Supplementary material of the paper "Multimillennial synchronization of low and polar latitude ice cores by matching an absolute time constrained Alpine record with an accurate Arctic chronology"

Paolo Gabrielli[1,2], Theo M. Jenk[3,4], Michele Bertó[5], Giuliano Dreossi[6], Daniela Festi[7], Werner Kofler[7], Mai Winstrup[8], Klaus Oeggl[7], Margit Schwikowski[3,4,9], Barbara Stenni[5] and Carlo Barbante[5,6]

[1]Byrd Polar and Climate Research Center, The Ohio State University, Columbus, 43210, USA

[2]School of Earth Sciences, The Ohio State University, 275 Mendenhall Laboratory, Columbus, 43210, USA

[3]Laboratory of Environmental Chemistry, Paul Scherrer Institut, 5232, Villigen PSI, Switzerland

[4]Oeschger Centre for Climate Change Research, University of Bern, CH-3012 Bern, Switzerland

[5]Department of Environmental Sciences, Informatics and Statistics, Ca' Foscari University of Venice, Venice-Mestre, 30170, Italy

[6]Institute of Polar Sciences-CNR, Venice-Mestre, 30170, Italy

[7]Institute for Botany, University of Innsbruck, Innsbruck, 6020, Austria

[8]DTU Space, Technical University of Denmark, Kongens Lyngby, Denmark

[9]Department of Chemistry and Biochemistry, University of Bern, CH-3012 Bern, Switzerland

Correspondence to: Paolo Gabrielli (gabrielli.1@osu.edu)

Supplementary text 1: The Colle Gnifetti ice core time scale

The Colle Gnifetti ice core (Mt. Rosa, Western Alps) is currently the oldest record in the Alps, dating back >15000 years (Jenk et al., 2009). The Colle Gnifetti Pb record was previously published by Schwikowski et al. (2004) and Gabrieli and Barbante (2014) and its chronology was based on the dating by Jenk et al., (2009). Here, we take advantage of a revised dating of the Colle Gnifetti ice core (CG03B) and a Pb record presented accordingly to CG03B. Compared to the timescale published by Jenk et al. (2009), CG03B (see details in Fig. S1) includes revised counting annual layers (ALC) based on additional reference horizons of historical Sahara dust layers (SDL) and volcanic layers (VL) (Sigl et al., 2018), and also includes two additional ^{14}C-dates (Sigl et al., 2009). Briefly, CG03B is based on ALC (2003–1763 CE), a maximum ^{3}H peak, historical SDL, VL and was independently confirmed by ^{210}Pb activity (Jenk et al., 2009; Sigl et al., 2018). CG03B was previously used in Sigl et al., 2018 and Brugger et al., 2021 for the last millennium. Before 1763 CE ages are modeled as an exponential equation constrained by ^{14}C-dates from the measured organic fraction of carbonaceous particles (Jenk et al., 2009; Sigl et al., 2009), thereby assuming steady-state conditions (Jenk et al., 2009). CG03B has a relatively small uncertainty back to 1763 CE (up to a maximum of around ± 5 years) that increases significantly to ~ ± 250 years at the beginning of the record at ~ 350 CE.

In figures S2-4 we provide a comparison of the Colle Gnifetti non-crustal Pb flux record with the corresponding: i) Alto dell'Ortles record; and ii) the SZ Arctic record which is the time reference of the Alto dell'Ortles core (see main text). In the Colle Gnifetti core the non-crustal Pb flux was obtained by using the average crustal Pb/Ti ratio and an assumed constant snow accumulation rate of 0.5 m y^{-1}; note that this flux is just a linear transformation of the Pb concentrations that remains independent from the time scale.

