Supplementary information

Immediate temperature response in northern Iberia to last deglacial changes in the North Atlantic

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1. Cave setting, present-day climate and monitoring survey

Ostolo cave is located at 248 m a.s.l. in the Bidasoa river valley (43°11'16"N, 1°43'56"W) near Arantza village, which is located in the easternmost part of the Cantabrian mountain range (Basque Mountains), Western Pyrenees, North Spain (Fig.1). Its main summits are Auza (1305 m), Iparla (1049 m), Legate (870 m), Mendaur (1131 m), Erakurri (1142 m), Mandoegi (1046 m), Peñas de Aia (832 m) and Larrun (900 m). Although these mountains have a moderate altitude, it is an area with a very high altitudinal differences, sometimes exceeding 1,000 m. Due to the moderate altitude of the mountains, the transition from the rainy oceanic climate to the drier Mediterranean climate is gradual, giving rise to numerous intermediate climatic nuances. The accumulated annual rainfall varies between 900 mm south of the Urbasa mountain range and 2500 mm in the wettest areas. The mean annual air temperature ranges between 14.5°C in the temperate zones of the Cantabrian valleys and 8.5°C in the coldest areas of the interior.

Ostolo cave developed in Carboniferous shallow-marine limestones of the Cinco Villas Massif at 22 km southeast of the Atlantic coast. The host rock has a U concentration of 200-300 ppb, associated to a high organic content. The cave is located in a region characterized by an oceanic climate (*Cfb* type of the Köppen climate classification) with a dominant influence of the Atlantic, with temperate summers (18-20°C average) and rain distributed throughout the year, and no dry season (Fig. S1). Average annual rainfall is significant, exceeding 2000 mm. The mean annual temperature outside the cave is close to 13.5 °C (Fig. S1). The vegetation in the cave area is a dense forest mainly composed of oak (*Quercus robur* and *Quercus pyrenaica*), some alder (*Alnus glutinosa*) and beech (*Fagus sylvatica*). Atlantic-type polycultures, dry farming, mowing meadows, ferns (*Pteridophyta*) and heaths (*Ericaceae*) are abundant.

The cave is 631 m long and has a vertical extent of 39 m (Fig. S2). The only entrance is formed by a short (0.5 – 1 m) and narrow passage (~1 m) with a permanent water outflow, making impossible the access and monitoring during rainy days (which is quite common due to the high frequency of rainfall; Fig. S1). The cave passages exhibit an elongated branchwork pattern, where diagnostic morphologies of paragenetic processes such as roof pendants, ceiling channels, anastomotic bedding planes, and fluviokarstic sediments filling the conduits are present. The temperature inside the cave varies between 13-14°C (monitoring period covering from September 2018 to January 2020) without a clear seasonal pattern.

Drip water samples from 5 different drip sites were analyzed for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ (Table S1, Fig. S2). $\delta^{18}\text{O}$ values in the dripwaters are very stable during the year (with values that vary between -6.09 and -6.58‰), without a clear seasonality according to outside temperature indicating that the signal has been homogenized in the epikarst. The difference within summer values (July 2020) and winter or fall values (Sept 2019 and Jan 2020) is too small (0.2 – 0.3‰) to be considered it as a response to seasonal

temperature change. $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of the stream at the cave entrance are -6.87‰ and -40.3‰, respectively (sampled in fall 2018).

Figure S1. Climate diagram of the Artikutza weather station located 6 km from the cave site. Data interval: 1931-2018. Light blue bars: Monthly precipitation, blue line: minimum average monthly temperature, orange line: mean average monthly temperature, red line: maximum average monthly temperature. Data source: Government of Navarre.

Table S1. Drip water samples analyzed to determine the variations of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ from 5 different drip sites (7A, 7B, 7C, 14 and 21) in 3 different cave galleries, including the one from where the stalagmites analyzed in this work were obtained.

