Supplements

Early Holocene cold snaps and their expression in the moraine record of the Eastern European Alps

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Content **p.**

1 Quartz contents in rock samples

Table S1: Quartz yields of rock samples collected from Jamtal (JAM) and Laraintal (LAR); values range between 0.3 and 26.1 % with a median of 4.1 %.

Sample ID	Start weight [g]	Quartz yield [g]	Quartz yield [%]
JAM-18-01	538	31.34	5.8 %
JAM-18-02	765	11.68	1.5 %
JAM-18-03	785	7.36	0.9 %
JAM-18-04	613	20.43	3.3 %
JAM-18-06	613	23.03	3.8 %
JAM-18-07	797	12.01	1.5 %
JAM-18-16	663	25.24	3.8 %
JAM-18-17	411	10.69	2.6 %
JAM-18-18	605	23.65	3.9 %
JAM-19-21	926	31.28	3.4 %
JAM-19-22	683	29.33	4.3 %
LAR-18-03	477	24.02	5.0 %
LAR-18-09	918	19.01	2.1 %
LAR-18-10	675	7.09	1.1 %
LAR-19-12	493	116.01	23.5 %
LAR-19-13	537	25.09	4.7 %
LAR-19-14	692	2.74	0.4 %
LAR-19-15	1001	79.72	8.0 %
LAR-19-16	989	2.64	0.3 %
LAR-19-17	834	69.92	8.4 %
LAR-19-18	385	70.51	18.3 %
LAR-19-19	517	78.5	15.2 %
LAR-19-20	677	63.91	9.4 %
LAR-19-21	906	30.01	3.3 %
LAR-19-22	368	29.33	8.0 %
LAR-19-23	717	42.41	5.9 %
LAR-19-24	535	139.82	26.1 %
		Maximum	**26.1 %**
		Minimum	**0.3 %**
		Median	**3.9 %**

2 Organization of ^{10}Be sample batches and analytical information of procedural blanks

Table S2: A total of 27 rock samples was processed according to the LDEO protocol (Schaefer et al., 2009;Braumann et al., 2020). Samples were processed in four batches each of them including two to three procedural blanks (in bold). The number 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, 4 and 5), the average of both blanks was used for blank correction. An exception is batch 6: LAR-19-23 (c. 30 g) required a larger amount of HF compared to the other samples in the batch (c. 150 ml vs c. 50 g for the rest of the samples). Therefore, an extra blank with the same HF-volume was processed and used for the correction of LAR-19-23. BLK-2 of batch 6 was spiked with Fe and was therefore used to quantify the background in samples LAR-19-14 and LAR-19-16 highlighted in brown. BLK-3 represents the background of the rest of the samples. Blank correction ranged from 0.1% to 6.5% depending on the total number of ^{10}Be atoms in the samples. Concentrations of the LDEO ^{9}Be carriers are corrected for evaporation.

Batch #	Sample ID	^{10}Be/^{9}Be AMS ratio	1σ anal. unc. AMS ratio	1σ anal. unc. AMS ratio [%]	^{10}Be atoms [atoms/sample]	1σ anal. unc. [atoms/sample]	Blank correction [%]	Carrier conc. [ppm]
	Blk1_2019May23	**8.36E-16**	**2.09E-16**	**25.0%**	**10270**	**2570**	**-**	
	Blk2_2019May23	**6.18E-16**	**1.72E-16**	**27.8%**	**7690**	**2140**	**-**	
	JAM-18-01	6.70E-13	1.22E-14	1.8%	8250920	149650	0.1%	
	JAM-18-04	4.25E-13	7.88E-15	1.9%	5196240	96270	0.2%	
3	JAM-18-07	4.59E-14	1.52E-15	3.3%	572360	18940	1.6%	**Carrier 7 1028**
	JAM-18-16	6.51E-14	1.37E-15	2.1%	804960	17000	1.1%	
	JAM-18-18	1.30E-14	7.07E-16	5.4%	161890	8780	5.5%	
	LAR-18-03	4.03E-13	7.47E-15	1.9%	5004560	92710	0.2%	
	LAR-18-09	3.51E-13	6.16E-15	1.8%	4340820	76280	0.2%	
	BLK1-2019June6	**4.32E-16**	**1.44E-16**	**33.4%**	**5355**	**1786**	**-**	
	BLK2-2019June6	**2.81E-16**	**9.95E-17**	**35.4%**	**3492**	**1236**	**-**	
	JAM-18-02	2.54E-13	4.13E-15	1.6%	3151010	51230	0.1%	
4	JAM-18-03	1.65E-13	3.08E-15	1.9%	2045060	38160	0.2%	**Carrier 7 1030**
	JAM-18-06	7.00E-15	8.79E-16	12.6%	86600	10880	5.1%	
	JAM-18-17	5.47E-15	6.82E-16	12.5%	67820	8460	6.5%	
	LAR-18-10	1.12E-13	2.11E-15	1.9%	1404080	26340	0.3%	

Batch #	Sample ID	$^{10}Be/^{9}Be$ AMS ratio	1σ anal. unc. AMS ratio	1σ anal. unc. AMS ratio [%]	^{10}Be atoms [atoms/sample]	1σ anal. unc. [atoms/sample]	Blank correction [%]	Carrier conc. [ppm]
	BLK1-2020Jan17	**4.00E-16**	**1.00E-16**	**25.0%**	**4858**	**1214**	**-**	
	BLK2-2020Jan17	**4.10E-16**	**1.14E-16**	**27.7%**	**5013**	**1389**	**-**	
	LAR-19-12	2.08E-13	3.34E-15	1.6%	2536340	40710	0.2%	
	LAR-19-13	2.22E-13	4.11E-15	1.9%	2676390	49580	0.2%	
	LAR-19-15	2.11E-13	3.90E-15	1.9%	2561640	47470	0.2%	
5	LAR-19-17	1.95E-13	3.61E-15	1.9%	2366110	43840	0.2%	**Carrier 7 1030**
	LAR-19-18	2.08E-13	5.36E-15	2.6%	2520430	65070	0.2%	
	LAR-19-19	1.87E-13	3.47E-15	1.9%	2319930	42980	0.2%	
	LAR-19-20	2.02E-13	3.75E-15	1.9%	2460270	45620	0.2%	
	LAR-19-21	1.89E-13	3.51E-15	1.9%	2281230	42290	0.2%	
	LAR-19-22	1.93E-13	3.58E-15	1.9%	2335410	43280	0.2%	
	BLK1-2020Jan30	**5.60E-16**	**1.14E-16**	**20.4%**	**6730**	**1370**	**-**	
	BLK2-2020Jan31	**9.11E-16**	**1.86E-16**	**20.4%**	**6330**	**1290**	**-**	
	BLK3-2020Jan31	**5.05E-16**	**1.46E-16**	**28.9%**	**6240**	**1800**	**-**	
	JAM-19-21	2.18E-13	4.08E-15	1.9%	2703360	50630	0.2%	
6	JAM-19-22	2.21E-13	2.75E-15	1.2%	2739710	34110	0.2%	**Carrier 7 1032**
	LAR-19-14	1.00E-13	2.51E-15	2.5%	686210	17190	0.9%	
	LAR-19-16	9.01E-14	1.80E-15	2.0%	627350	12550	1.0%	
	LAR-19-23	4.20E-14	9.61E-16	2.3%	507590	11630	1.3%	
	LAR-19-24	2.24E-13	4.19E-15	1.9%	2767560	51800	0.2%	
	Blank min.	**2.81E-16**						
	Blank max.	**9.11E-16**						

3 Sensitivity test: Boulder surface erosion

Table S3: Comparison between ages calculated without erosion correction and ages calculated using an erosion rate of 1 mm/ka, a value that is often used on the Holocene time scale. Uncorrected ages are at most 1% younger than corrected ages.

	^{10}Be ages w/o erosion		^{10}Be ages with erosion		
Sample ID	**Age [yrs]**	**Uncertainty [yrs]**	**Age [yrs]**	**Uncertainty [yrs]**	**Difference [%]**
JAM-18-01	11020	200	11120	200	0.9%
JAM-18-02	11280	180	11380	190	0.9%
JAM-18-03	11850	220	11950	230	0.8%
JAM-18-04	10680	200	10770	200	0.8%
JAM-18-06	270	30	270	30	0.0%
JAM-18-07	1500	50	1500	50	0.0%
JAM-18-16	1070	20	1070	20	0.0%
JAM-18-17	240	30	240	30	0.0%
JAM-18-18	270	20	270	20	0.0%
JAM-19-21	10920	210	11010	210	0.8%
JAM-19-22	10660	130	10740	140	0.8%
LAR-18-03	10160	190	10240	190	0.8%
LAR-18-09	11540	200	11650	210	1.0%
LAR-18-10	10880	210	10970	210	0.8%
LAR-19-12	10890	180	10980	180	0.8%
LAR-19-13	11120	210	11220	210	0.9%
LAR-19-14	11200	280	11310	290	1.0%
LAR-19-15	10860	200	10950	210	0.8%
LAR-19-16	11060	220	11170	230	1.0%
LAR-19-17	11070	210	11170	210	0.9%
LAR-19-18	11330	290	11430	300	0.9%
LAR-19-19	10730	200	10820	200	0.8%
LAR-19-20	11480	210	11580	220	0.9%
LAR-19-21	10660	200	10750	200	0.8%
LAR-19-22	11210	210	11310	210	0.9%
LAR-19-23	700	20	700	20	0.0%
LAR-19-24	10930	210	11030	210	0.9%
				Maximum	**1.0%**
				Median	**0.8%**

JAM-18-01 **^{10}Be exposure age: 10,020 ±200 yrs**

COORDINATES N 46.8766 | E 10.1736
ALTITUDE 2350 m
L x B x H 8.0 x 2.5 x 3.0 m³

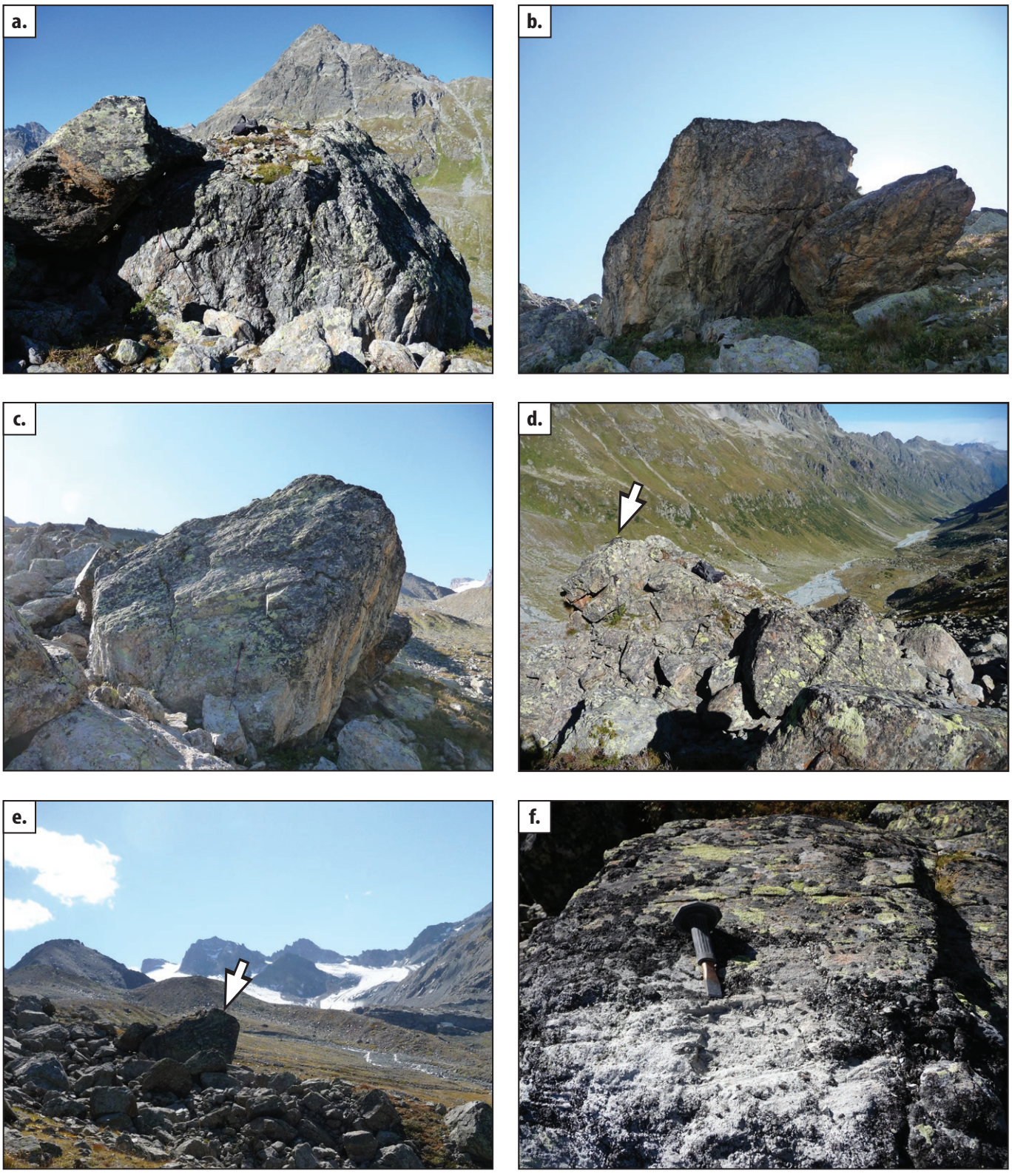

Figure S1: JAM-18-01. a. View towards W. b. View towards E. c. View towards S. d. View towards NW. e. View towards S with Jamtalferner in the background. f. Sampled rock surface.