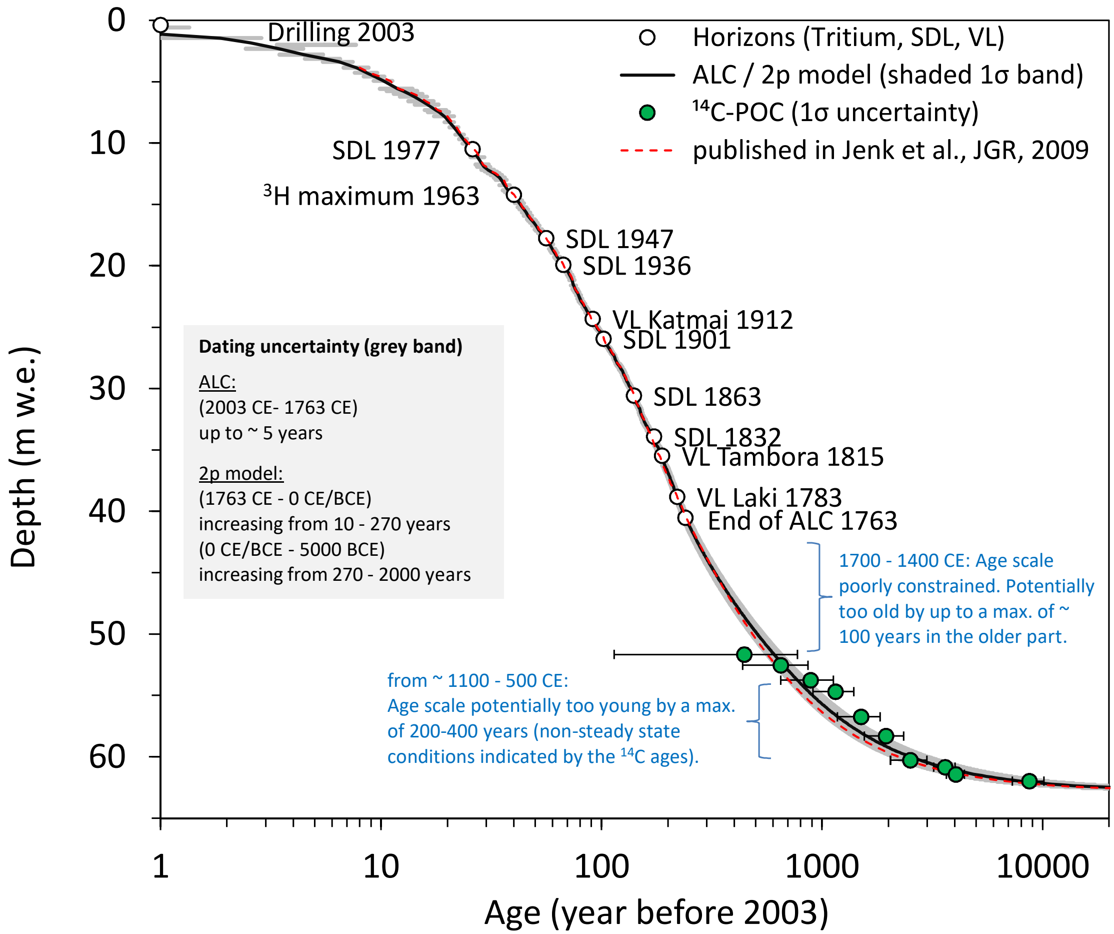


Figure S1: Dating of the Colle Gnifetti ice core (CG03B). Note the logarithmic age axis. This is a revised dating of Jenk et al. (2009) (red dashed line). This update also includes a revised counting of annual layers (ALC) based on additional reference horizons of historical Sahara dust layers (SDL) and volcanic layers (VL) (Sigl et al., 