Drips OSTOLO	$\delta^{18}\text{O}$ (‰)	$\delta^2\text{H}$ (‰)
OST 7A September 2019	-6,53	-39,39
OST 7A January 2020	-6,58	-40,46
OST 7A July 2020	-6,40	-39,24
OST 7B September 2019	-6,47	-39,18
OST 7B January 2020	-6,47	-39,44
OST 7B July 2020	-6,31	-38,24
OST 7C September 2019	-6,58	-40,40
OST 7C January 2020	-6,43	-39,57
OST 7C July 2020	-6,30	-38,37
OST 14 September 2019	-6,32	-38,11
OST 14 January 2020	-6,30	-38,16
OST 14 July 2020	-6,40	-38,62
OST 21 September 2019	-6,24	-37,55
OST 21 January 2020	-6,48	-39,43
OST 21 July 2020	-6,09	-37,14

Two glass plates were recovered, and farmed calcite was analyzed from the only one gallery with present active calcite precipitation inside the cave (Fig. S2). The first sample corresponds to a year of farmed calcite (2018-2019), while the second one was kept during the winter and spring months, from December 2019 to July 2020. The results indicate similar values in $\delta^{18}\text{O}$ (-5.06‰ for the annual sample and -4.94‰ for the second sample). These values support our interpretation of $\delta^{18}\text{O}$ as annual signal since calcite is precipitating throughout the year, at least at present-day. Additionally, current $\delta^{18}\text{O}$ calcite values are more positive (warmer) than previous periods (colder) of the last glacial (eg. GS-1 or GS-2a), in clear coherence with our interpretation of Ostolo $\delta^{18}\text{O}$ record as an air temperature proxy. Three stalagmites (next to each other) were extracted from the same gallery (Fig. S2).

Figure S2. Plan view (top panel) and vertical section (bottom panel) of Ostolo cave. Locations where speleothems were extracted are marked in red (OST1, OST2 and OST3). Sites where host rock, drip water and farmed calcite were sampled and air temperature was logged are marked. Cave survey map courtesy of Santez, K., Garcia, C., Ferreira, C., and del Cura, N. (Aranzadi Speleological Group).

2. Materials and methods

The three stalagmites (OST1, OST2 and OST3) cover almost the same time interval and share the same macroscopic features. OST-2 is the focus of this study, and OST-1 and OST-3 were analyzed for

replication (Table S2). The stalagmites were collected under non-active drips and were sectioned along their central growth axis to obtain a pair of slabs per stalagmite, which were subsequently polished. One of the slabs was used for chronological and isotopic results, while petrological analyses (thin sections) were performed on the other half (Fig. S3). In order to identify the presence of hiatuses and examine textural changes along the three speleothems, 46 thin sections were made (17 in OST1, 16 in OST2 and 13 for OST3) and analyzed using optical microscopy. The code for the different fabrics and the construction of a petrographic log (Frisia, 2015) is simplified and follows Muñoz-García et al. (2016). The observed fabric is columnar and corresponds to elongated (Ce), compact (C) and microcrystalline (Cm) types.

A total of 61 powder samples were collected for U-Th dates from the three stalagmites (17 samples of OST1, 26 of OST2 and 18 of OST3 - Fig. S4). The samples were taken with a handheld drill and a tungsten carbide drill bit. The analyses were performed using a MC-ICP-MS (Thermo-Finnigan Neptune) at the University of Xi'an and the University of Minnesota, following previously described methods (Cheng et al., 2013). To calculate the corrected ages in conjunction with the decay constant (Cheng et al., 2013) an initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$ was used (Table S2). The high U content (10-80 ppm) leads to very low errors in the obtained dates. The ages obtained span the Lateglacial until the onset of the Holocene. This work focuses on the last deglaciation. The age models are built using StalAge (Scholz and Hoffmann, 2011).

A total of 1234 $\delta^{18}\text{O}$ samples were collected along the central axis at 300 μm increments for OST2 and OST3. In the case of OST1, the samples were taken at 5 mm increments. Isotopic analyses were performed in the University of Innsbruck, using a ThermoFisher Delta V Plus linked to a GasBench II, following the methodology described in Spötl (2011). The long-term reproducibility (1 sigma) of the $\delta^{18}\text{O}$ analyses is 0.08‰ (Spötl, 2011). All the values are reported as $\delta^{18}\text{O}$ 'per mille' (‰) with respect to the Vienna Pee Dee Belemnite standard (VPDB). The $\delta^{18}\text{O}_{\text{speleo}}$ values were corrected for the ice-volume effect following Bintanja et al. (2005) (Fig. S5).

Table S2. ^{230}Th dating results (2σ error). U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013). * $\delta^{234}\text{U} = ([^{234}\text{U}/^{238}\text{U}]_{\text{activity}} - 1) \times 1000$. ** $\delta^{234}\text{U}_{\text{initial}}$ was calculated based on ^{230}Th age (T), i.e., $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{\lambda_{234} \times T}$. Corrected ^{230}Th ages assume the initial $^{230}\text{Th}/^{232}\text{Th}$ atomic ratio of $4.4 \pm 2.2 \times 10^{-6}$. Those are the values for a material at secular equilibrium, with the bulk earth $^{232}\text{Th}/^{238}\text{U}$ value of 3.8. The errors are arbitrarily assumed to be 50%. ***B.P. stands for "Before Present" where the "Present" is defined as the year 1950 A.D.

