88749	0.1%	
	JAM-20-24	1.59E-13	2.97E-15	1.9%	1987961	37023	0.1%	
	JAM-20-25	2.65E-13	5.22E-15	2.0%	3289758	64839	0.1%	
	JAM-20-26	1.88E-13	4.01E-15	2.1%	2335435	49824	0.1%	
	JAM-20-27	2.10E-13	3.90E-15	1.9%	2613912	48590	0.1%	
	Blank min.	2.29E-16						
	Blank max.	8.36E-16						

3 LANDFORM AGE CALCULATIONS

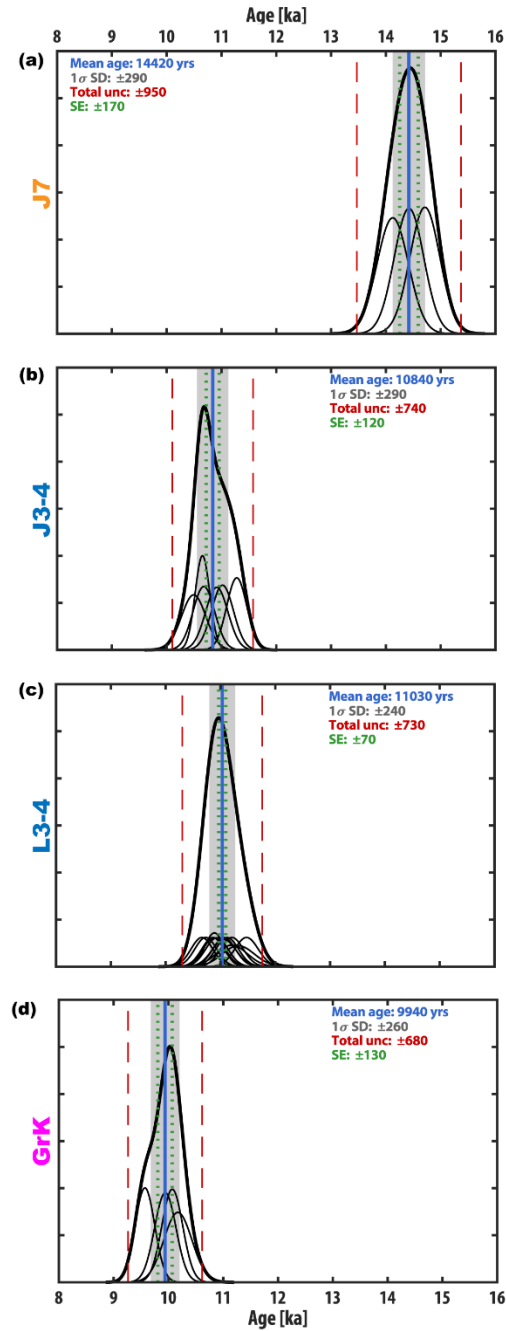


Figure S 1: Kernel plots of moraine ages shown in Figure 6. (a.) J7 ($n=3$; samples: JAM-18-11, JAM-19-19, JAM-20-23). (b.) J3-4 ($n=6$; samples: JAM-18-01, JAM-18-02, JAM-18-04, JAM-19-21, JAM-19-22, JAM-20-26). (c.) L3-4 ($n=13$; samples: LAR-18-10, LAR-19-12, LAR-19-13, LAR-19-14, LAR-19-15, LAR-19-16, LAR-19-17, LAR-19-18, LAR-19-19, LAR-19-20, LAR-19-21, LAR-19-22, LAR-19-24). (d.) GrK ($n=4$; samples: GrK-17-01, GrK-17-02, GrK-17-03, GrK-17-04). The gray-shaded bars indicate the 1σ standard deviation (SD) of the landform ages calculated from the analytical uncertainties of individual samples. Dashed red lines add the production rate uncertainty and the uncertainty of the carrier concentration to the 1σ SD and show the total uncertainty. Dotted green lines are the standard error (SE), which describes the dispersion of different sample means from the population mean.

4 GEOMORPHOLOGICAL OBSERVATIONS AND SAMPLE DOCUMENTATION



Figure S 2: Confluence zone of the Jamtäl glacier and the tributary Futschöl glacier. Lateral moraines J7, J6 and J5 are dated using ^{10}Be surface exposure dating. The resulting ages are stratigraphically in order: Three boulders from J7 produce a landform age of 14.4 ± 1.0 ka falling into the (Pre)-Bølling period. J6 and J5 both date to the Younger Dryas (YD) with the upper ridge indicating an ice margin during the first half of the YD, and the lower ridge marking the final phase of the YD.