JAM-18-02 **^{10}Be exposure age: 11,280 ±180 yrs**

COORDINATES N 46.8767 | E 10.1735
ALTITUDE 2339 m
L x B x H 6.0 x 6.0 x 4.0 m^3

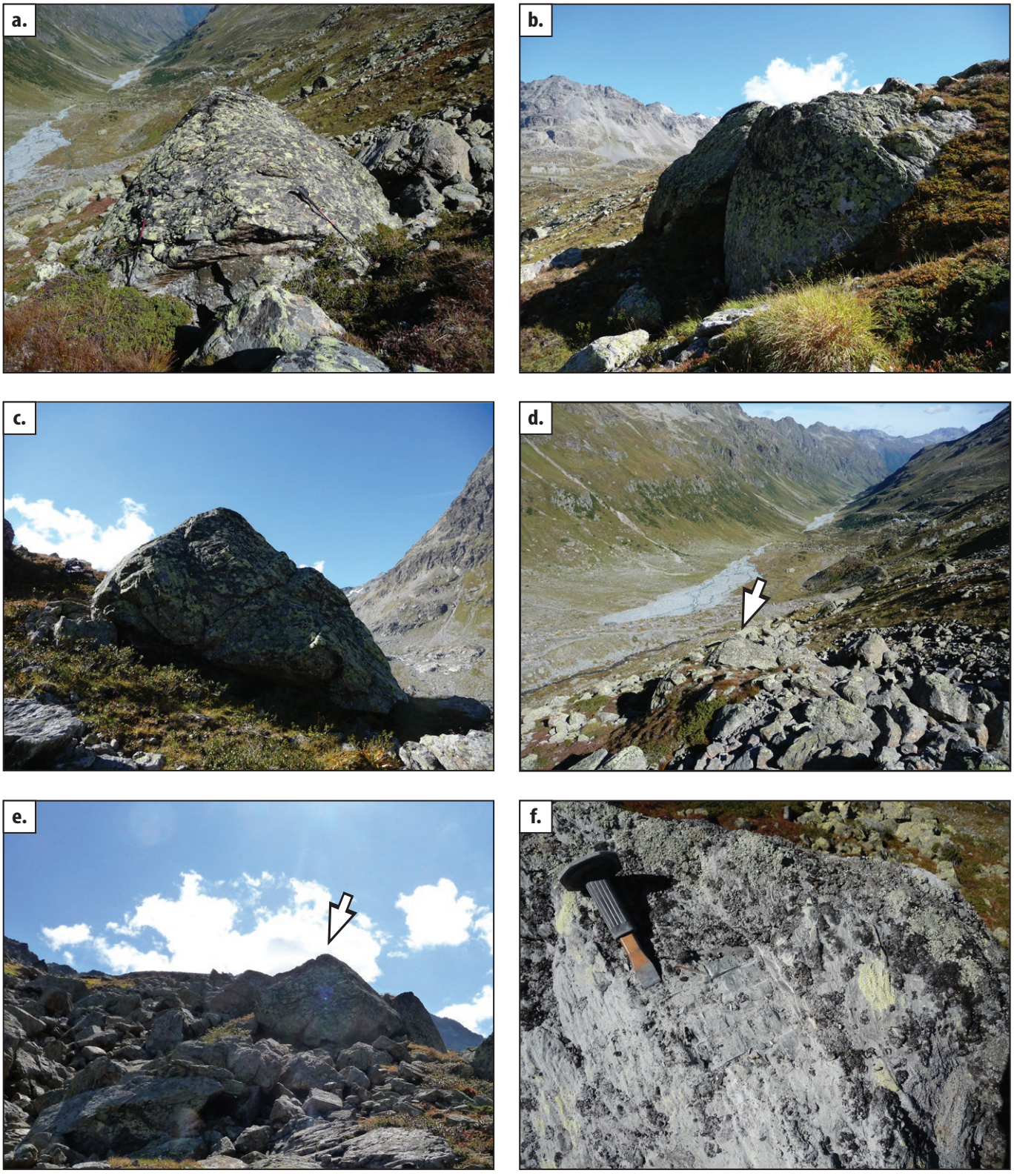

Figure S2: JAM-18-02. a. View towards N. b. View towards NE. c. View towards S. d. View towards NW; sampled boulder indicated with arrow. e. View towards SE. f. Sampled rock surface.

JAM-18-03 **^{10}Be exposure age: 11,850 ±220 yrs**

COORDINATES N 46.8770 | E 10.1734
ALTITUDE 2328 m
L x B x H 2.1 x 1.9 x 1.2 m^3

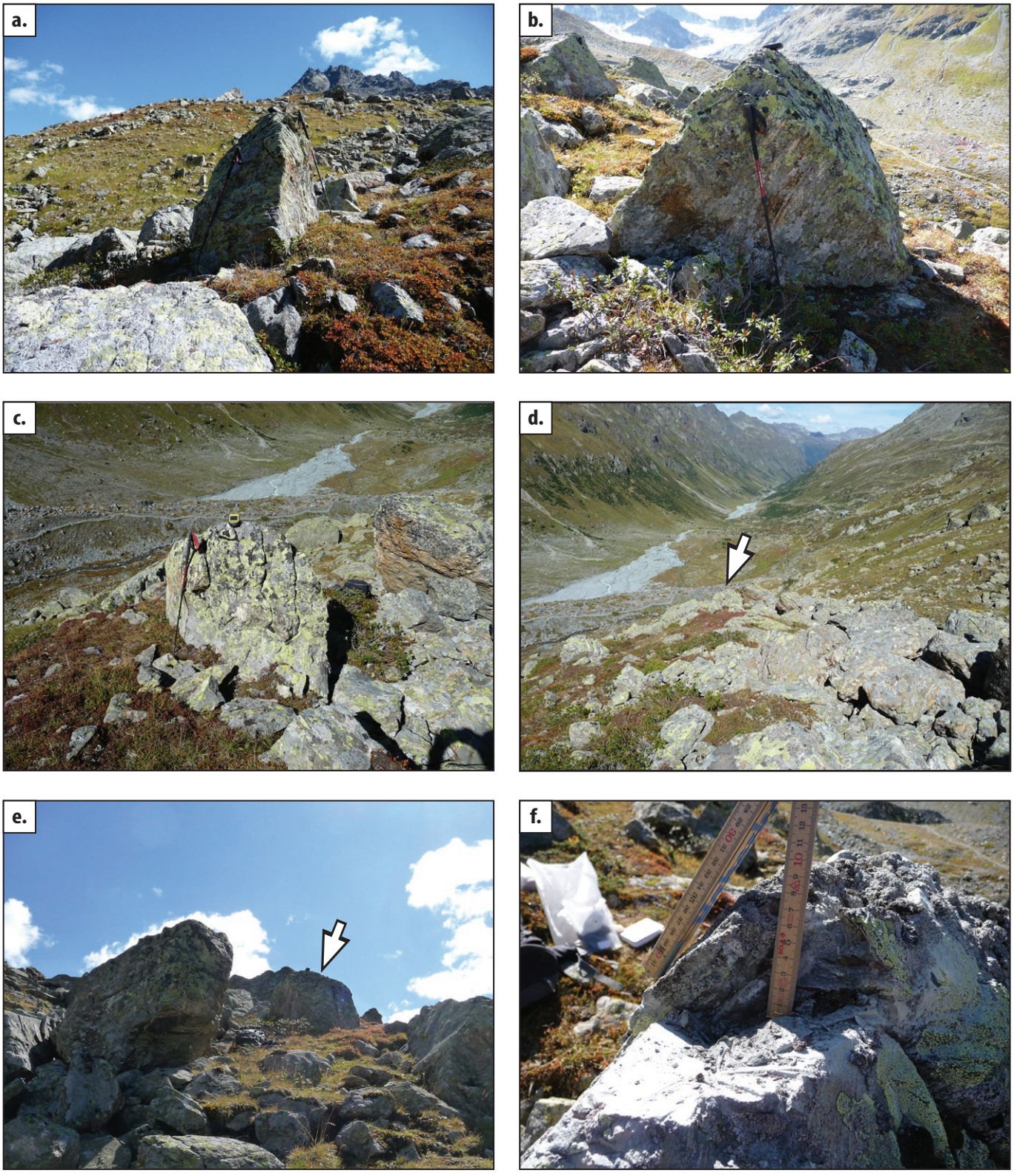

Figure S3: JAM-18-03. a. View towards E. b. View towards S. c. View towards NW. d. View towards NNW. e. View towards SE. f. Sampled rock surface.

JAM-18-04 **^{10}Be exposure age: 10,680 ±200 yrs**

COORDINATES N 46.8771 | E 10.1739
ALTITUDE 2335 m
L x B x H 3.6 x 1.7 x 1.2 m

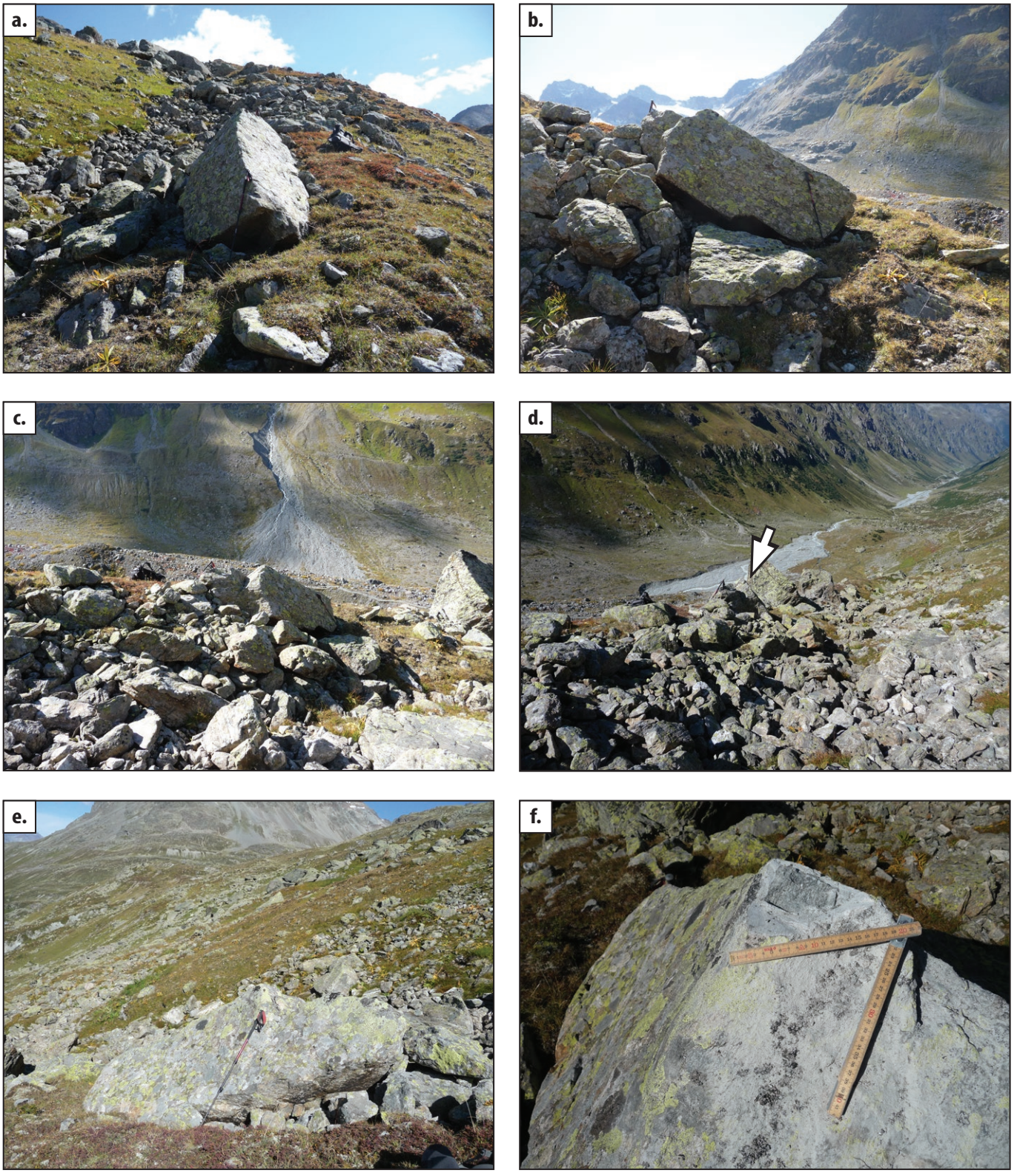

Figure S4: JAM-18-04. a. View towards SE. b. View towards S. c. View towards W. d. View towards NNW. e. View towards SE. f. Sampled rock surface.

JAM-18-06 **^{10}Be exposure age: 270 ±30 yrs**

COORDINATES N 46.8823 | E 10.1684
ALTITUDE 2223 m
L x B x H 4.0 x 2.2 x 2.4 m

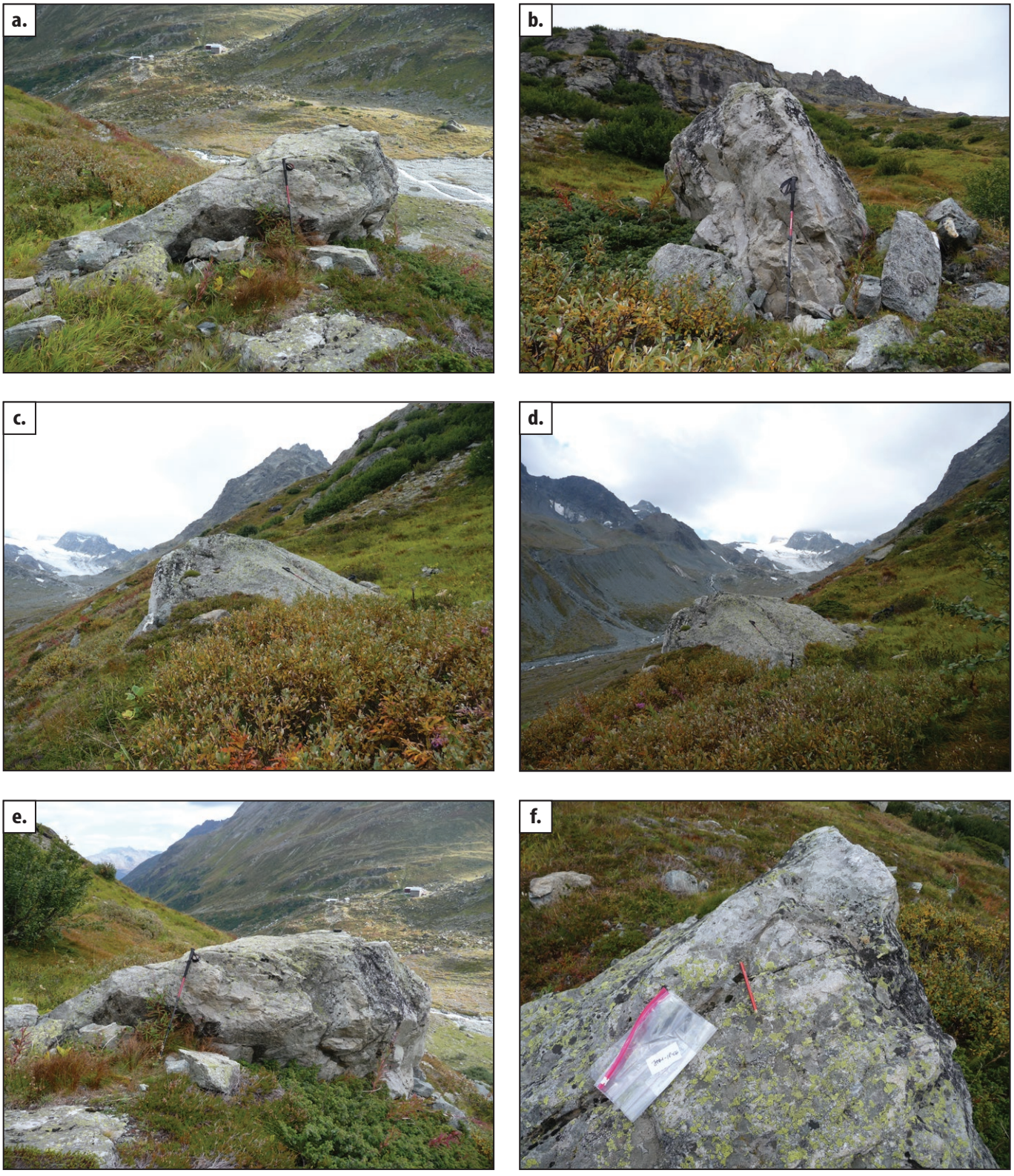

Figure S5: JAM-18-06. a. View towards NE with Jamtalhütte in the background. b. View towards W. c. View towards S. d. View towards SE. e. View towards NE. f. Sampled rock surface.