Sample Number	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th/ ²³² Th (atomic x10 ⁻⁶)	δ ²³⁴ U* (measured)	²³⁰ Th/ ²³⁸ U (activity)	²³⁰ Th Age (yr) (uncorrected)	²³⁰ Th Age (yr) (corrected)	δ ²³⁴ U _{initial} ** (corrected)	²³⁰ Th Age (yr BP)***
OST1-0	13945.1 ±26.3	5698 ±122	6334 ±136	-9.1 ±1.4	0.1570 ±0.0005	18809 ±74	18797 ±75	-10 ±1	18727 ±75
OST1-25	16910.5 ±33.6	2623 ±66	16019 ±405	-9.8 ±1.5	0.1507 ±0.0005	18008 ±67	18004 ±67	-10 ±2	17934 ±67
OST1-40	18546.4 ±37.2	525 ±40	86759 ±6662	-10.1 ±1.5	0.1490 ±0.0005	17795 ±69	17794 ±69	-11 ±2	17724 ±69
OST1-60	16650.8 ±34.4	1148 ±45	34136 ±1354	-12.9 ±1.8	0.1428 ±0.0005	17042 ±69	17040 ±69	-14 ±2	16970 ±69
OST1-95	24753.8 ±50.3	4390 ±97	12652 ±281	-9.8 ±1.5	0.1361 ±0.0004	16126 ±57	16121 ±57	-10 ±2	16051 ±57
OST1-112	25552.9 ±52.0	1166 ±46	47967 ±1880	-11.5 ±1.4	0.1328 ±0.0004	15734 ±56	15733 ±56	-12 ±1	15663 ±56
OST1-120	18286.7 ±36.2	1154 ±46	34379 ±1359	-8.8 ±1.5	0.1316 ±0.0005	15539 ±63	15537 ±63	-9 ±2	15467 ±63
OST1-150	12432.3 ±29.3	292 ±10	89161 ±2977	-8.9 ±1.5	0.1269 ±0.0004	14946 ±52	14945 ±52	-9 ±2	14875 ±52
OST1-210	13435.8 ±26.7	658 ±41	40454 ±2531	-8.0 ±1.6	0.1202 ±0.0004	14085 ±57	14084 ±57	-8 ±2	14014 ±57
OST1-245	17304.5 ±34.9	296 ±39	114524 ±15177	-12.4 ±1.6	0.1189 ±0.0004	13997 ±53	13996 ±53	-13 ±2	13926 ±53
OST1-275	4872.4 ±7.1	479 ±14	20443 ±609	-6.2 ±1.6	0.1219 ±0.0005	14268 ±70	14265 ±70	-7 ±2	14195 ±70
OST1-294	18944.7 ±37.2	871 ±43	40784 ±2006	-10.3 ±1.4	0.1137 ±0.0004	13315 ±49	13314 ±49	-11 ±1	13244 ±49
OST1-305	17151.9 ±33.3	1535 ±50	20714 ±677	-4.7 ±1.3	0.1124 ±0.0004	13073 ±49	13070 ±49	-5 ±1	13000 ±49
OST1-315	11717.0 ±22.4	658 ±41	30632 ±1918	-3.5 ±1.3	0.1043 ±0.0004	12059 ±51	12057 ±51	-4 ±1	11987 ±51
OST1-325	10580.9 ±20.6	1069 ±45	16335 ±685	-1.9 ±1.4	0.1001 ±0.0004	11522 ±52	11519 ±52	-2 ±1	11449 ±52
OST1-335	6405.7 ±9.8	486 ±15	22980 ±710	-0.6 ±1.3	0.1057 ±0.0003	12191 ±41	12189 ±41	-1 ±1	12119 ±41
OST1-350	6592.3 ±12.7	6919 ±145	1251 ±27	-0.8 ±1.5	0.0796 ±0.0005	9056 ±58	9025 ±62	-1 ±2	8955 ±62
OST1-360	4098.0 ±14.2	5531 ±112	234 ±5	24.6 ±1.9	0.0192 ±0.0001	2061 ±9	2022 ±29	25 ±2	1952 ±29
OST2-1	31476.0 ±86.2	1016 ±22	78800 ±1736	-11.1 ±1.6	0.1542 ±0.0005	18495 ±71	18494 ±71	-12 ±2	18424 ±71