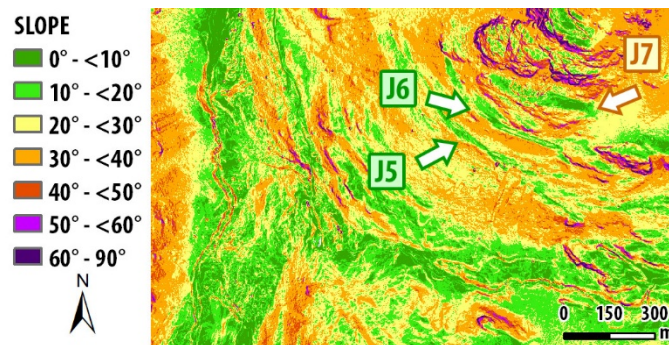


Figure S 3: Slope map of LG moraine set J7, J6 and J5. The landforms appear as linear elements in green-yellow color indicating lower slope angles, and are highlighted by arrows.

JAM-18-11

^{10}Be exposure age: $14,710 \pm 270$ yrs

COORDINATES N 46.8904 | E 10.1871
ALTITUDE 2520 m
L x B x H 2.7 x 1.3 x 1.1 m



Figure S4: JAM-18-11. (a) View towards W. (b) View towards N. (c) View towards W. (d) View towards S with Augstenferner and Jamtalferner in the background. (e) View towards E. (f) Sampled rock surface indicated by pencil.

COORDINATES N 46.8901 | E 10.1838
ALTITUDE 2432 m
L x B x H 2.3 x 1.0 x 1.5 m



Figure S5: JAM-18-13. (a) View towards W. (b) View towards N. (c) View towards W. (d) View towards SE (Futschöltal). (e) View towards NW. (f) Sampled rock surface indicated by pencil.

COORDINATES N 46.8904 | E 10.1875
 ALTITUDE 2522 m
 L x B x H 2.0 x 1.2 x 0.9m



Figure S6: JAM-19-19. (a) View towards E; note person sitting on the boulder for scale. (b) View towards S with Jamtalferner and Totenfeld in the background. (c) View towards SE. (d) View towards W. (e) Sampling, view towards W. (f) Sampled rock surface.

COORDINATES N 46.8893 | E 10.1865
ALTITUDE 2445 m
L x B x H 1.9 x 0.7 x 0.6 m

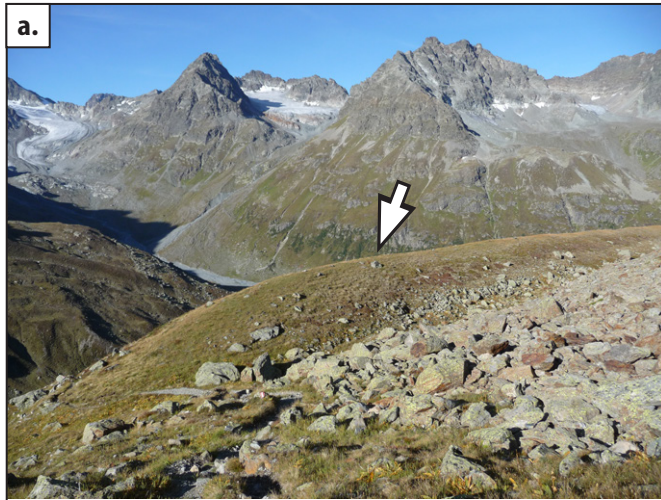


Figure S7: JAM-19-10. (a) View towards SW. (b) View towards W. (c) View towards W (close-up). (d) View towards S. (e) Sampling, view towards E. (f) Sampled rock surface.

COORDINATES N 46.8904 | E 10.1872
 ALTITUDE 2521 m
 L x B x H 2.5 x 1.3 x 0.9 m



Figure S8: JAM-20-23. (a) View towards SE with Augustenferner and Futschölpäss in the background. (b) View towards SSW with Totenfeld and Jamtalferner in the background. (c) View towards NNE. (d) View towards W. (e) View towards SSE. (f) Sampled rock surface.