2018), as well as two additional ^{14}C-dates (Sigl et al., 2009).

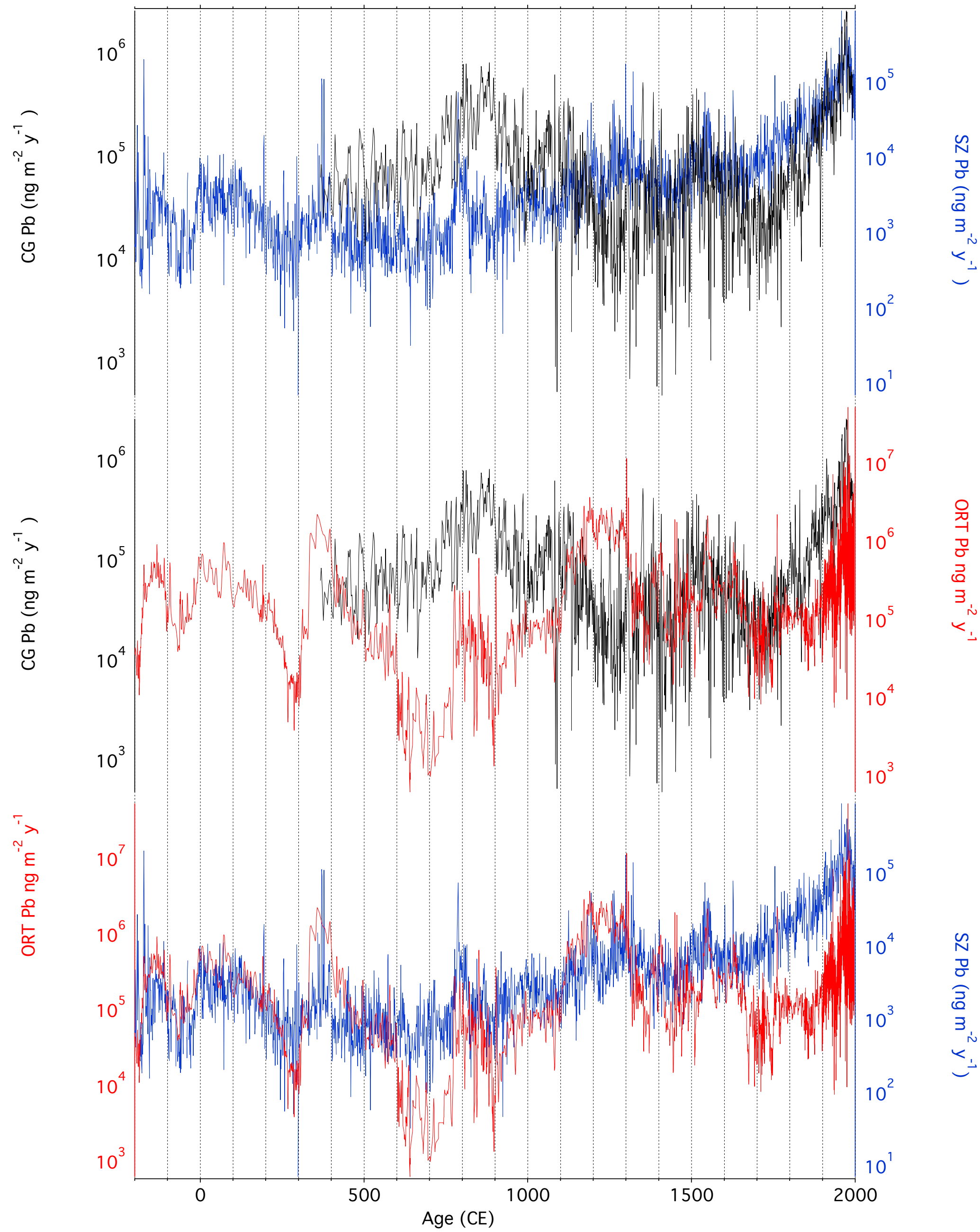


Figure S2: Comparison of the non-crustal Pb fluxes from the Colle Gnifetti ice core (CG; black) with the synchronized records from Alto dell'Ortles #3 (ORT; red) and Severnaya Zemlya (SZ; blue), the latter taken as a time reference during the 171 BCE -1907 CE time period.