JAM-18-07 **^{10}Be exposure age: 1500 ±50 yrs**

COORDINATES N 46.8820 | E 10.1682
ALTITUDE 2231 m
L x B x H 3.8 x 3.1 x 1.2 m

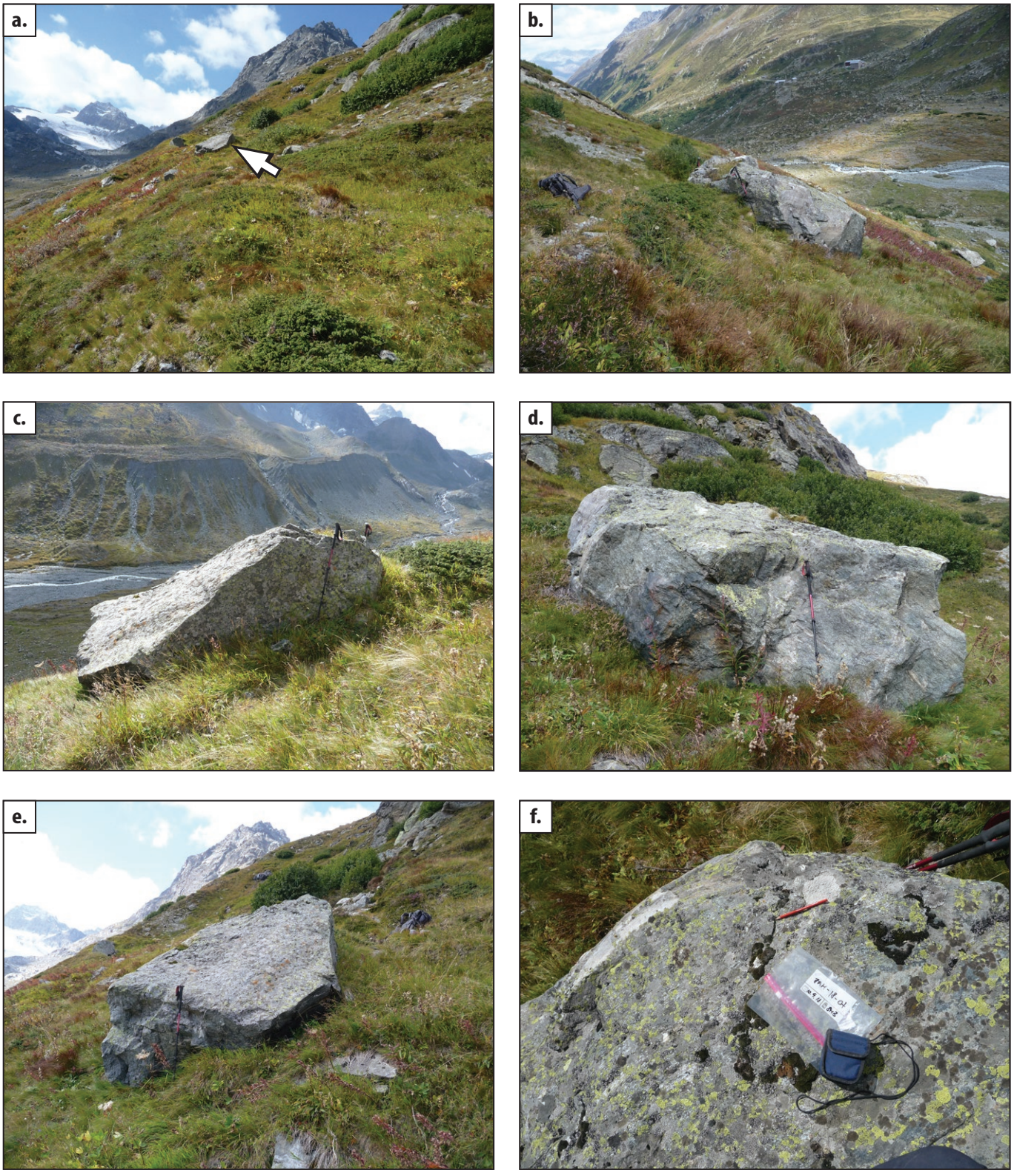

Figure S6: JAM-18-07. a. View towards S. b. View towards NE with Jamtalhütte in the background. c. View towards W with right-lateral J1 moraine in the background. d. View towards W. e. View towards SSW. f. Sampled rock surface.

JAM-18-16 **^{10}Be exposure age: 1070 ±20 yrs**

COORDINATES N 46.8766 | E 10.1718
ALTITUDE 2316 m
L x B x H 2.3 x 0.8 x 1.3 m

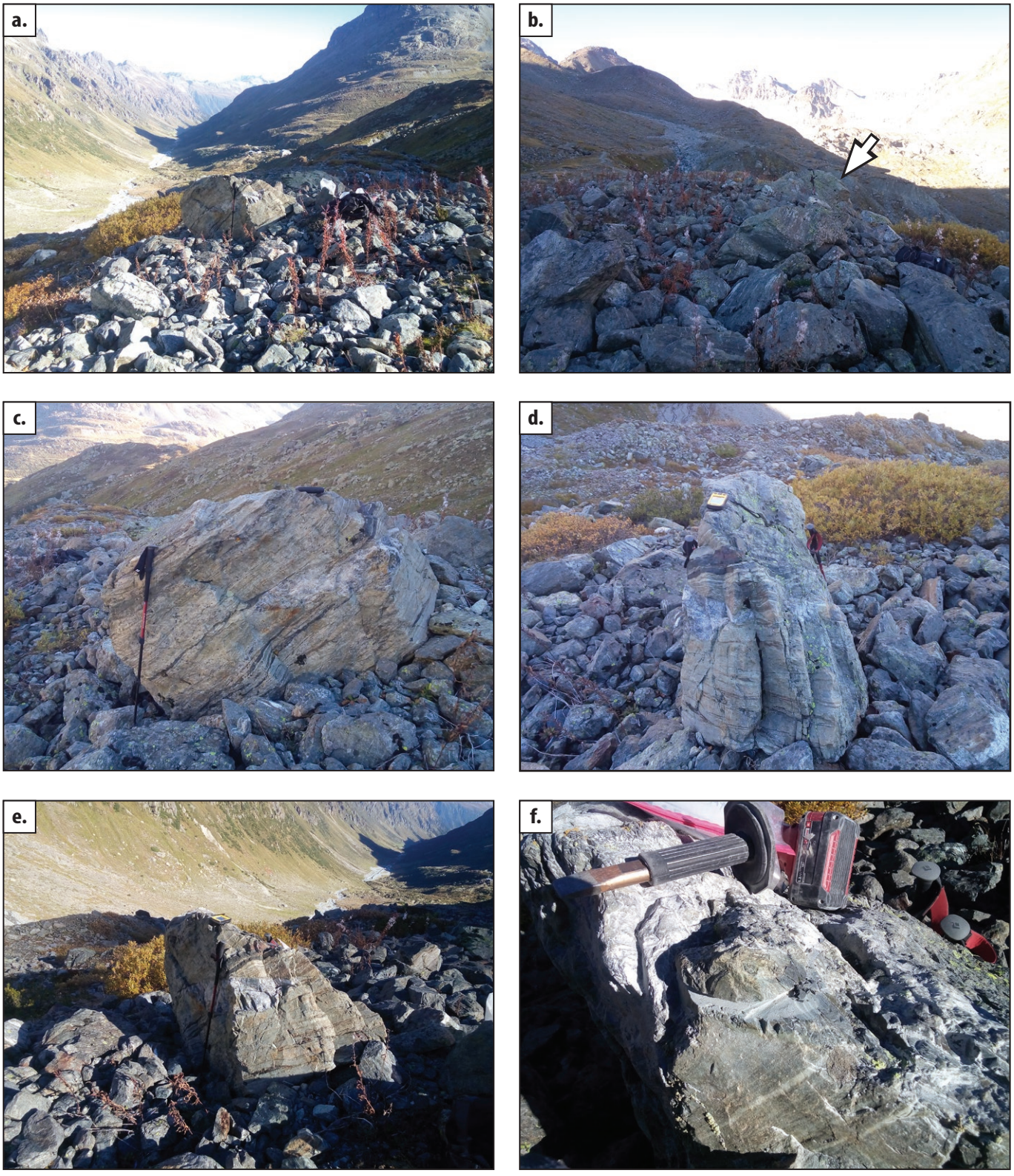

Figure S7: JAM-18-16; age is interpreted as minimum age as the boulder might have tilted over time. a. View towards N. b. View towards S. c. View towards NNE. d. View towards E. e. View towards NW. f. Sampled rock surface.

JAM-18-17 **^{10}Be exposure age: 240 ±30 yrs**

COORDINATES N 46.8774 | E 10.1723
ALTITUDE 2297 m
2.2 x 0.6 x 1.2 m

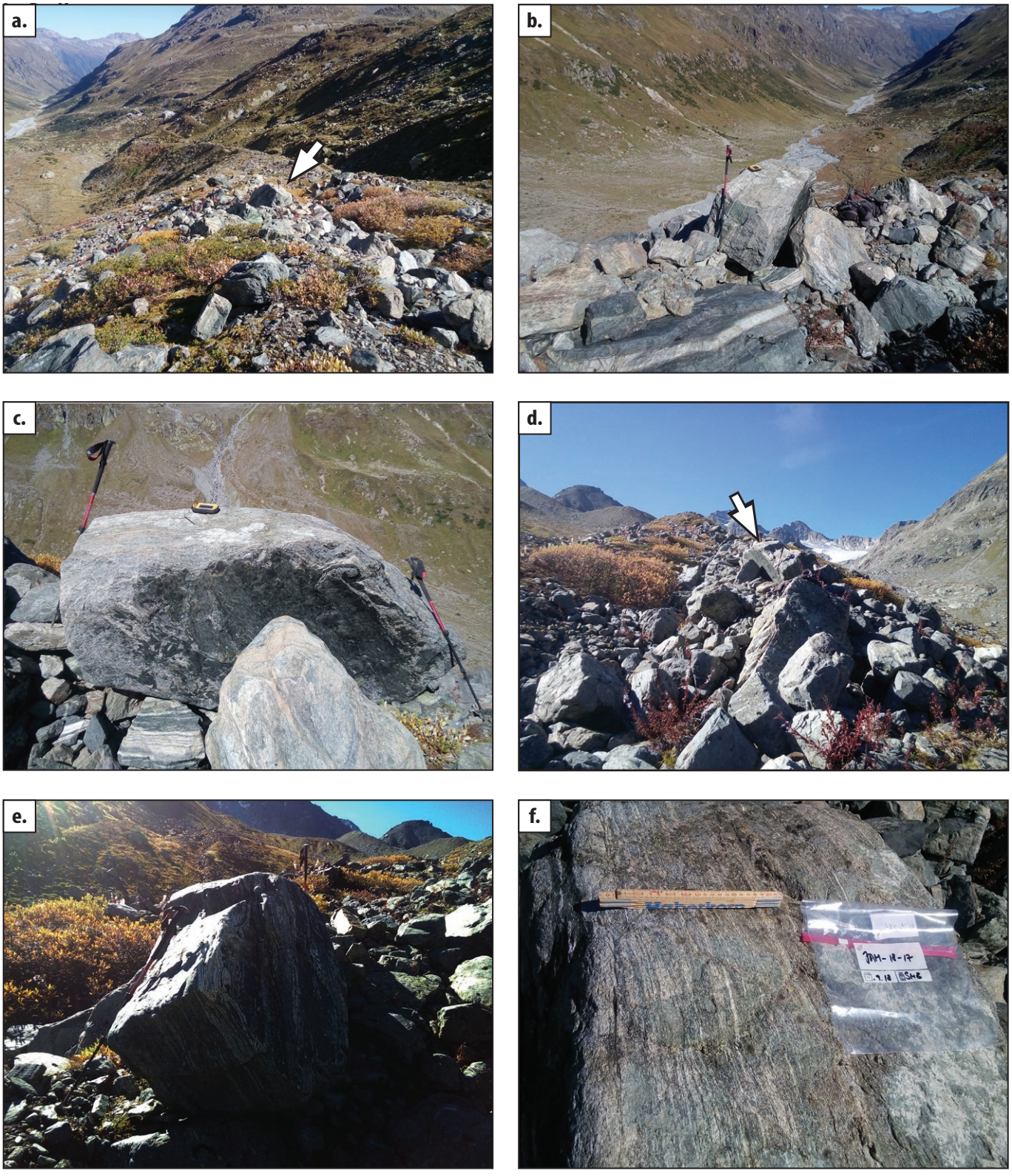

Figure S8: JAM-18-17. a. View towards N; J1 moraine. b. View towards NNW. c. View towards W. d. View towards S. e. View towards SE. f. Sampled rock surface.

JAM-18-18 **^{10}Be exposure age: 270 ±20 yrs**

COORDINATES N 46.8776 | E 10.1725
ALTITUDE 2289 m
2.1 x 2.0 x 2.3 m

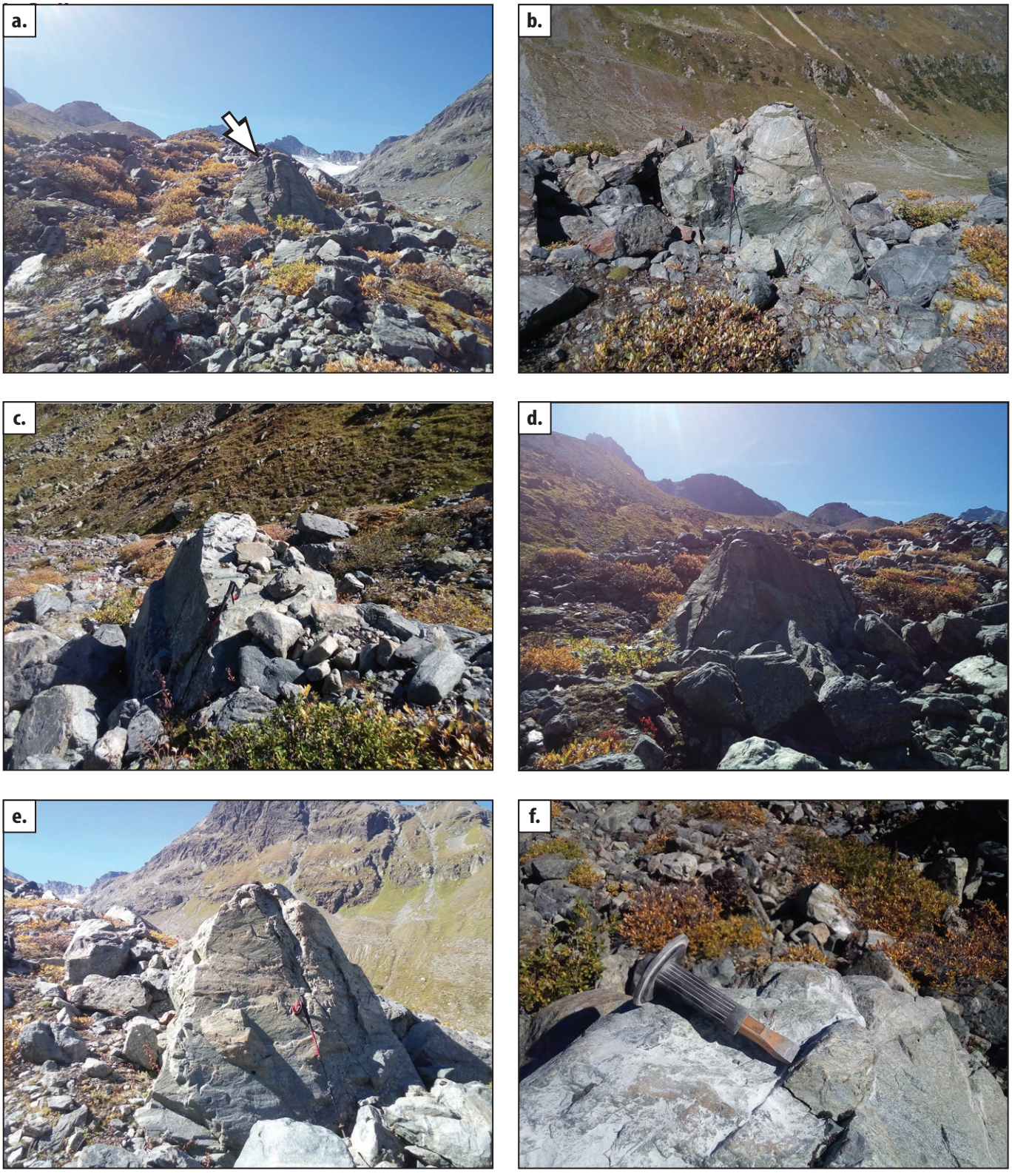

Figure S9: JAM-18-18. a. View towards S. b. View towards W. c. View towards E. d. View towards SE. e. View towards SSW. f. Sampled rock surface.