COORDINATES N 46.8895 | E 10.1829
ALTITUDE 2380 m
L x B x H 1.9 x 1.7 x 1.3 m

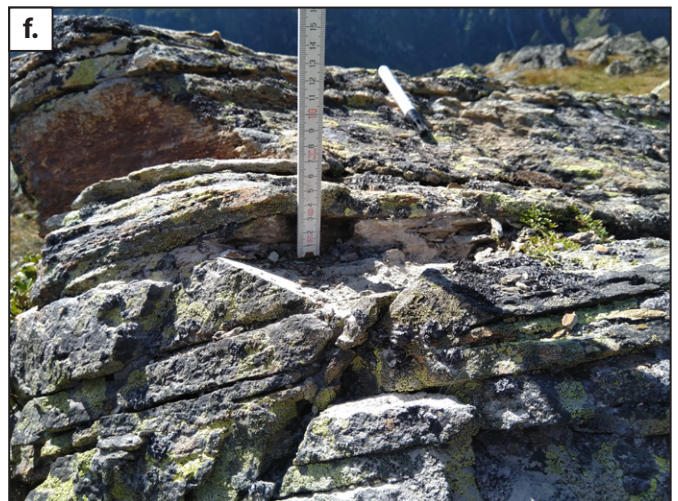
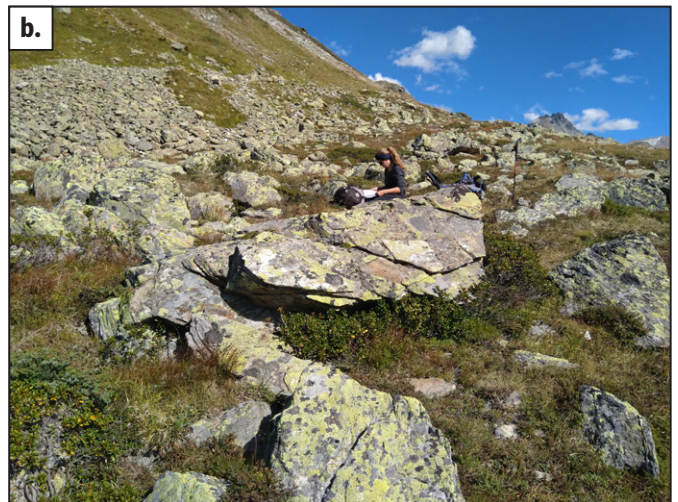


Figure S9: JAM-20-24. (a) View towards SW. (b) View towards E. (c) View towards SW. (d) View towards W. (e) View towards S. (f) Sampled rock surface.

COORDINATES N 46.8893 | E 10.1835
ALTITUDE 2389 m
L x B x H 2.0 x 1.5 x 1.1 m

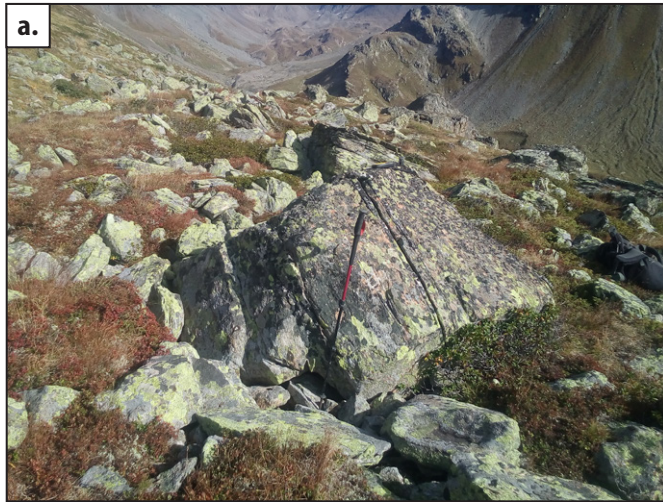


Figure S10: JAM-20-25. (a) View towards E. (b) View towards W. (c) View towards SW with Augustenferner in the background. (d) View towards S. (e) View towards N. (f) Sampled rock surface.

COORDINATES N 46.8898 | E 10.1740
 ALTITUDE 2065 m
 L x B x H 2.3 x 1.9 x 0.5 m



Figure S11: JAM-20-26. (a) View towards SE. (b) View towards S with Jamtalferner in the background. (c) View towards W. (d) View towards NW. (e) View towards N with Jambach (floodplane) in the background. (f) Sampled rock surface next to handheld GPS device.