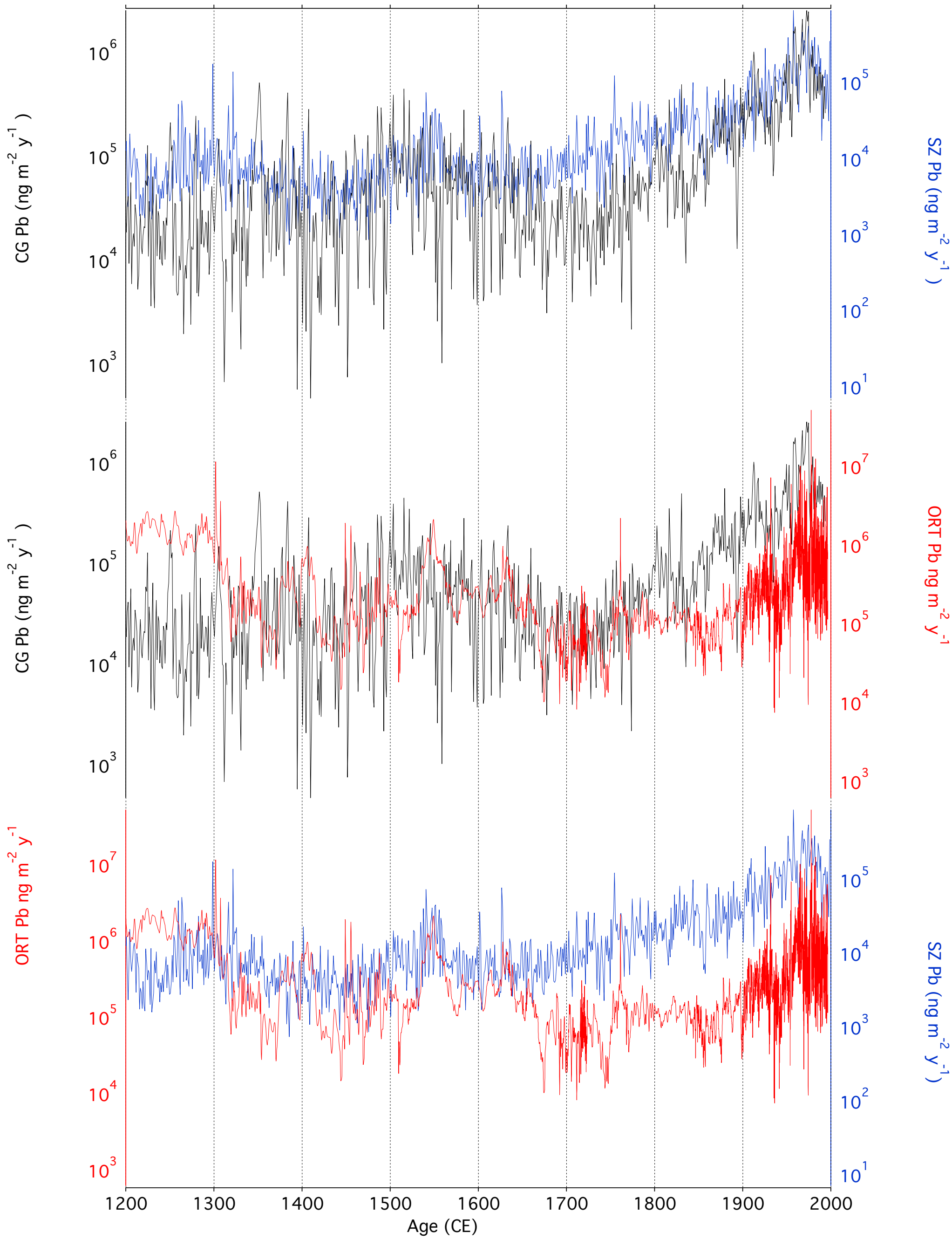
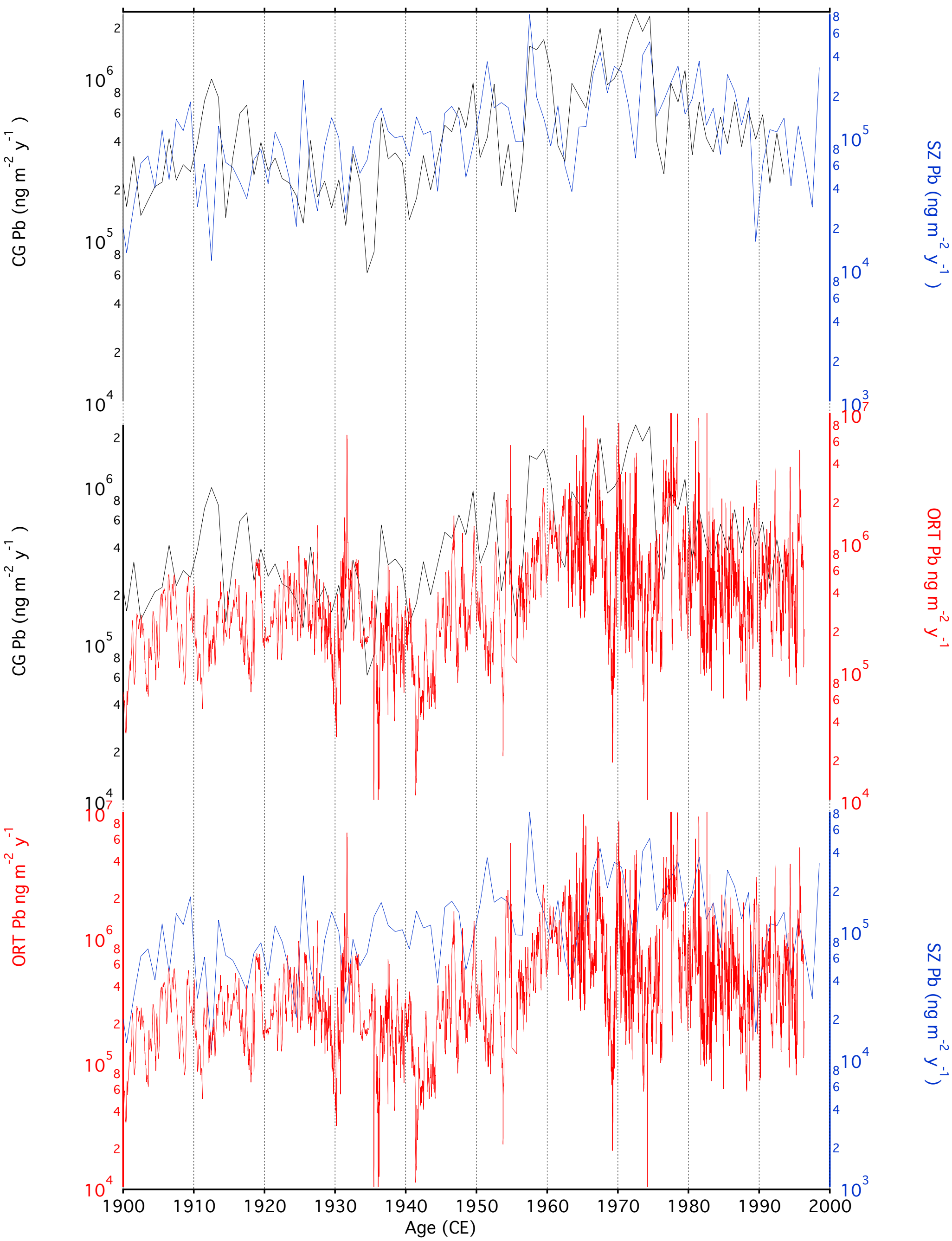