JAM-19-21 — ^{10}Be exposure age: 10,920 ±210 yrs

COORDINATES N 46.8776 | E 10.1738
ALTITUDE 2318 m
L x B x H 3.6 x 1.7 x 1.1 m

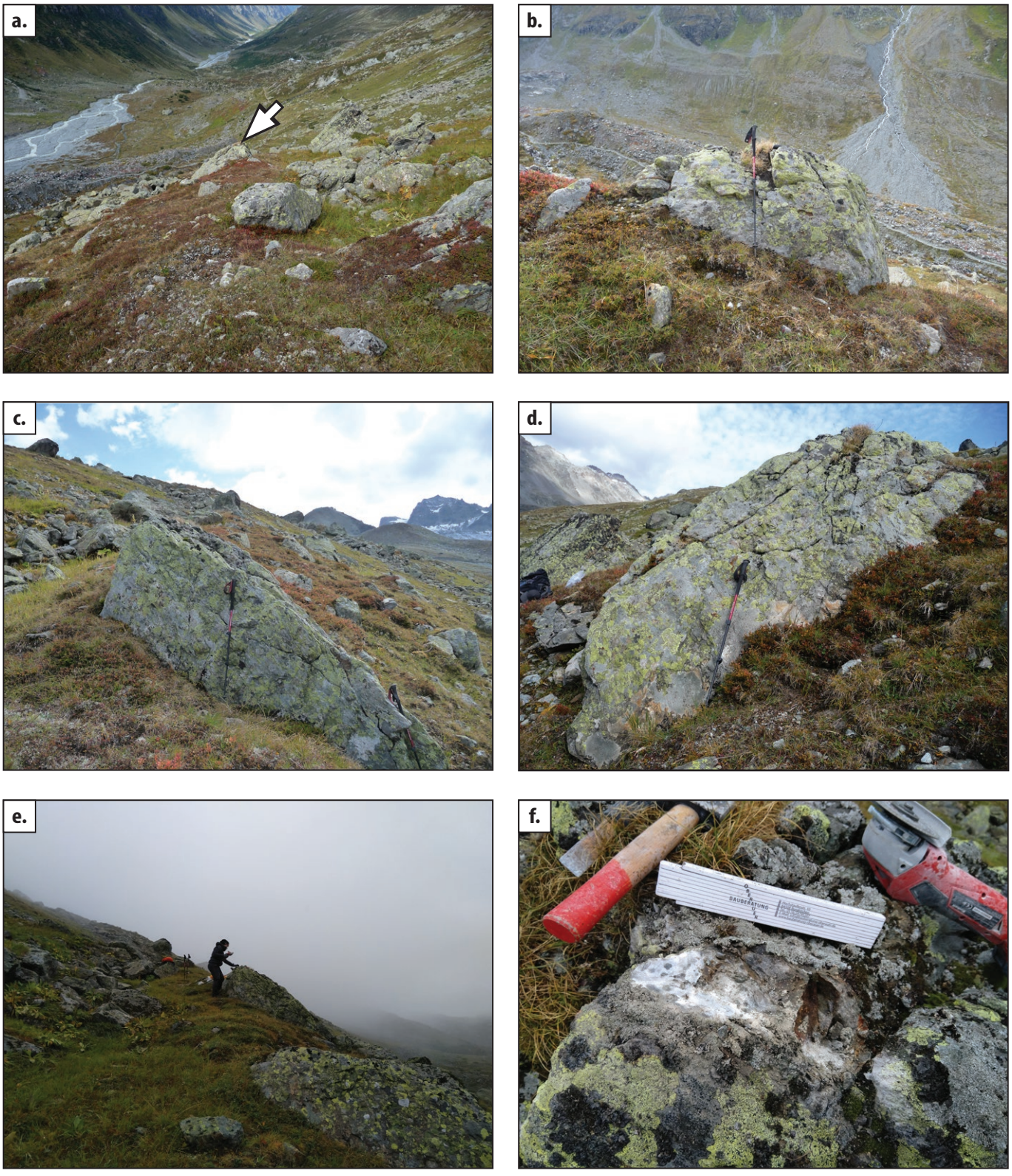

Figure S10: JAM-19-21. a. View towards N. b. View towards W. c. View towards SE. d. View towards E. e. View towards S with a lot of fog in the background. f. Sampled rock surface.

JAM-19-22 **^{10}Be exposure age: 10,660 ±130 yrs**

COORDINATES N 46.8773 | E 10.1738
ALTITUDE 2329 m
L x B x H 2.9 x 2.8 x 2.5 m

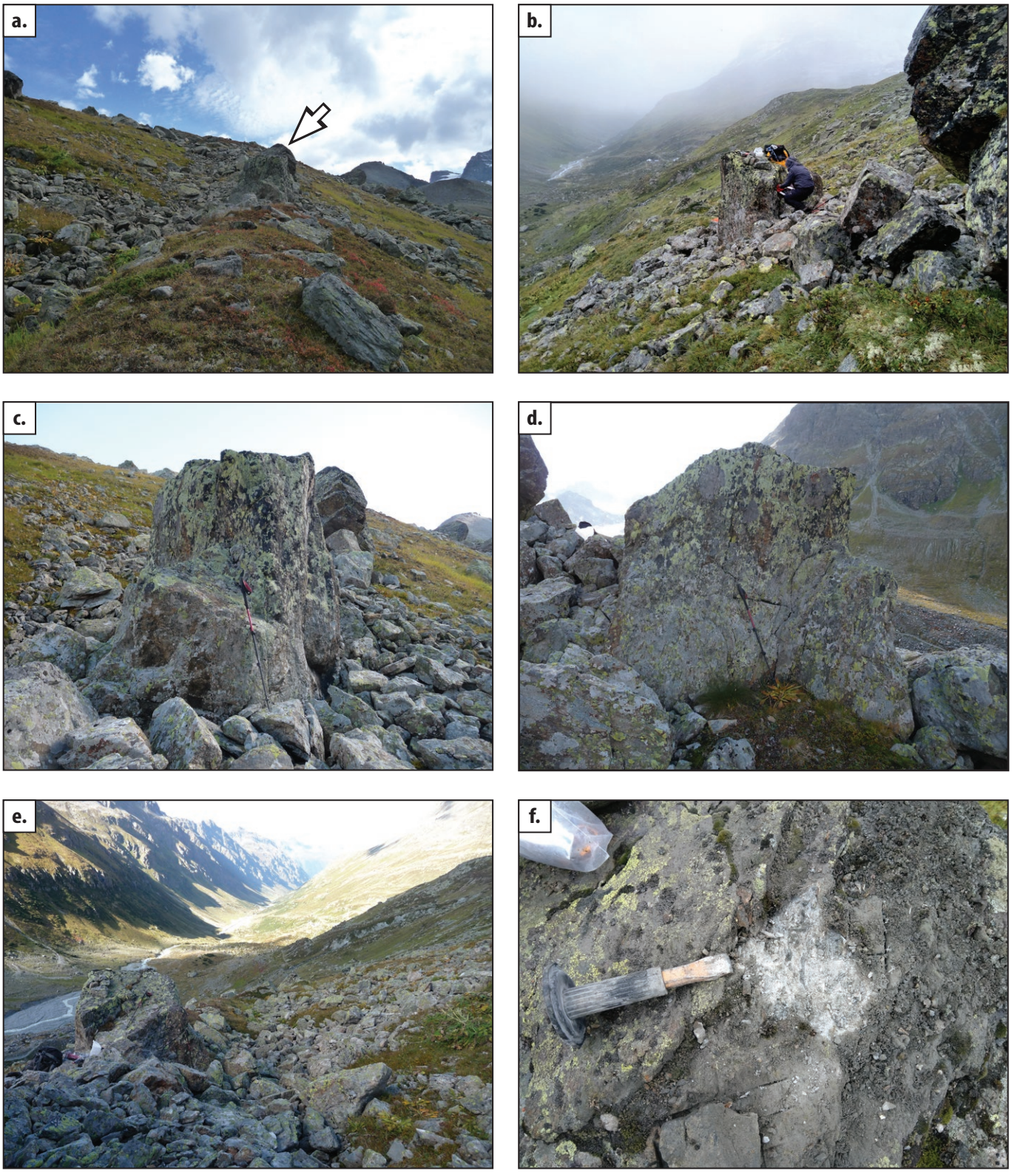

Figure S11: JAM-19-22. a. View towards SE. b. View towards NE. c. View towards SE. d. View towards SW. e. View towards NNW. f. Sampled rock surface.

LAR-18-03 **^{10}Be exposure age: 10,160 ±190 yrs**

COORDINATES N 46.9273 | E10.2220
ALTITUDE 2162 m
L x B x H 2.0 x 2.0 x 1.4 m³

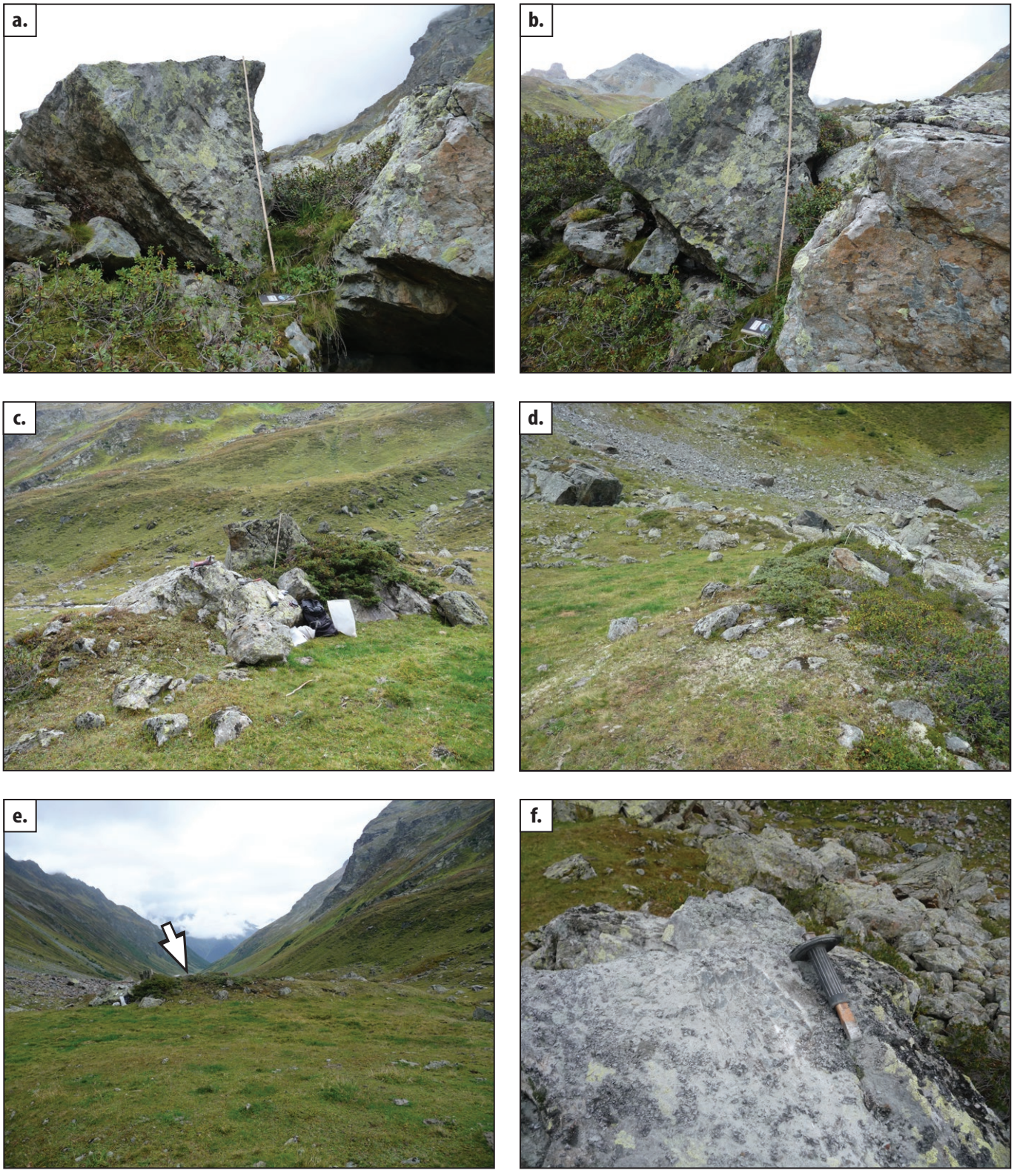

Figure S12: LAR-18-03. a. View towards N. b. View towards S from glacier-proximal side of moraine ridge. c. View towards E. d. View towards W. e. View towards N. f. Sampled rock surface.