COORDINATES N 46.8908 | E 10.1733
ALTITUDE 2047 m
L x B x H 2.0 x 1.7 x 0.8 m

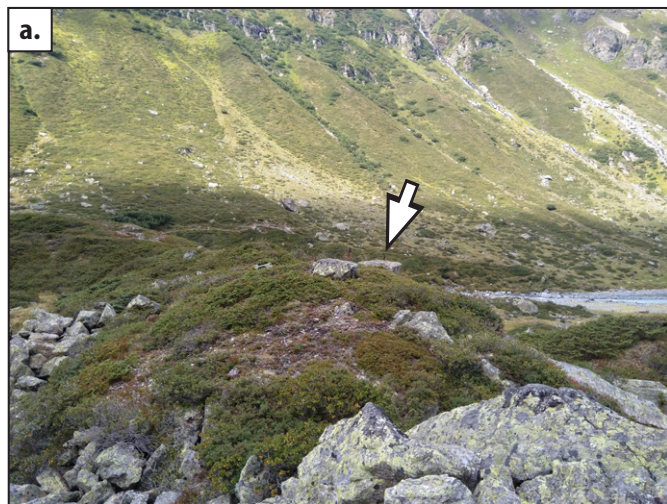


Figure S12: JAM-20-27. (a) View towards NW. (b) View towards W. (c) View towards E. (d) View towards SSE. (e) View towards SSE. (f) Sampled rock surface next to chisel.

COORDINATES N 46.9429 | E 10.2697
 ALTITUDE 2044 m
 L x B x H 2.6 x 1.8 x 1.5 m

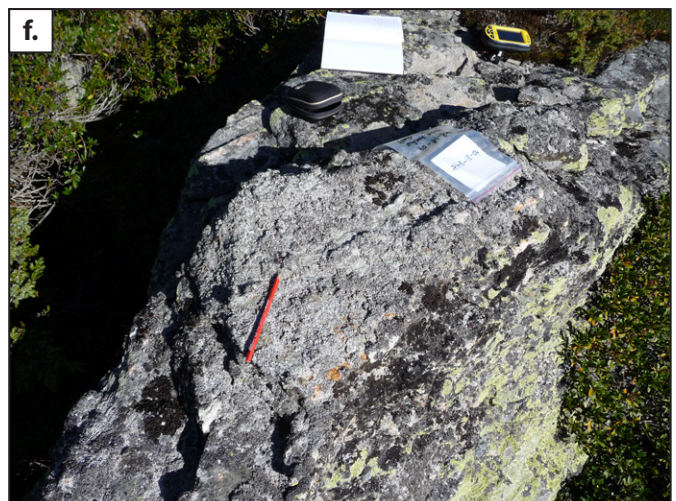


Figure S13: FMB-18-04. (a) View towards SE; note poles (length ca. 1.10 m) for scale. (b) View towards E. (c) View towards NW (downstream) with moraine F4 in the background. (d) View towards SSW. (e) View towards SSW (closeup). (f) Sampled rock surface indicated by pencil.

COORDINATES N 46.9436 | E 10.2698
ALTITUDE 2040 m
L x B x H 6.0 x 3.0 x 1.9 m



Figure S14: FMB-18-05. (a) View towards SW. (b) View towards S with F3 (middle-right section) in the background. (c) View towards E. (d) View towards NE. (e) View towards NW. (f) Sampled rock surface.

COORDINATES N 46.9438 | E 10.2688
ALTITUDE 2043 m
L x B x H 2.0 x 1.0 x 1.2 m

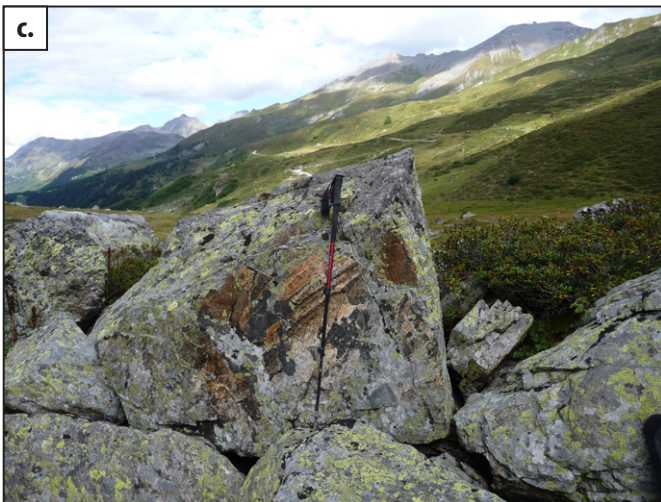
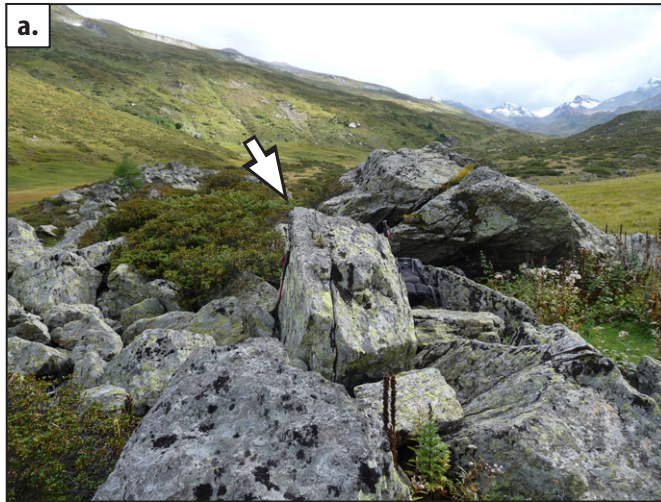