Figure S3: A section of Fig. S2 focusing on the 1200-2011 CE time period.



5

Figure S4: A section of Fig. S2 focusing on the 1900-2011 CE time period.

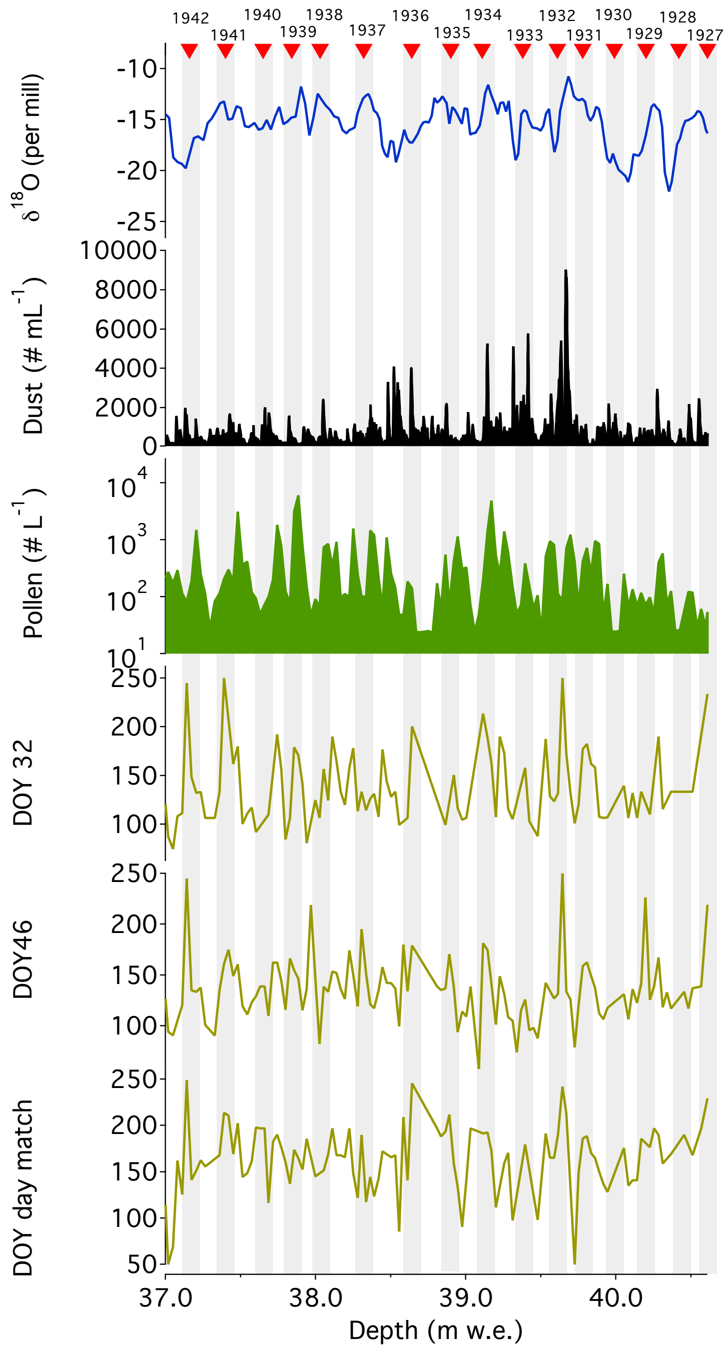


Figure S5: Annual layers between 37 and 41 m water equivalent (w.e) in core #1 as a combination of $\delta^{18}O$, dust and pollen concentrations, DOY 32 and 46 and DOY match (see main text).

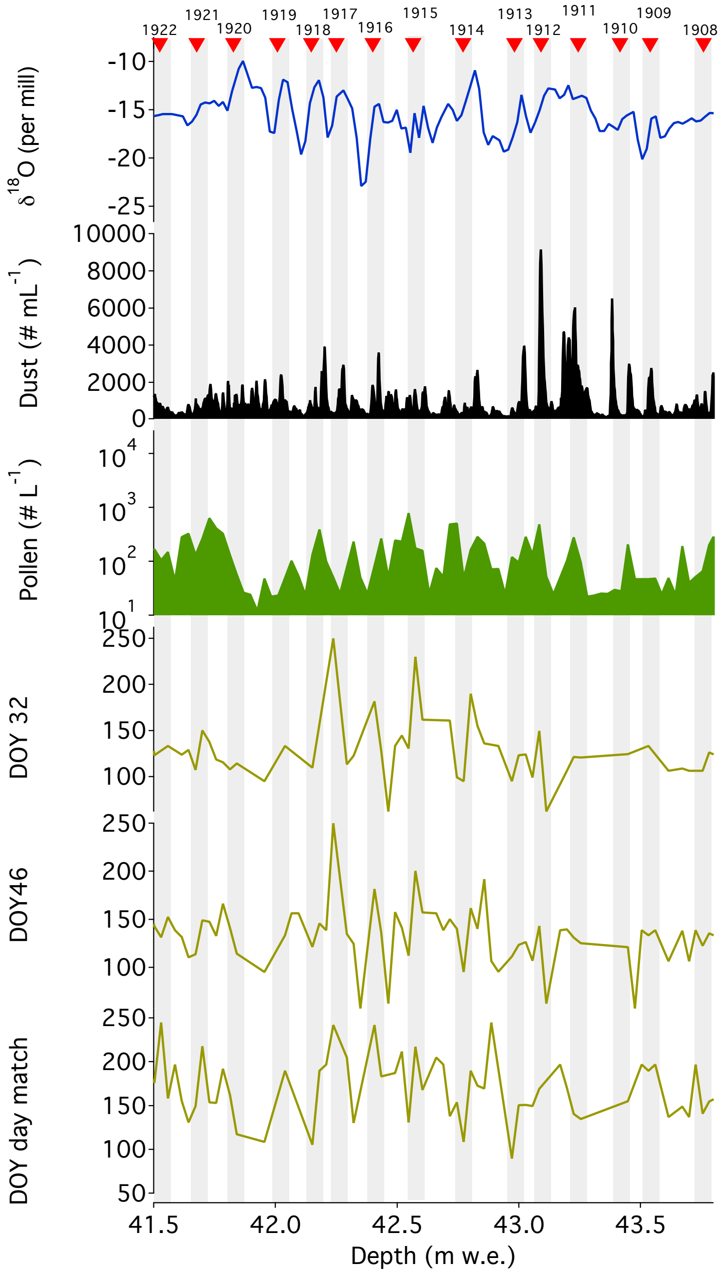


Figure S6: Annual layers between 41.5 and 43.5 m water equivalent (w.e) in core #1 as a combination of $\delta^{18}O$, dust and pollen concentrations, DOY 32 and 46 and DOY match (see main text).