LAR-18-09 **^{10}Be exposure age: 11,540 ±200 yrs**

COORDINATES N 46.9267 | E10.2225
ALTITUDE 2177 m
L x B x H 2.0 x 2.0 x 1.4 m^3

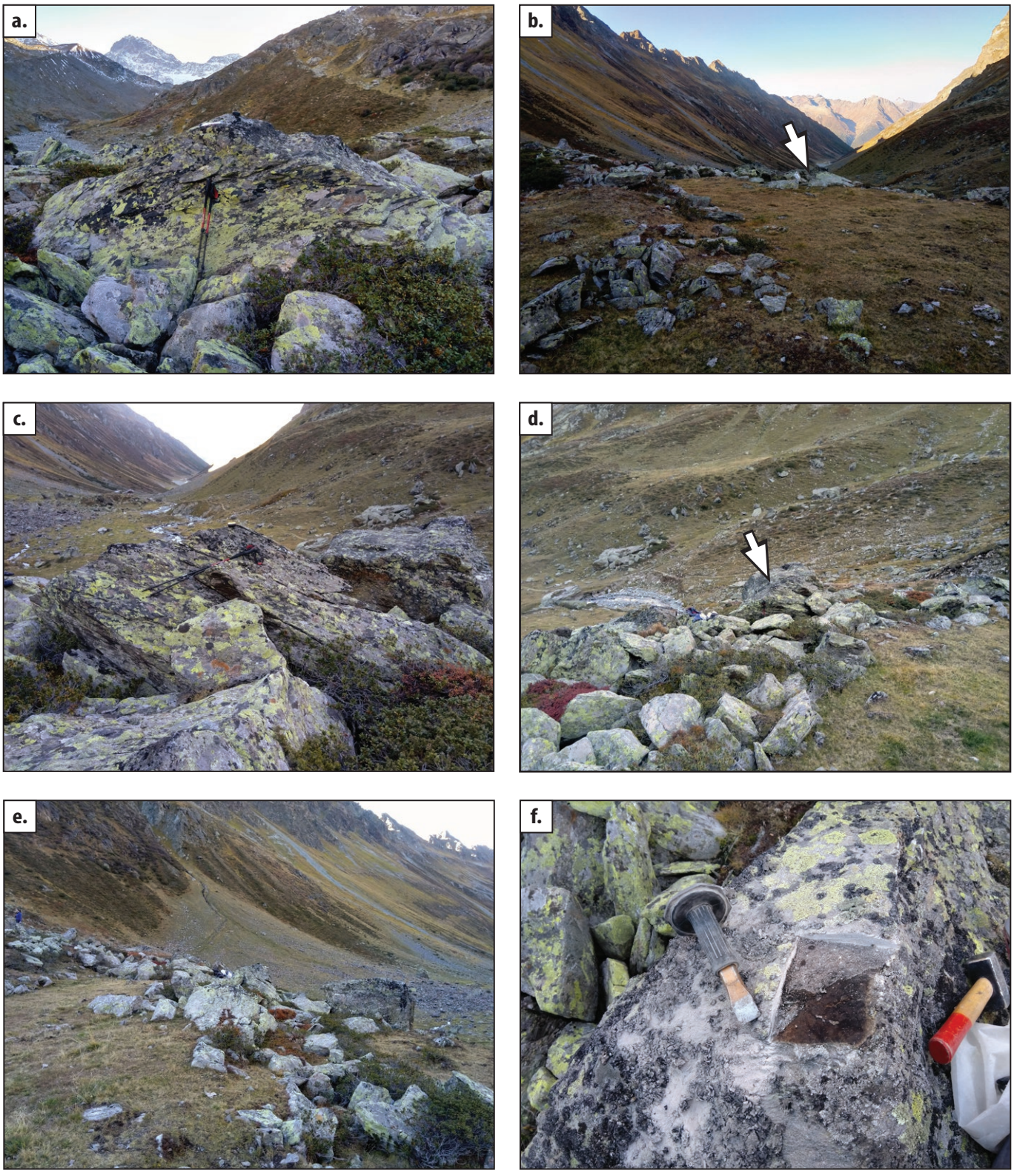

Figure S13: LAR-18-09. a. View towards S. b. View towards N. c. View towards N with Zollhütte in the background. d. View towards E. e. View towards W. f. Sampled rock surface.

LAR-18-10 — ^{10}Be exposure age: 10,880 ±210 yrs

COORDINATES N 46.9272 | E10.2225
ALTITUDE 2161 m a.s.l.
L x B x H 3.6 x 1.6 x 1.0 m³

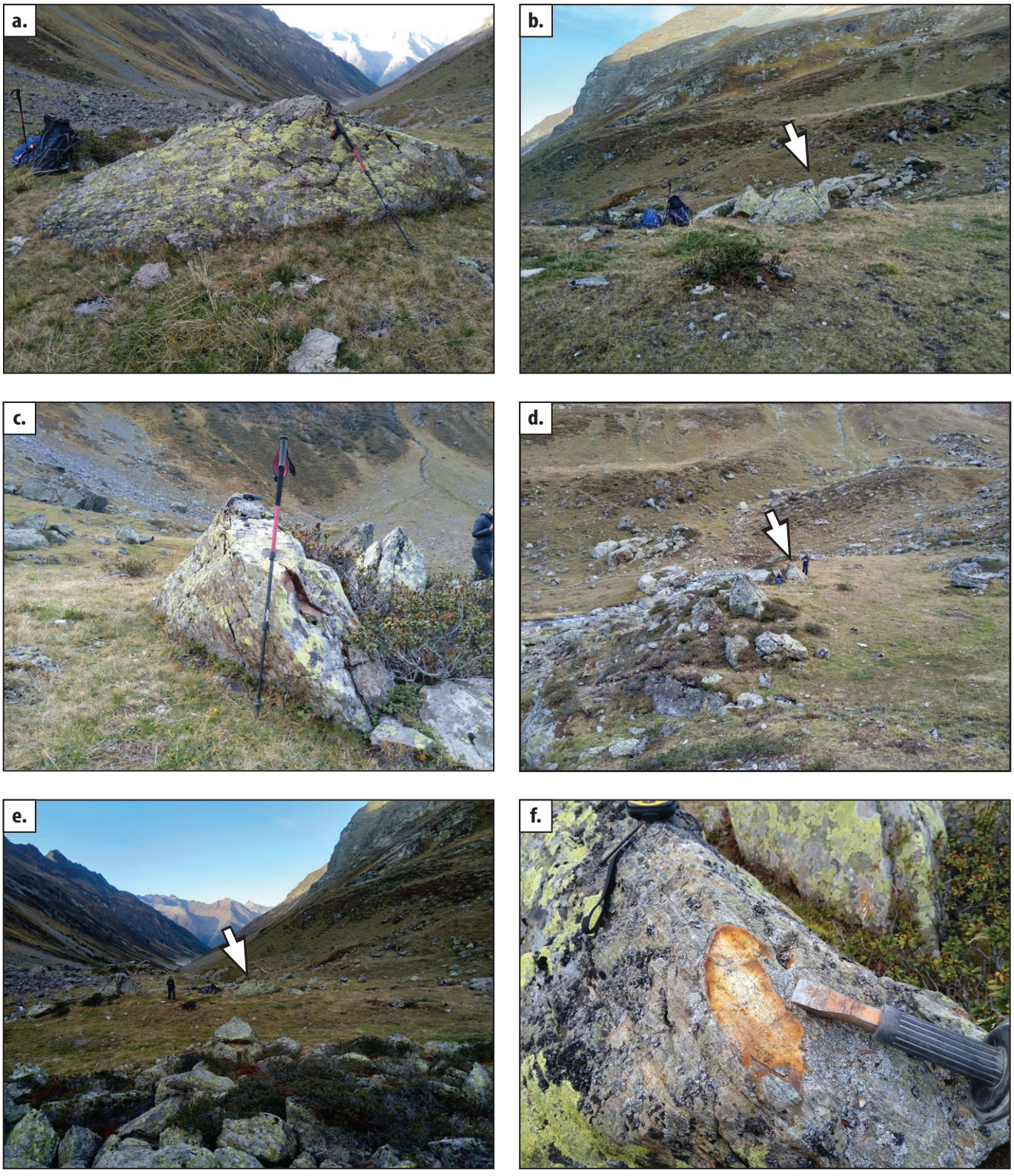

Figure S14: LAR-18-10. a. View towards N. b. View towards E with scarp in the background. c. View towards W. d. View towards E. e. View towards N. f. Sampled rock surface.

LAR-19-12 **^{10}Be exposure age: 10,890 ±180 yrs**

COORDINATES N 46.9231 | E 10.2261
ALTITUDE 2295 m a.s.l.
L x B x H 4.0 x 1.6 x 2.3 m^3

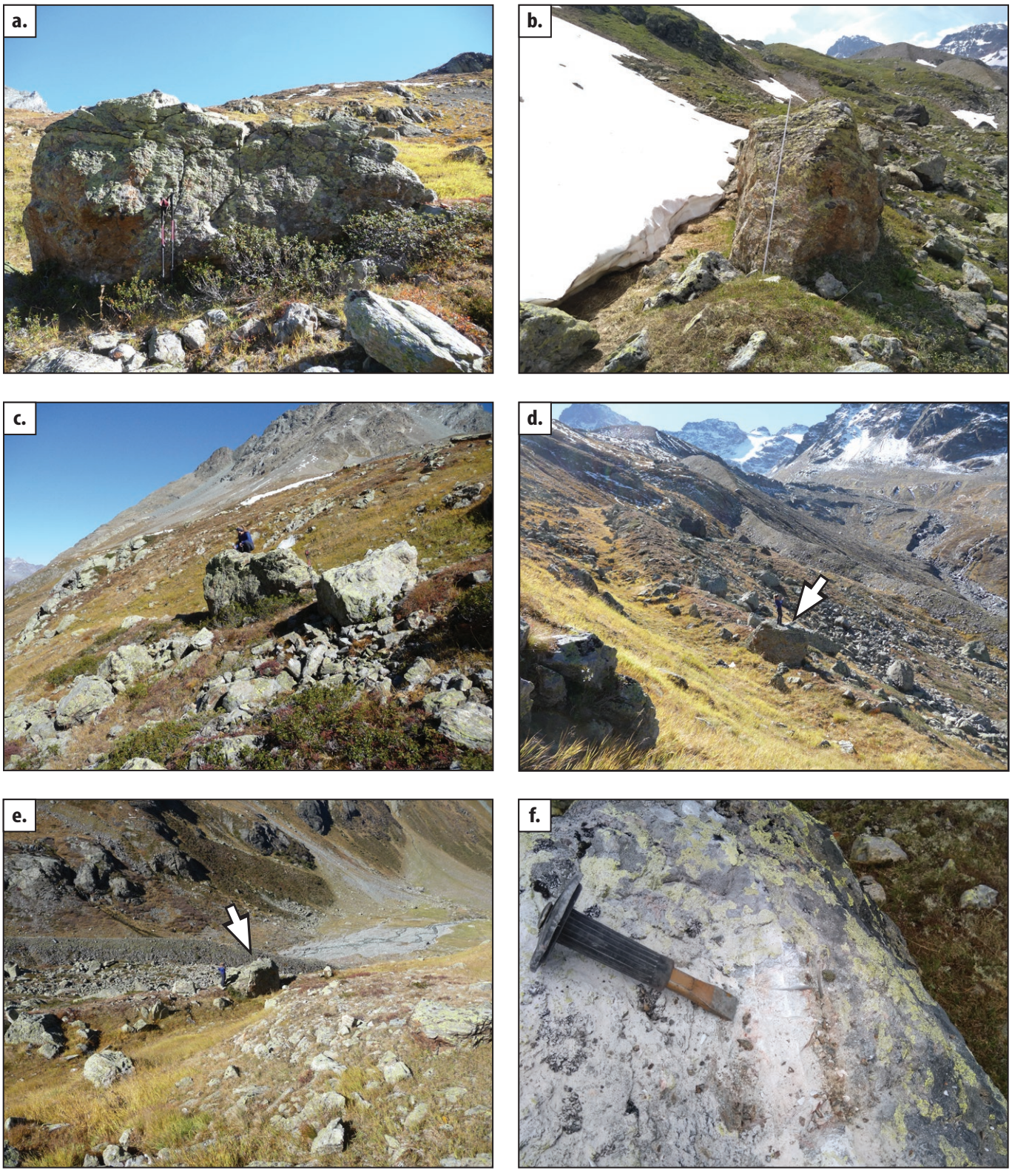

Figure S15: LAR-19-12. a. View towards E. b. View towards SE. c. View towards NE. d. View towards S, note person standing on the boulder for scale. e. View towards W. f. Sampled rock surface.

LAR-19-13 **^{10}Be exposure age: 11,120 ±210 yrs**

COORDINATES N 46.9224 | E 10.2258
ALTITUDE 2303 m
L x B x H 2.0 x 2.5 x 2.5 m^3

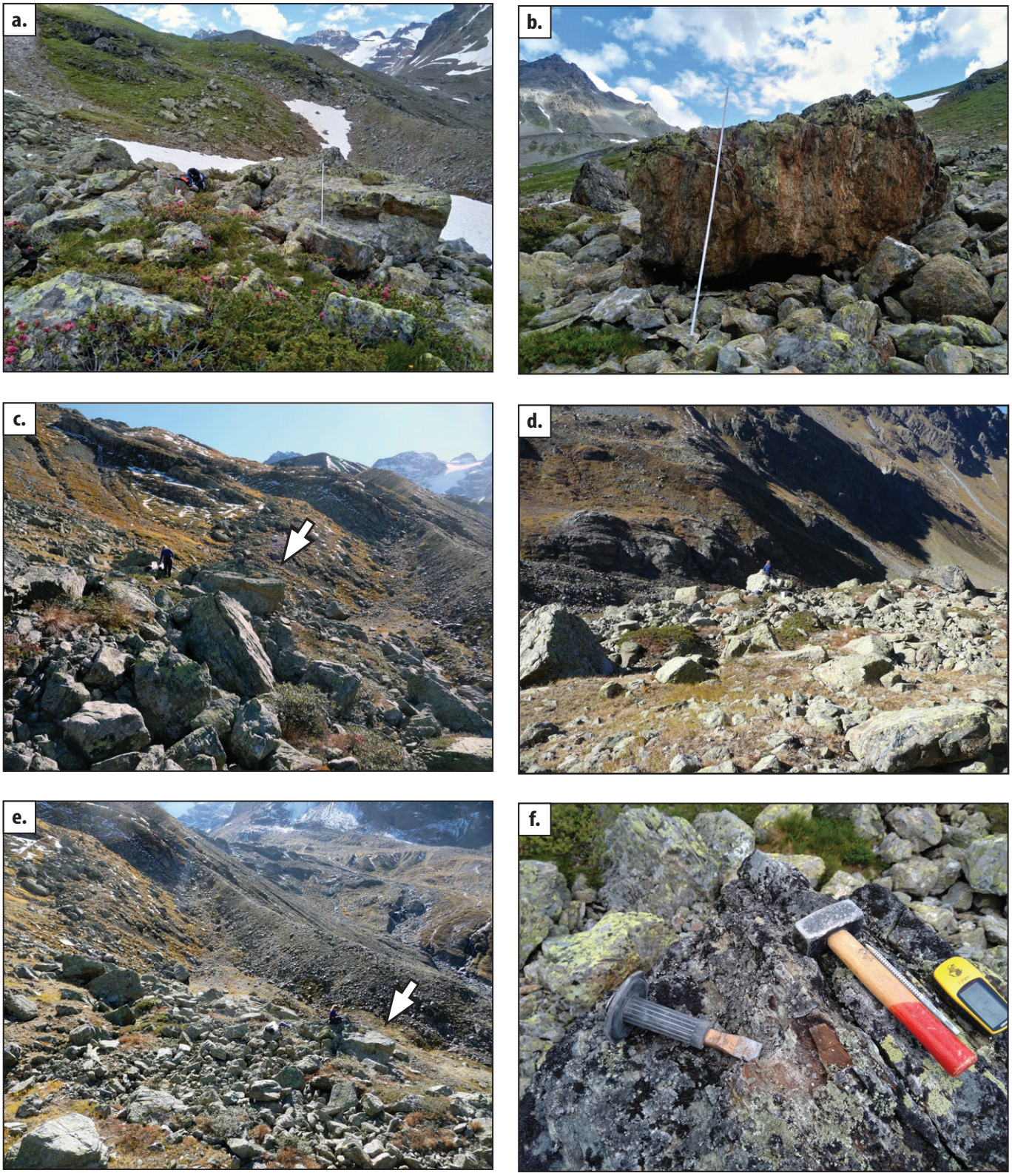

Figure S16: LAR-19-13. a. View towards N. b. View towards NE from glacier-proximal side of moraine ridge. c. View towards S. d. View towards W. e. View towards SE. f. Sampled rock surface.