Figure S15: FMB-18-08. (a) View towards S. (b) View towards E. (c) View towards NE. (d) View towards N. (e) View towards W. (f) Sampled rock surface.

COORDINATES N 46.9438 | E 10.2689
 ALTITUDE 2042 m
 L x B x H 1.1 x 1.5 x 1.4 m



Figure S16: FMB-18-09. (a) View towards N. (b) View towards E with Fimbabach (creek) in the background. (c) View towards S. (d) View towards W. (e) View towards NW. (f) Sampled rock surface indicated by pencil.

COORDINATES N 46.9435 | E 10.2699
ALTITUDE 2041 m
L x B x H 2.5 x 2.0 x 1.1 m

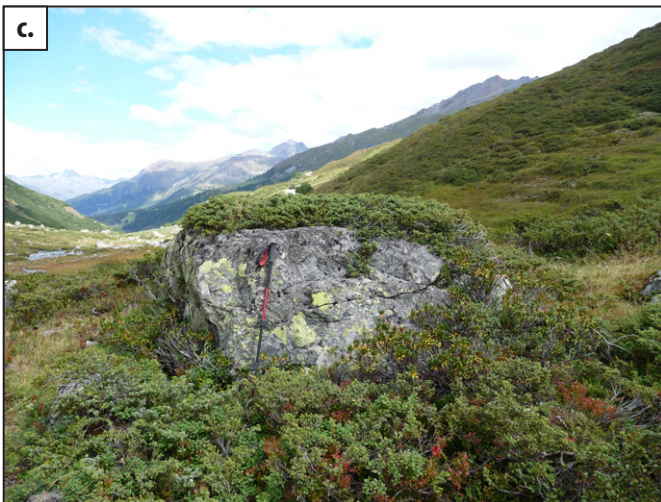


Figure S17: FMB-19-12. (a) View towards S. (b) View towards E. (c) View towards N. (d) View towards W. (e) View towards SW with F3 with little tree on top in the background. (f) Sampled rock surface.

COORDINATES N 46.9432 | E 10.2694
ALTITUDE 2044 m
L x B x H 2.9 x 2.0 x 0.7 m

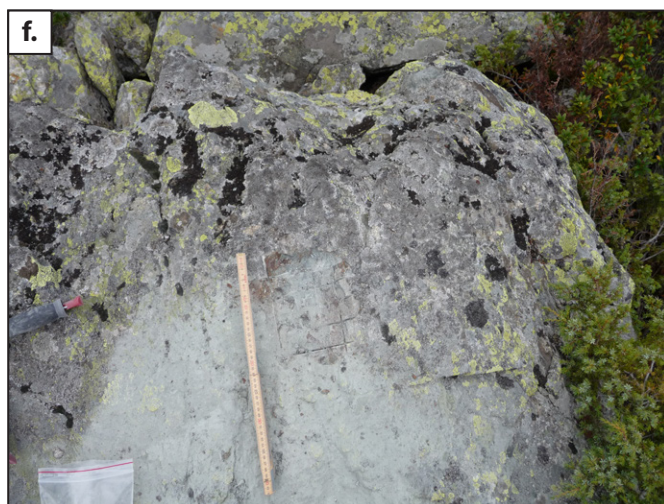


Figure S18: FMB-19-13. (a) View towards SW. (b) View towards E. (c) View towards N. (d) View towards W. (e) View towards S. (f) Sampled rock surface.

REFERENCES

- 1 *Schaefer, J. M. et al. High-Frequency Holocene Glacier Fluctuations in New Zealand Differ from the Northern Signature. Science 324, 622-625, doi:10.1126/science.1169312 (2009).*
- 2 *Braumann, S. M. et al. Holocene glacier change in the Silvretta Massif (Austrian Alps) constrained by a new Be-10 chronology, historical records and modern observations. Quaternary Sci Rev 245, doi:10.1016/j.quascirev.2020.106493 (2020).*