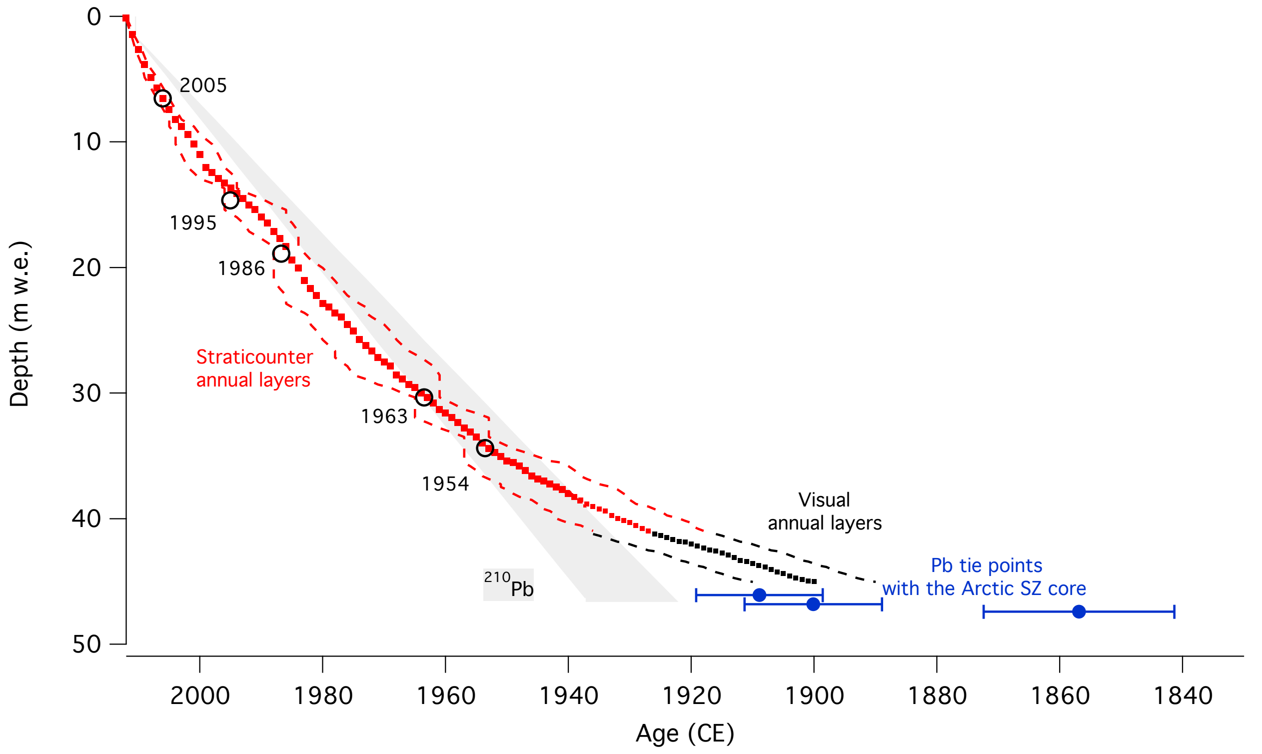


Figure S7: Comparison of the different time markers obtained in the shallow (recent) part of the Alto dell'Ortles cores. StratiCounter annual layer automatic counting (red dots; within 95% uncertainty) superimposed to 5 fixed time markers (open circles; see also Table 2); ^{210}Pb ages from the TC2016 chronology within their uncertainty (grey area; from Gabrielli et al., (2016); annual layers visual counting (black dots within an assumed 10 years uncertainty); and the most recent tie points obtained by matching the Alto dell'Ortles and the Severnaya Zemlya (SZ) Pb records (blue dots within an assumed 10% age uncertainty).

Supplementary Table 1: Tie points (TC2016 and SZ ages) used to synchronize the Alto dell'Ortles TC2016 and the Severnaya Zemlya core time reference) chronologies.

Depth in core #3 (m)	Depth in core #2 (m)	Depth in core #2 (m w.e.)	TC2016 Age (yrs b2012)	TC2016 Age 5.0%-(yrs b2012)	TC2016 Age 95.0%- (yrs b2012)	SZ Age(yb2012)	Delta TC2016-SZ Age
56.56	57.63	45.34	88	78	100	103	15
57.31	58.40	46.05	93	78	109	112	19
58.71	59.88	47.41	108	86	138	155	47
59.58	60.95	48.39	123	96	164	194	71
60.16	61.86	49.21	136	103	182	241	104
60.67	62.16	49.48	150	112	202	259	109
61.20	62.72	50.00	167	126	223	280	113
63.05	63.87	51.05	253	180	336	339	86
63.98	64.55	51.69	314	218	419	385	71
64.52	65.19	52.27	355	243	476	450	95
64.86	65.57	52.62	383	259	509	478	95
66.19	67.00	53.93	514	334	687	655	141
67.80	68.42	55.23	717	452	988	907	190
68.23	68.94	55.71	784	485	1077	1000	216
68.64	69.42	56.14	850	524	1173	1108	257
69.46	70.27	56.92	1007	645	1365	1247	240
69.88	70.74	57.36	1102	736	1465	1368	266
70.66	71.47	58.02	1318	967	1654	1610	292
70.86	71.63	58.17	1378	1039	1724	1706	328
71.81	72.42	58.89	1747	1314	2148	2013	266
72.00	72.58	59.04	1841	1398	2253	2083	243

Supplementary Table 2 (part 1): Time markers employed in the revised chronology (this work).