LAR-19-14 **^{10}Be exposure age: 11,200 ±280 yrs**

COORDINATES N 46.9225 | E 10.2258
ALTITUDE 2303 m
L x B x H 3.7 x 3.1 x 2.8 m^3

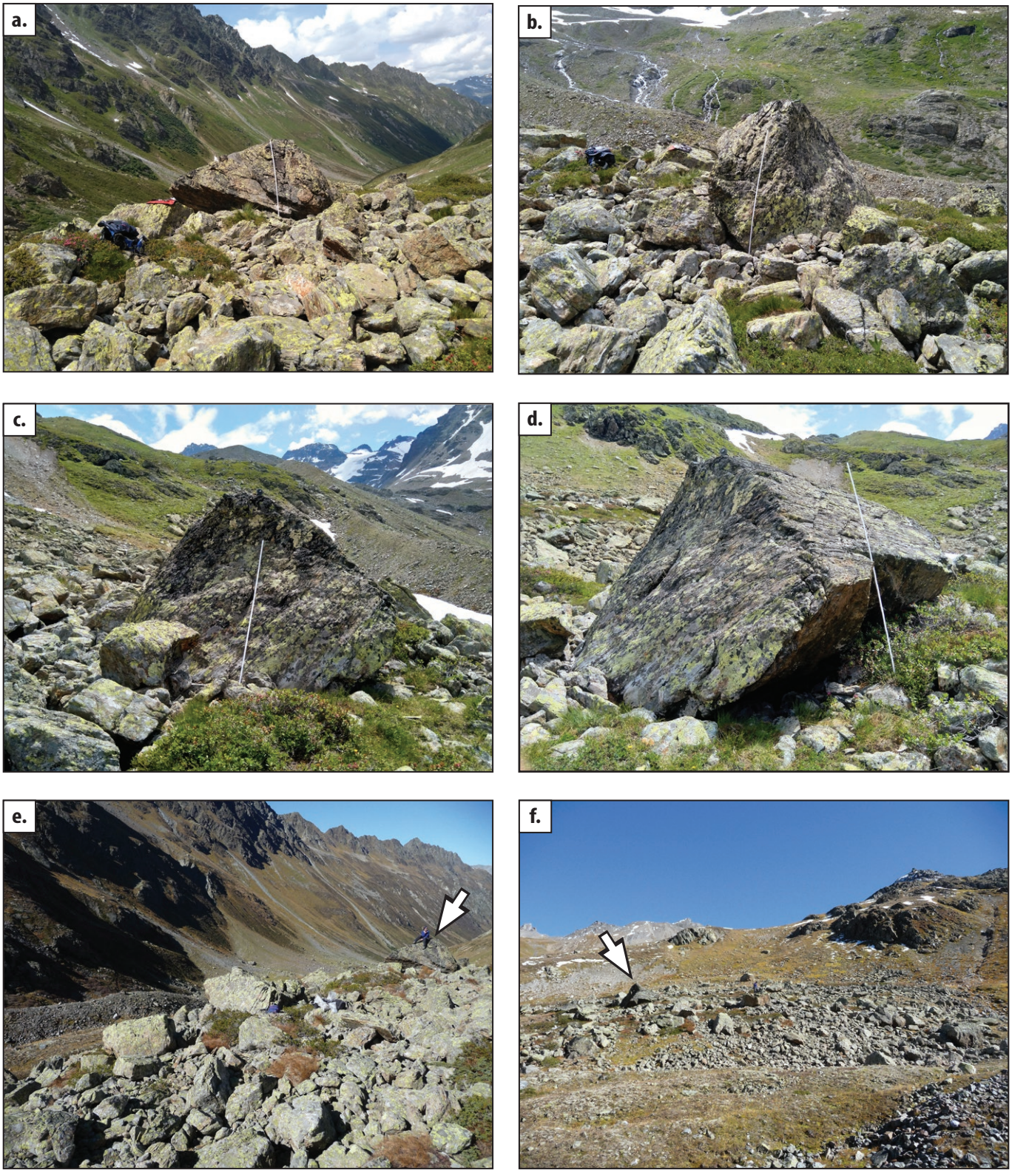

Figure S17: LAR-19-14. a. View towards NE. b. View towards W. c. View towards S. d. View towards SE e. View towards NW. f. View towards E.

LAR-19-15 **^{10}Be exposure age: 10,860 ±200 yrs**

COORDINATES N 46.9240 | E 10.2259
ALTITUDE 2275 m
L x B x H 3.6 x 2.1 x 2.4 m^3

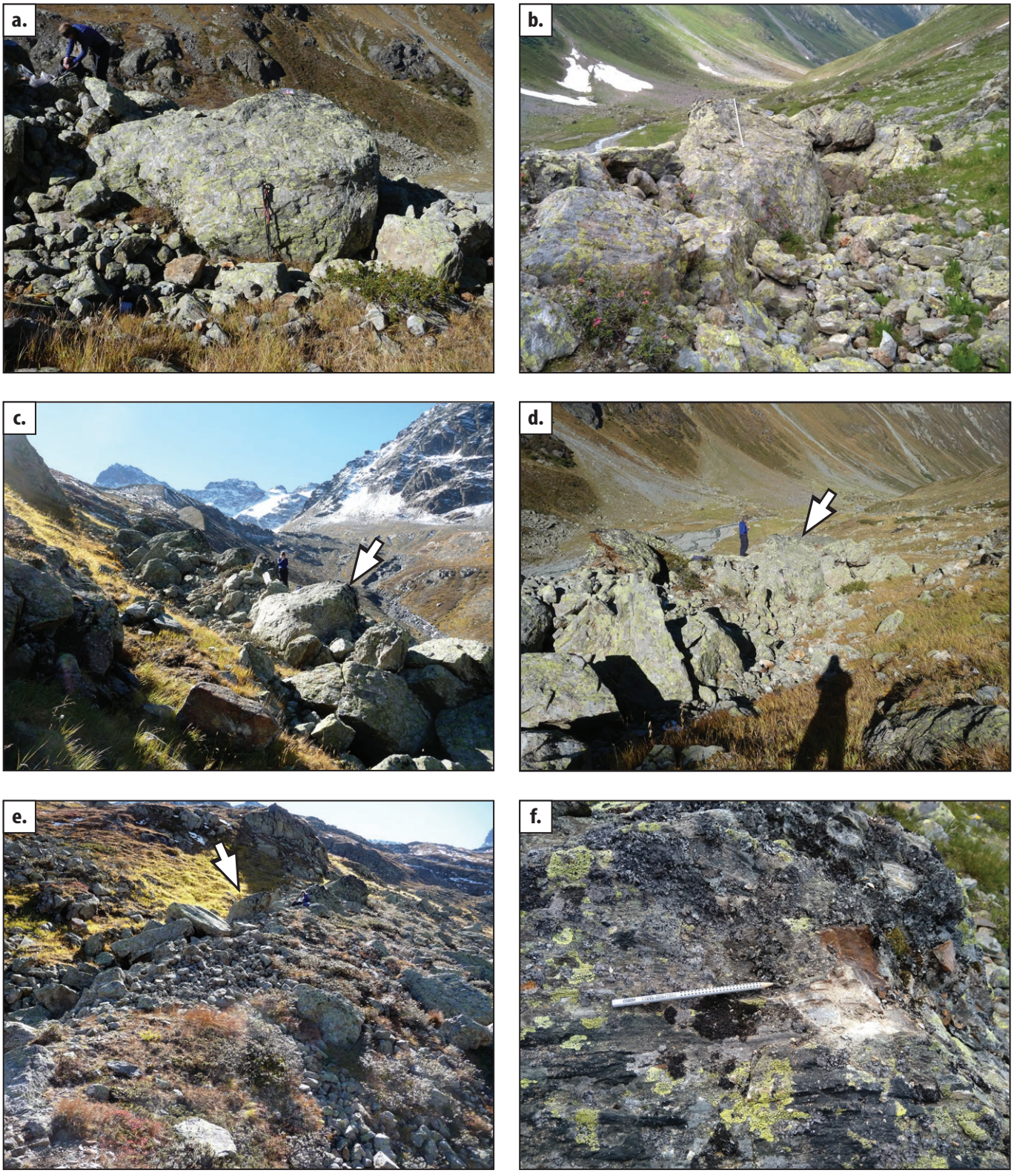

Figure S18: LAR-19-15. a. View towards NW with left-lateral L3 in the background. b. View towards N. c. View towards S. d. View towards NW. e. View towards SE. f. Sampled rock surface.

LAR-19-16 — ^{10}Be exposure age: 11,060 ±220 yrs

COORDINATES N 46.9238 | E 10.2260
ALTITUDE 2280 m
L x B x H 2.2 x 2.0 x 2.2 m³

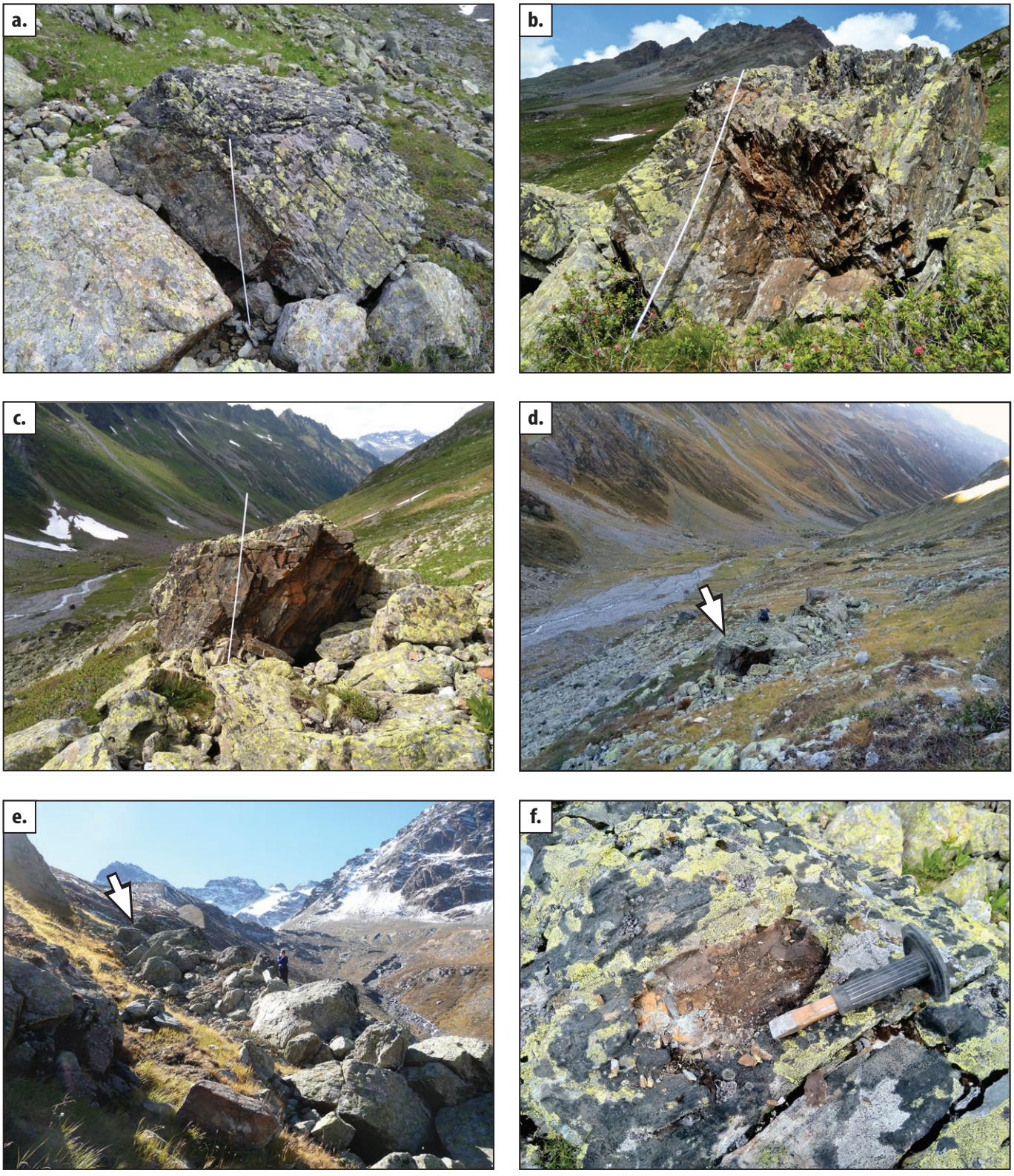

Figure S19: LAR-19-16. a. View towards S. b. View towards NE with Hoher Kogel peak in the background. c. View towards NE. d. View towards NE. e. View towards S. f. Sampled rock surface.

LAR-19-17 **^{10}Be exposure age: 11,070 ±210 yrs**

COORDINATES N 46.9267 | E 10.2223
ALTITUDE 2179 m
L x B x H 3.1 x 2.1 x 0.8 m^3

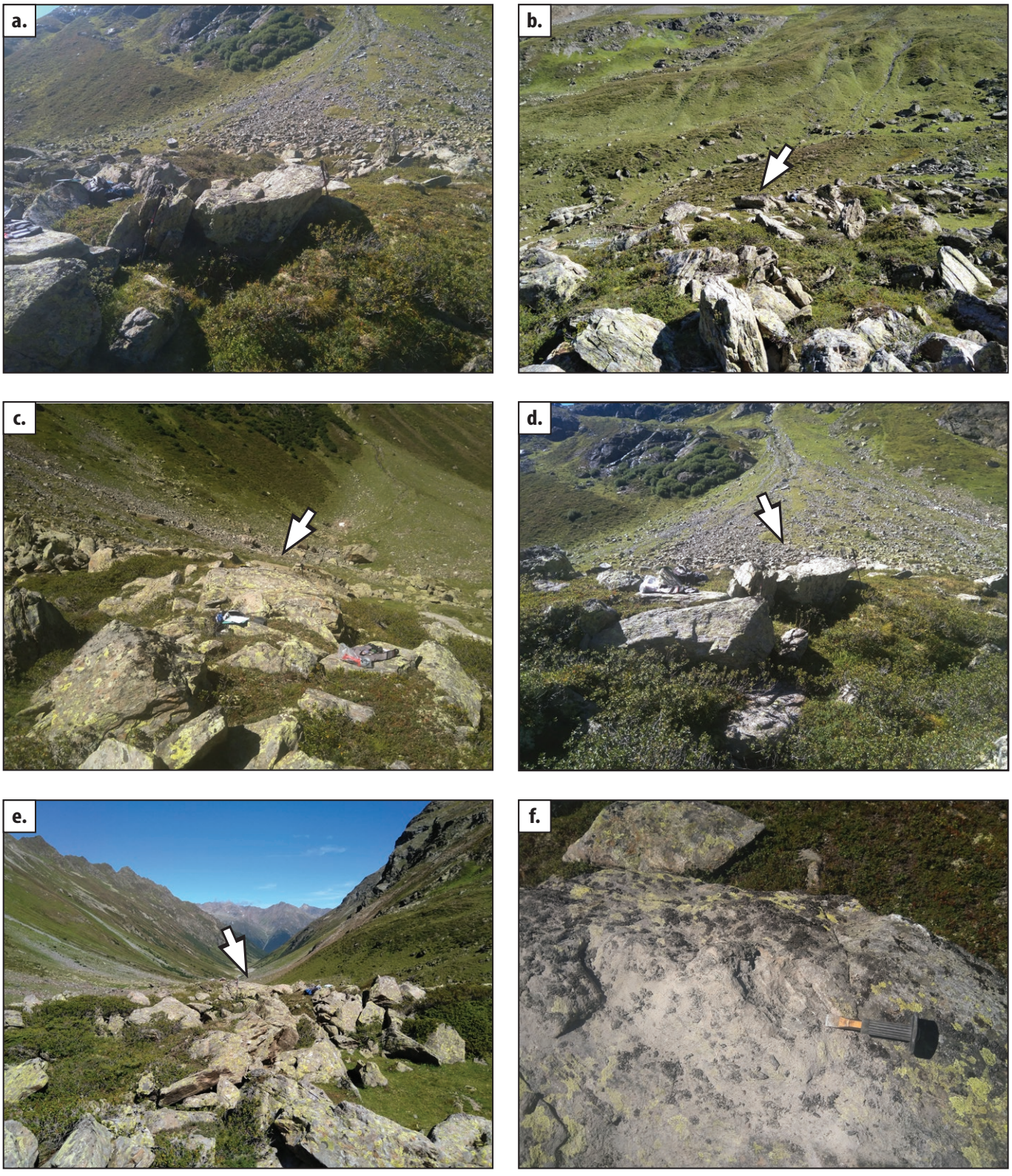

Figure S20: LAR-19-17. a. View towards W with left-lateral L3 cut by a debris cone in the background. b. View towards E. c. View towards NW. d. View towards W. e. View towards S. f. Sampled rock surface.