Depth in core #2 (m w.e.)	Age (yrsb2012)	Age uncertainty (years)	Type of time marker	Used in COPRA model
0.144	0	0.1	Annual layer (Straticounter)	✓
1.435	1	0.2	Annual layer (Straticounter)	✓
2.652	2	0.5	Annual layer (Straticounter)	✓
3.843	3	0.5	Annual layer (Straticounter)	✓
4.868	4	1	Annual layer (Straticounter)	✓
5.713	5	1	Annual layer (Straticounter)	✓
6.551	6	1	Annual layer (Straticounter) and 2006 pollen peak	✓
7.404	7	1	Annual layer (Straticounter)	✓
8.217	8	1	Annual layer (Straticounter)	✓
8.761	9	2	Annual layer (Straticounter)	✓
9.407	10	2	Annual layer (Straticounter)	✓
10.182	11	3	Annual layer (Straticounter)	✓
11.022	12	3	Annual layer (Straticounter)	✓
12.017	13	3	Annual layer (Straticounter)	✓
12.457	14	3	Annual layer (Straticounter)	✓
12.931	15	3	Annual layer (Straticounter)	✓
13.268	16	2	Annual layer (Straticounter)	✓
13.687	17	1	Annual layer (Straticounter) and 1995 pollen peak	✓
14.116	18	2	Annual layer (Straticounter)	✓
14.509	19	3	Annual layer (Straticounter)	✓
15.011	20	4	Annual layer (Straticounter)	✓
15.402	21	5	Annual layer (Straticounter)	✓
16.001	22	4	Annual layer (Straticounter)	✓
16.454	23	4	Annual layer (Straticounter)	✓
17.121	24	4	Annual layer (Straticounter)	✓
17.712	25	3	Annual layer (Straticounter)	✓
18.332	26	2	Annual layer (Straticounter) and 1986 Beta peak	✓
19.395	27	3	Annual layer (Straticounter)	✓
20.036	28	4	Annual layer (Straticounter)	✓
21.048	29	5	Annual layer (Straticounter)	✓
21.660	30	5	Annual layer (Straticounter)	✓
22.223	31	5	Annual layer (Straticounter)	✓
22.884	32	6	Annual layer (Straticounter)	✓
23.162	33	6	Annual layer (Straticounter)	✓
23.615	34	5	Annual layer (Straticounter)	✓
23.952	35	5	Annual layer (Straticounter)	✓
24.536	36	6	Annual layer (Straticounter)	✓
25.043	37	6	Annual layer (Straticounter)	✓
25.761	38	6	Annual layer (Straticounter)	✓
26.200	39	6	Annual layer (Straticounter)	✓
26.633	40	6	Annual layer (Straticounter)	✓
27.166	41	7	Annual layer (Straticounter)	✓
27.510	42	7	Annual layer (Straticounter)	✓
27.849	43	7	Annual layer (Straticounter)	✓

Supplementary Table 2 (part 2): Time markers employed in the revised chronology (this work).

Depth in core #2 (m w.e.)	Age (yrsb2012)	Age uncertainty (years)	Type of time marker	Used in COPRA model
28.550	44	7	Annual layer (Straticounter)	✓
28.880	45	6	Annual layer (Straticounter)	✓
29.307	46	5	Annual layer (Straticounter)	✓
29.573	47	4	Annual layer (Straticounter)	✓
29.985	48	3	Annual layer (Straticounter)	✓
30.327	49	2	Annual layer (Straticounter) and 1963 tritium beta peaks	✓
30.802	50	3	Annual layer (Straticounter)	✓
31.295	51	4	Annual layer (Straticounter)	✓
31.599	52	5	Annual layer (Straticounter)	✓
31.966	53	6	Annual layer (Straticounter)	✓
32.334	54	5	Annual layer (Straticounter)	✓
32.775	55	4	Annual layer (Straticounter)	✓
33.118	56	3	Annual layer (Straticounter)	✓
33.496	57	2	Annual layer (Straticounter) and 1955 start of beta peak	✓
33.964	58	3	Annual layer (Straticounter)	✓
34.427	59	4	Annual layer (Straticounter)	✓
34.710	60	5	Annual layer (Straticounter)	✓
35.061	61	6	Annual layer (Straticounter)	✓
35.399	62	7	Annual layer (Straticounter)	✓
35.549	63	8	Annual layer (Straticounter)	✓
35.819	64	8	Annual layer (Straticounter)	✓
36.153	65	8	Annual layer (Straticounter)	✓
36.603	66	8	Annual layer (Straticounter)	✓
36.831	67	8	Annual layer (Straticounter)	✓
37.014	68	8	Annual layer (Straticounter)	✓
37.252	69	8	Annual layer (Straticounter)	✓
37.468	70	9	Annual layer (Straticounter)	✓
37.675	71	9	Annual layer (Straticounter)	✓
38.002	72	9	Annual layer (Straticounter)	✓
38.244	73	9	Annual layer (Straticounter)	✓
38.503	74	8	Annual layer (Straticounter)	✓
38.819	75	8	Annual layer (Straticounter)	✓
39.020	76	9	Annual layer (Straticounter)	✓
39.227	77	9	Annual layer (Straticounter)	✓
39.391	78	9	Annual layer (Straticounter)	✓
39.739	79	9	Annual layer (Straticounter)	✓
39.977	80	10	Annual layer (Straticounter)	✓
40.171	81	10	Annual layer (Straticounter)	✓
40.329	82	10	Annual layer (Straticounter)	✓
40.533	83	9	Annual layer (Straticounter)	✓
40.796	84	9	Annual layer (Straticounter)	✓
40.966	85	9	Annual layer (Straticounter)	✓

Supplementary Table 2 (part 3): Time markers employed in the revised chronology (this work).