LAR-19-18 — ^{10}Be exposure age: 11,330 ±290 yrs

COORDINATES N 46.9268 | E 10.2223
ALTITUDE 2178 m
L x B x H 3.0 x 2.3 x 1.7 m^3

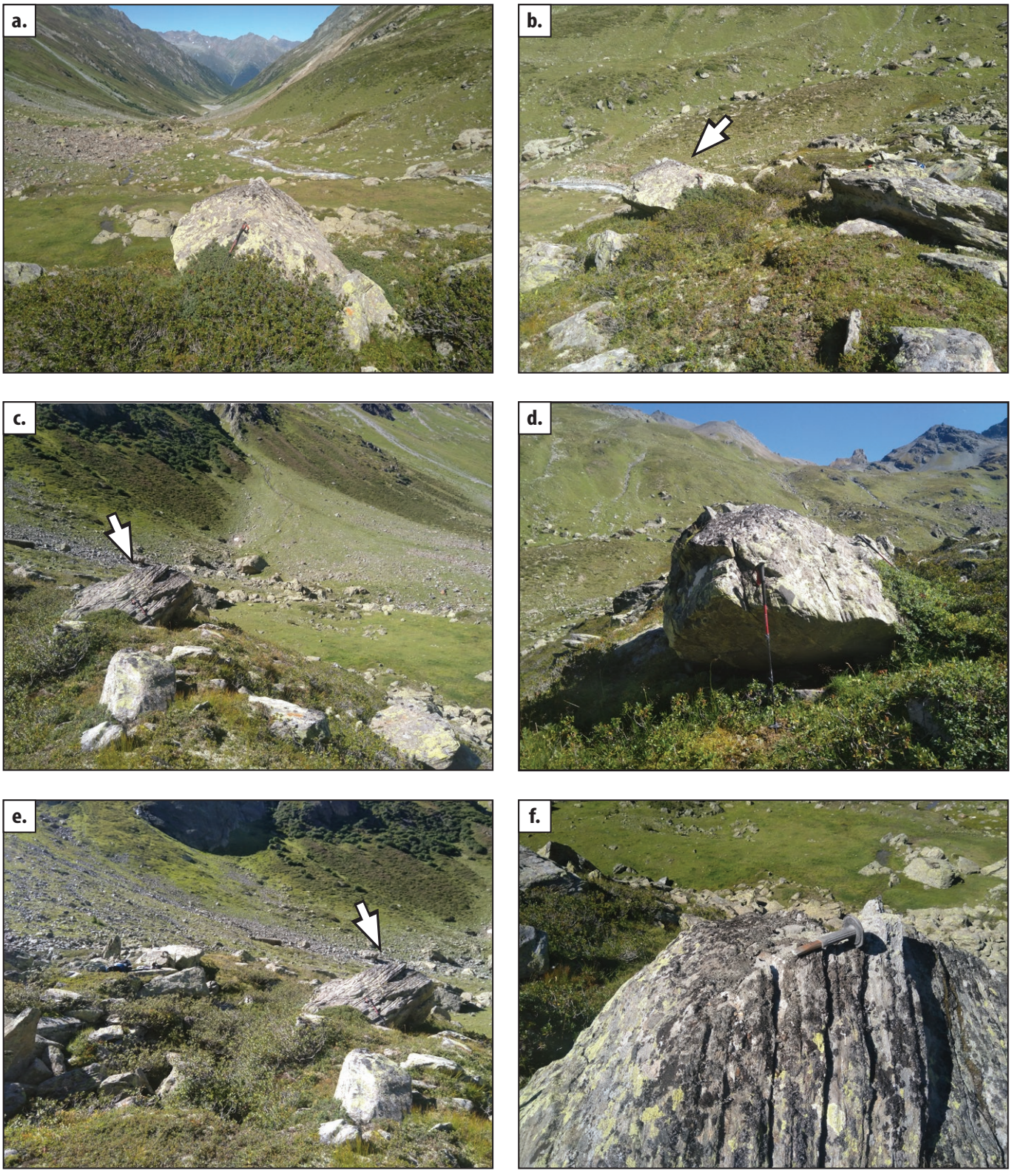

Figure S21: *LAR-19-18.* ***a.*** *View towards N with Zollhütte and L5 in the background.* ***b.*** *View towards E.* ***c.*** *View towards NW.* ***d.*** *View towards E with Ritzenjoch in the background.* ***e.*** *View towards W with LAR-18-17 in background (backpack).* ***f.*** *Sampled rock surface.*

LAR-19-19 — ^{10}Be exposure age: 10,730 ±200 yrs

COORDINATES N 46.9267 | E 10.2226
ALTITUDE 2178 m
L x B x H 2.1 x 1.7 x 1.1 m³

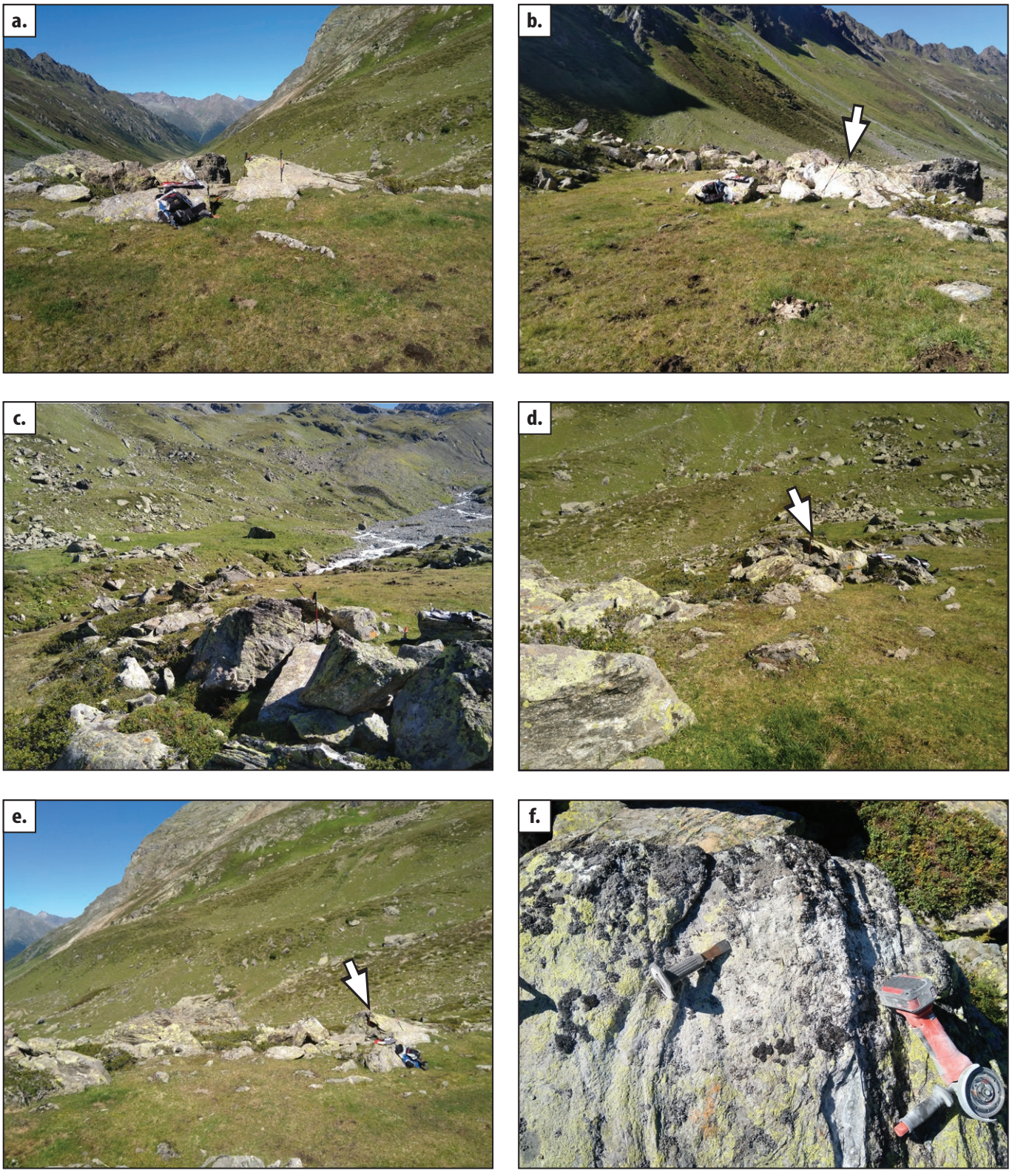

Figure S22: *LAR-19-19.* ***a.*** *View towards N.* ***b.*** *View towards NW.* ***c.*** *View towards SE with terminal section of L1 ridges in the background.* ***d.*** *View towards E.* ***e.*** *View towards NE.* ***f.*** *Sampled rock surface.*

LAR-19-20 **^{10}Be exposure age: 11,480 ±210 yrs**

COORDINATES N 46.9267 | E 10.2224
ALTITUDE 2180 m
L x B x H 0.8 x 1.6 x 1.5 m^3

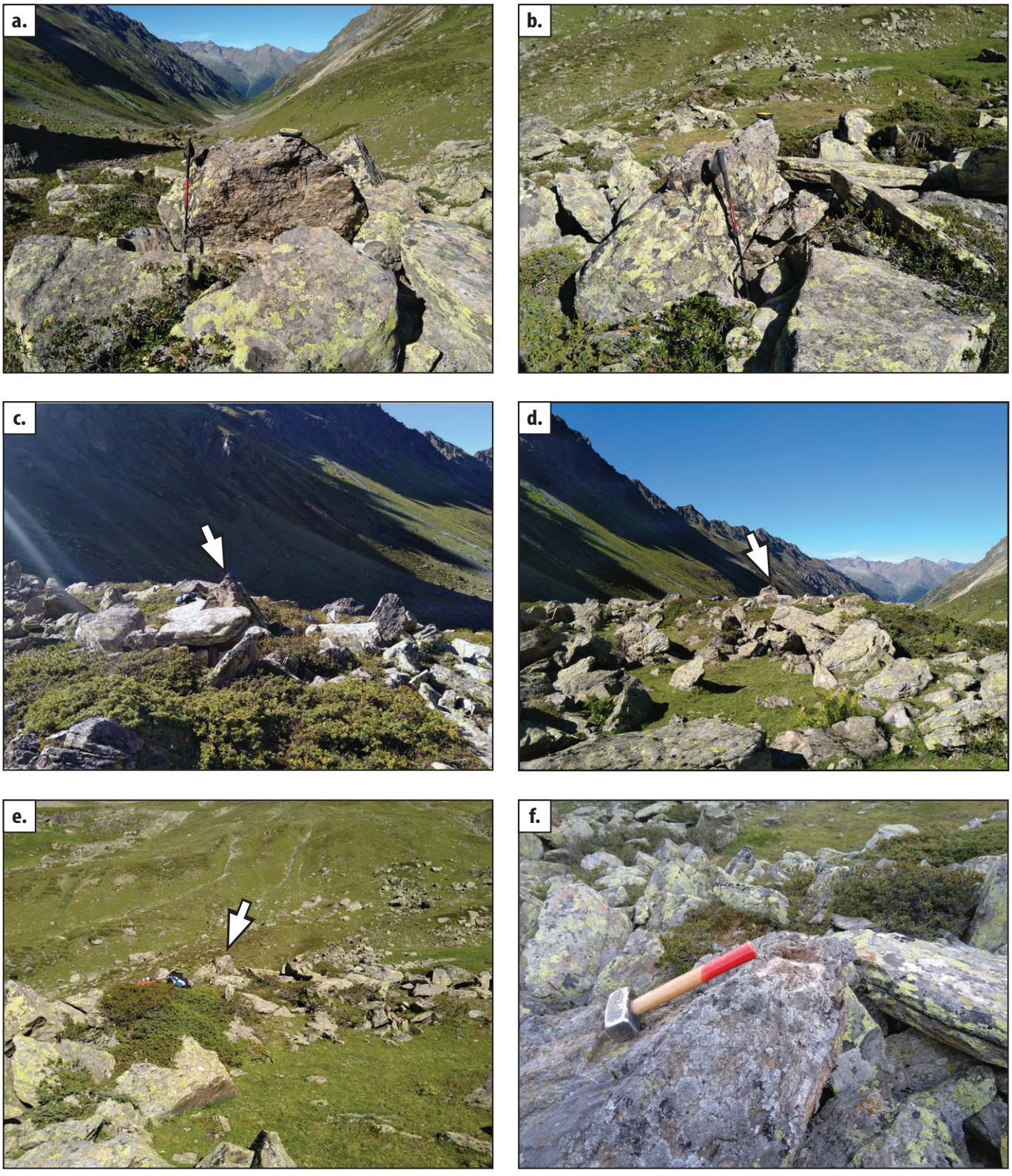

Figure S23: *LAR-19-20.* ***a.*** *View towards N.* ***b.*** *View towards E.* ***c.*** *View towards NW.* ***d.*** *View towards N.* ***e.*** *View towards E.* ***f.*** *Sampled rock surface.*

LAR-19-21 **^{10}Be exposure age: 10,660 ±200 yrs**

COORDINATES	**N 46.9273 | E 10.2222**
ALTITUDE	**2160 m**
L x B x H	**2.0 x 1.2 x 1.3 m^3**