Depth in core #2 (m w.e.)	Age (yrsb2012)	Age uncertainty (years)	Type of time marker	Used in COPRA model
41.227	86	10	Annual layer (Visual counting)	*X*
41.354	87	10	Annual layer (Visual counting)	*X*
41.509	88	10	Annual layer (Visual counting)	*X*
41.677	89	10	Annual layer (Visual counting)	*X*
41.834	90	10	Annual layer (Visual counting)	*X*
41.885	91	10	Annual layer (Visual counting)	*X*
42.037	92	10	Annual layer (Visual counting)	*X*
42.188	93	10	Annual layer (Visual counting)	*X*
42.367	94	10	Annual layer (Visual counting)	*X*
42.511	95	10	Annual layer (Visual counting)	*X*
42.595	96	10	Annual layer (Visual counting)	*X*
42.732	97	10	Annual layer (Visual counting)	*X*
42.911	98	10	Annual layer (Visual counting)	*X*
43.092	99	10	Annual layer (Visual counting)	*X*
43.311	100	10	Annual layer (Visual counting)	*X*
43.410	101	10	Annual layer (Visual counting)	*X*
43.566	102	10	Annual layer (Visual counting)	*X*
43.739	103	10	Annual layer (Visual counting)	*X*
43.851	104	10	Annual layer (Visual counting)	*X*
44.061	105	10	Annual layer (Visual counting)	*X*
44.247	106	10	Annual layer (Visual counting)	*X*
44.397	107	10	Annual layer (Visual counting)	*X*
44.569	108	10	Annual layer (Visual counting)	*X*
44.728	*109*	*10*	Annual layer (Visual counting)	*Averaged*
44.836	*110*	*10*	Annual layer (Visual counting)	*Averaged*
44.951	*111*	*10*	Annual layer (Visual counting)	*Averaged*
45.023	*112*	*10*	Annual layer (Visual counting)	*Averaged*
45.342	*103*	*10*	Pb tie point with SZ core	*Averaged*
46.049	*112*	*11*	Pb tie point with SZ core	*Averaged*
45.155	109.5	10	Average of the previous 6 values	✓
47.408	155	16	Pb tie point with SZ core	✓
48.393	194	19	Pb tie point with SZ core	✓
49.207	241	24	Pb tie point with SZ core	✓
49.481	259	26	Pb tie point with SZ core	✓
49.998	280	28	Pb tie point with SZ core	✓
51.053	339	34	Pb tie point with SZ core	✓
51.691	385	38	Pb tie point with SZ core	✓
52.266	450	45	Pb tie point with SZ core	✓
52.622	478	48	Pb tie point with SZ core	✓
53.926	655	65	Pb tie point with SZ core	✓
55.228	907	91	Pb tie point with SZ core	✓
55.710	1000	100	Pb tie point with SZ core	✓
56.141	1108	111	Pb tie point with SZ core	✓
56.921	1247	125	Pb tie point with SZ core	✓
57.363	1368	137	Pb tie point with SZ core	✓
58.020	*1610*	*161*	*Pb tie point with SZ core*	*Averaged*
58.172	*1706*	*171*	*Pb tie point with SZ core*	*Averaged*
58.400	*1570*	*288*	*^{14}C in bulk*	*Averaged*
58.197	1629	70	Average of the previous three values	✓
58.850	2244	126	^{14}C in macrofragment	*Averaged*
58.888	2013	201	Pb tie point with SZ core	*Averaged*
59.044	2083	208	Pb tie point with SZ core	*Averaged*
58.927	2113	119	Average of the previous three values	✓
59.470	2671	102	^{14}C in macrofragment	✓
60.288	4233	524	^{14}C in bulk	✓
60.510	5238	531	^{14}C in bulk	✓
60.712	6801	364	^{14}C in bulk	✓

Supplementary references

- Brugger, S. O., Schwikowski, M., Gobet, E., Schwörer, C., Rohr, C., Sigl, M., Henne, S., Pfister, C., Jenk, T. M., Henne, P. D., and Tinner, W.: Alpine Glacier Reveals Ecosystem Impacts of Europe's Prosperity and Peril Over the Last Millennium, Geophysical Research Letters, 48, e2021GL095039, https://doi.org/10.1029/2021GL095039, 2021.
- Gabrielli, P., Barbante, C., Bertagna, G., Bertó, M., Binder, D., Carton, A., Carturan, L., Cazorzi, F., Cozzi, G., Dalla Fontana, G., Davis, M., De Blasi, F., Dinale, R., Dragà, G., Dreossi, G., Festi, D., Frezzotti, M., Gabrieli, J., Galos, S., Ginot, P., Heidenwolf, P., Jenk, T. M., Kehrwald, N., Kenny, D., Magand, O., Mair, V., Mikhalenko, V. N., Lin, P. N., Oeggl, K., Piffer, G., Rinaldi, M., Schotterer, U., Schwikowski, M., Seppi, R., Spolaor, A., Stenni, B., Tonidandel, D., Uglietti, C., Zagorodnov, V. S., Zanoner, T., and Zennaro, P.: Age of the Mt. Ortles ice cores, the Tyrolean Iceman and glaciation of the highest summit of South Tyrol since the Northern Hemisphere Climatic Optimum, The Cryosphere, 10, 2779–2797, 10.5194/tc-10-2779-2016, 2016.
- Jenk, T. M., Szidat, S., Bolius, D., Sigl, M., Gäggeler, H. W., Wacker, L., Ruff, M., Barbante, C., Boutron, C. F., and Schwikowski, M.: A novel radiocarbon dating technique applied to an ice core from the Alps indicating late Pleistocene ages J. Geophys. Res. Atmos., 114, 10.1029/2009JD011860, 2009.
- Sigl, M., Abram, N. J., Gabrieli, J., Jenk, T. M., Osmont, D., and Schwikowski, M.: 19th century glacier retreat in the Alps preceded the emergence of industrial black carbon deposition on high-alpine glaciers, The Cryosphere, 12, 3311-3331, 10.5194/tc-12-3311-2018, 2018.
- Sigl, M., Jenk, T. M., Kellerhals, T., Szidat, S., Gäggeler, H. W., Wacker, L., Synal, H. A., Boutron, C. F., Barbante, C., Gabrieli, J., and Schwikowski, M.: Intruments and methods: towards radiocarbon dating of ice cores, J. Glaciol., 55, 985-996, 2009.