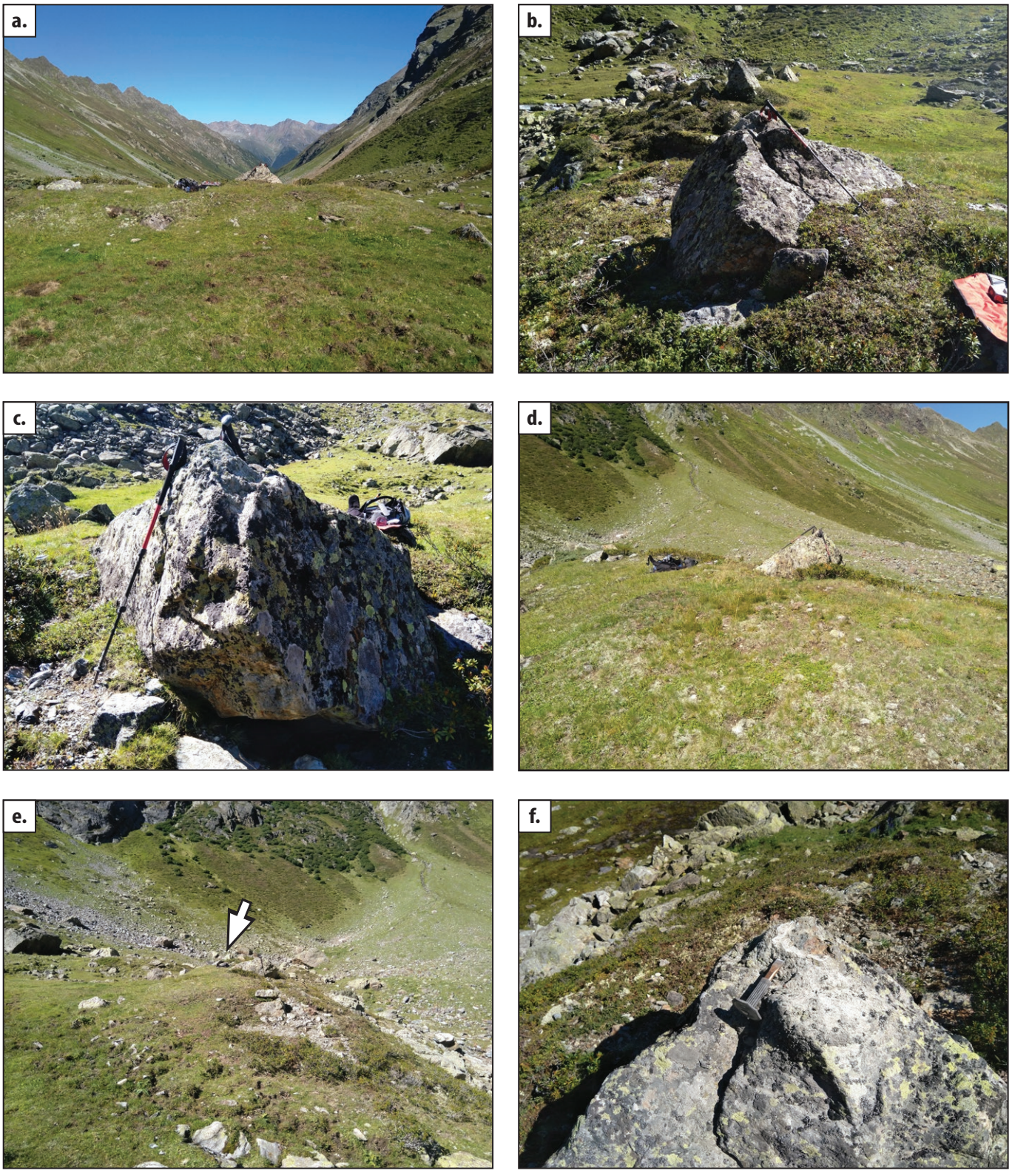

Figure S24: LAR-19-21. a. View towards N. b. View towards E. c. View towards NW. d. View towards N. e. View towards E. f. Sampled rock surface.

LAR-19-22 — ^{10}Be exposure age: 11,210 ±210 yrs

COORDINATES N 46.9245 | E 10.2213
ALTITUDE 2256 m
L x B x H 6.0 x 3.0 x 2.4 m³

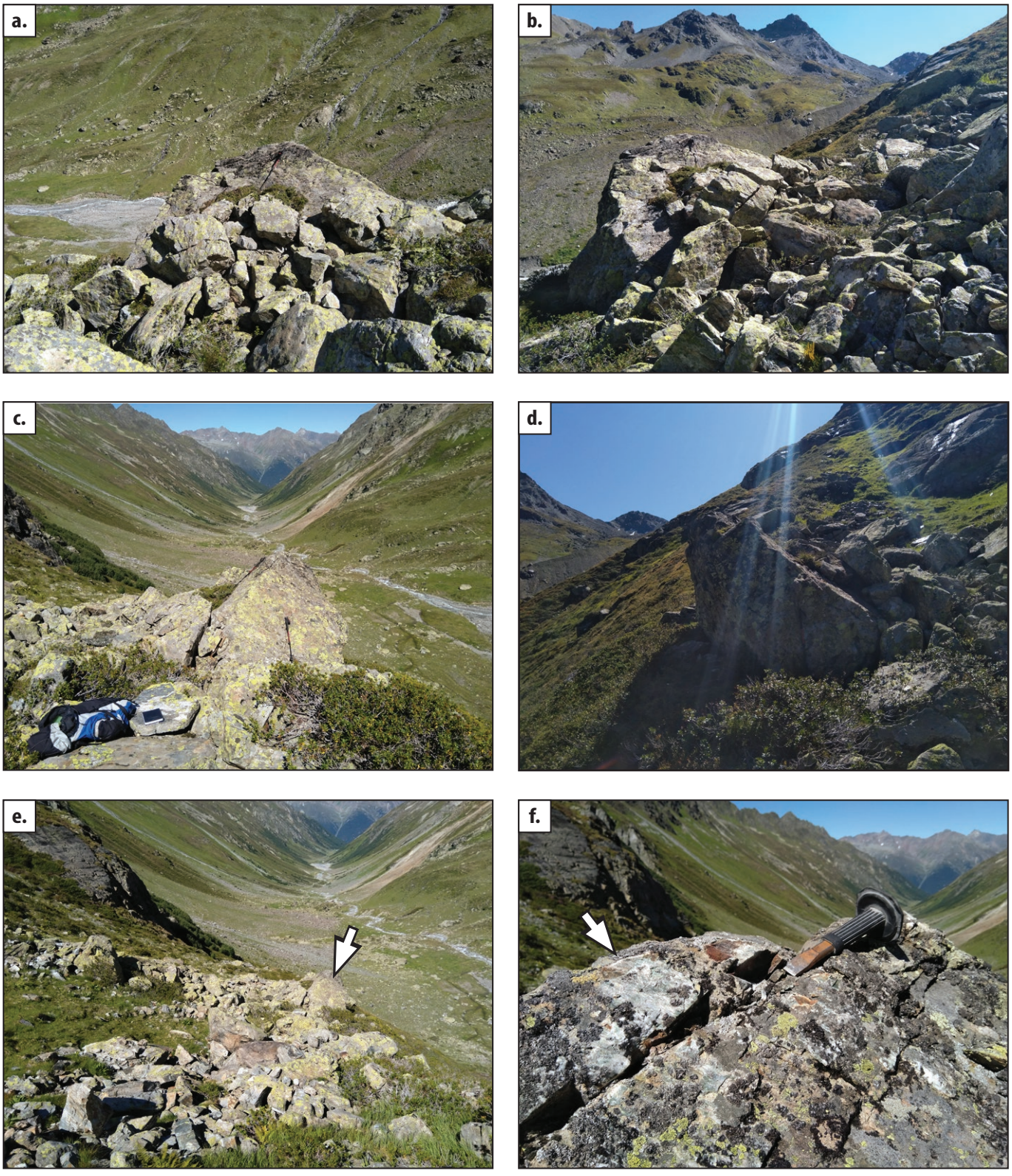

Figure S25: *LAR-19-22.* ***a.*** *View towards E.* ***b.*** *View towards SE.* ***c.*** *View towards N with rockfall pathway (brown line in the upper-right quarter of the image); source area Hoher Kogel.* ***d.*** *View towards S.* ***e.*** *View towards N.* ***f.*** *Sampled rock surface indicated by arrow.*

LAR-19-23 — ^{10}Be exposure age: 700 ±20 yrs

COORDINATES N 46.9234 | E 10.2216
ALTITUDE 2292 m
L x B x H 3.7 x 2.5 x 2.5 m³

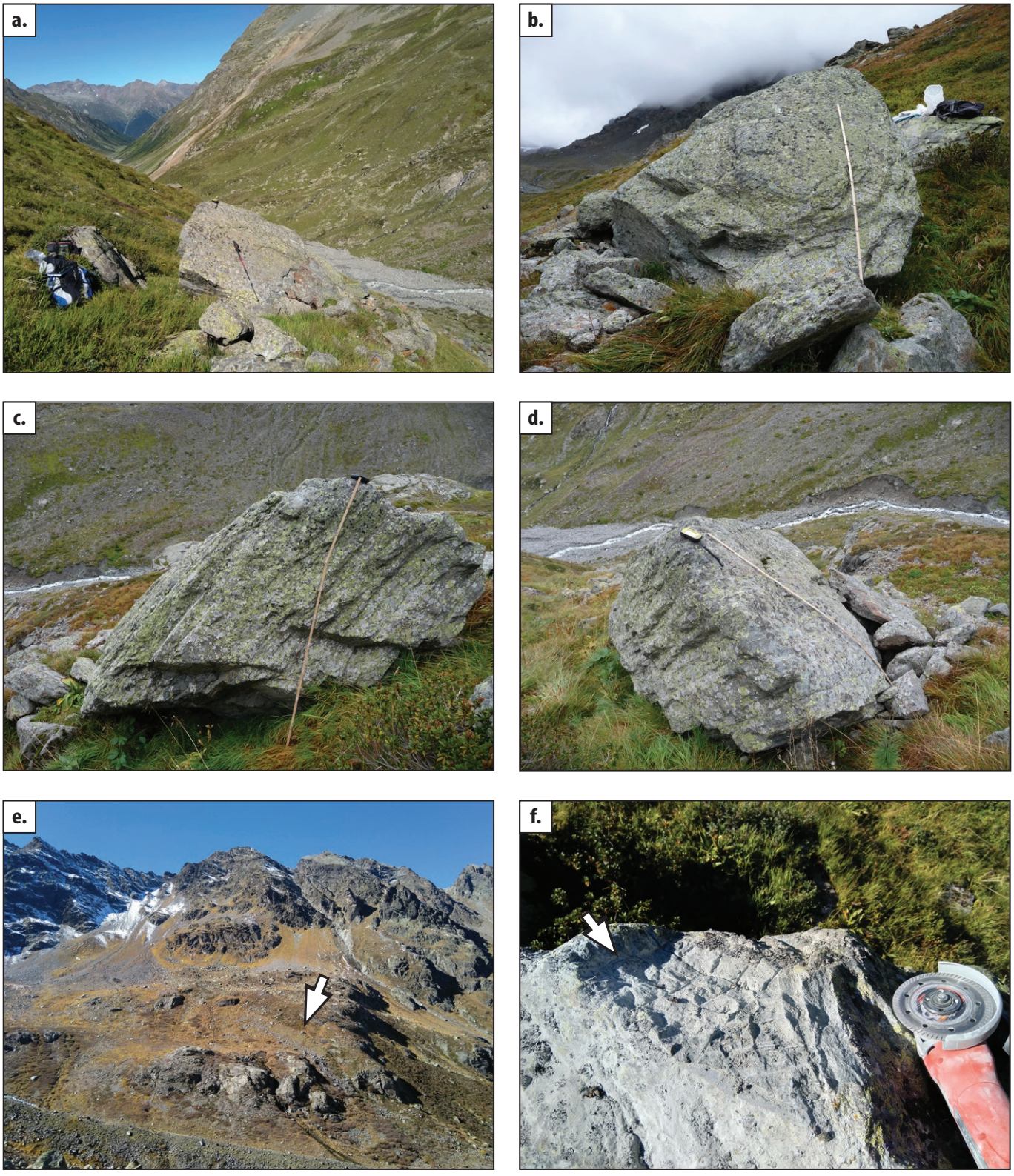

Figure S26: *LAR-19-23.* ***a.*** *View towards N.* ***b.*** *View towards SW.* ***c.*** *View towards E.* ***d.*** *View towards NE.* ***e.*** *View towards NNE.* ***f.*** *Sampled rock surface indicated by arrow.*

LAR-19-24 **^{10}Be exposure age: 10,930 ±210 yrs**

COORDINATES N 46.9225 | E 10.2201
ALTITUDE 2357 m
L x B x H 3.2 x 1.8 x 1.1 m^3

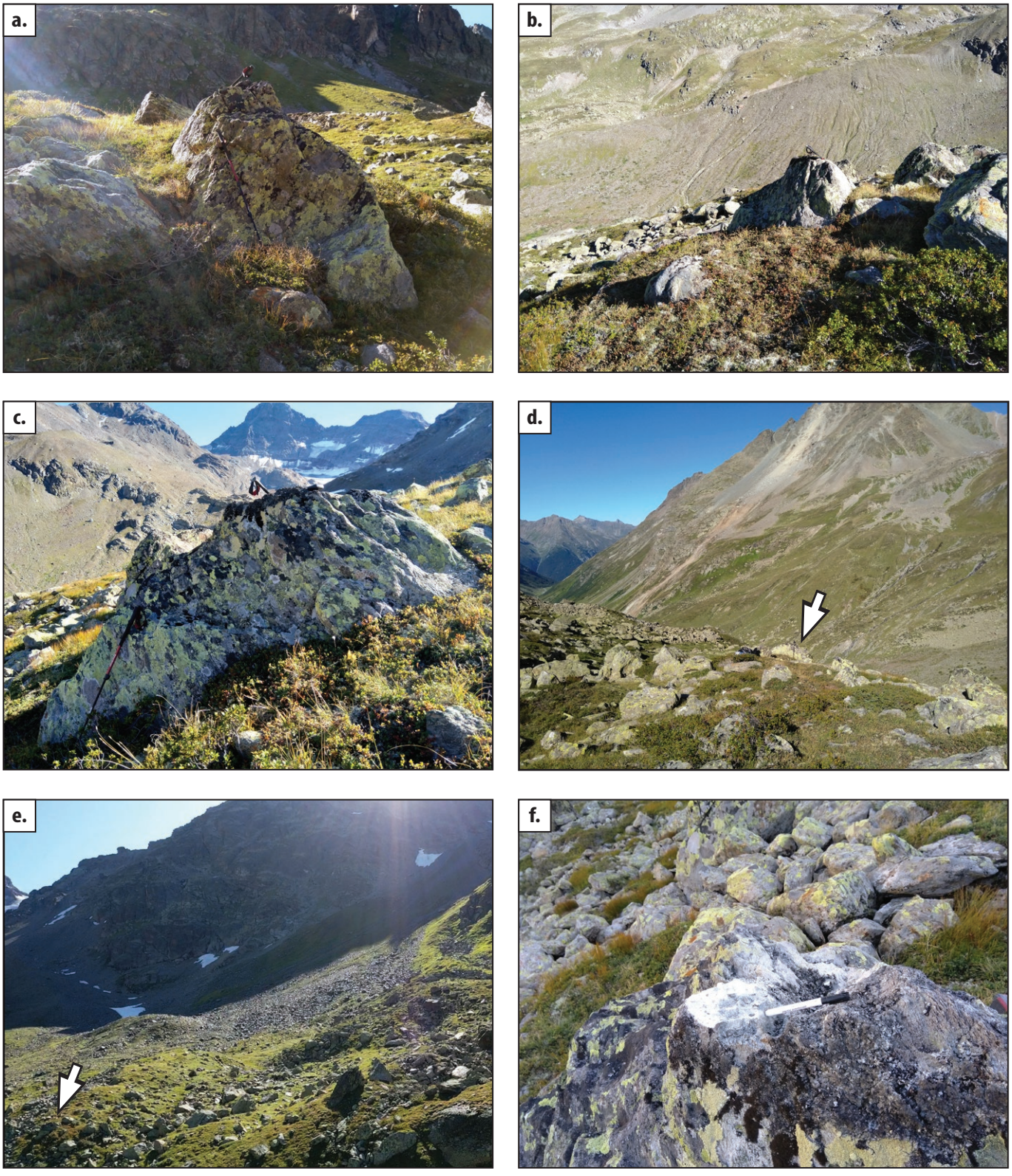

Figure S27: LAR-19-24. a. View towards NW. b. View towards E. c. View towards S. d. View towards NE with recent rock fall channel in the background. e. View towards SW (drone footage). f. Sampled rock surface indicated by arrow (dipping quartz vene).

References

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