OST2-3	50121.6 ±100.2	1516 ±54	79603 ±2819	-9.1 ±1.1	0.1460 ±0.0005	17388 ±62	17387 ±62	-10 ±1	17317 ±62
OST2-5	76331.7 ±186.3	4690 ±103	39563 ±873	-11.8 ±1.5	0.1474 ±0.0005	17626 ±72	17624 ±72	-12 ±2	17554 ±72
OST2-10	35554.0 ±55.6	2941 ±67	29666 ±675	-10.9 ±1.3	0.1488 ±0.0004	17788 ±55	17786 ±55	-11 ±1	17716 ±55
OST2-15	40467.9 ±85.7	874 ±43	111812 ±5486	-12.6 ±1.3	0.1464 ±0.0004	17505 ±61	17504 ±61	-13 ±1	17434 ±61
OST2-21	33913.7 ±73.6	1436 ±49	56448 ±1920	-11.2 ±1.3	0.1450 ±0.0004	17298 ±61	17297 ±61	-12 ±1	17227 ±61
OST2-26	32110.3 ±52.4	1838 ±48	41318 ±1088	-9.4 ±1.3	0.1434 ±0.0004	17062 ±53	17060 ±53	-10 ±1	16990 ±53
OST2-31	4246.7 ±4.5	179 ±4	56335 ±1187	-12.2 ±1.3	0.1444 ±0.0002	17239 ±36	17238 ±36	-13 ±1	17168 ±36
OST2-36	48396.3 ±89.3	1426 ±49	80626 ±2790	-9.0 ±1.1	0.1441 ±0.0004	17139 ±58	17138 ±58	-9 ±1	17068 ±58
OST2-40	80881.7 ±199.9	2557 ±65	78544 ±2006	-12.1 ±1.4	0.1506 ±0.0005	18042 ±69	18042 ±69	-13 ±2	17972 ±69
OST2-48	48083.7 ±78.3	2060 ±54	56423 ±1473	-10.5 ±1.1	0.1466 ±0.0004	17488 ±52	17486 ±52	-11 ±1	17416 ±52
OST2-55	57952.4 ±136.8	2679 ±67	52051 ±1308	-12.1 ±1.4	0.1459 ±0.0005	17434 ±68	17433 ±68	-13 ±2	17363 ±68
OST2-67	50486.5 ±102.1	1387 ±52	84878 ±3166	-9.7 ±1.2	0.1414 ±0.0004	16804 ±59	16803 ±59	-10 ±1	16733 ±59
OST2-77	49254.2 ±106.2	967 ±44	119564 ±5404	-13.1 ±1.2	0.1424 ±0.0004	16996 ±60	16996 ±60	-14 ±1	16926 ±60
OST2-85	28308.6 ±64.1	1106 ±23	59173 ±1252	-10.5 ±1.4	0.1402 ±0.0004	16665 ±53	16664 ±53	-11 ±1	16594 ±53
OST2-102	25135.9 ±61.3	981 ±21	58713 ±1237	-11.7 ±1.3	0.1389 ±0.0004	16525 ±55	16524 ±55	-12 ±1	16454 ±55
OST2-114	24161.3 ±32.5	2136 ±50	25557 ±596	-12.1 ±1.2	0.1370 ±0.0003	16288 ±43	16286 ±43	-13 ±1	16216 ±43
OST2-118	7312.6 ±11.4	316 ±8	51897 ±1345	-11.9 ±1.3	0.1362 ±0.0003	16175 ±42	16174 ±42	-12 ±1	16104 ±42
OST2-121	18919.3 ±20.3	1023 ±26	41362 ±1044	-12.0 ±1.2	0.1357 ±0.0002	16112 ±39	16110 ±39	-13 ±1	16040 ±39
OST2-135	11553.1 ±22.5	1234 ±46	20411 ±769	-11.5 ±1.5	0.1323 ±0.0005	15668 ±64	15665 ±64	-12 ±2	15595 ±64
OST2-145	17536.3 ±24.2	482 ±16	78095 ±2640	-12.2 ±1.5	0.1303 ±0.0003	15430 ±43	15429 ±43	-13 ±2	15359 ±43
OST2-146.5	12231.5 ±16.3	803 ±24	32498 ±986	-14.5 ±1.5	0.1294 ±0.0003	15360 ±43	15358 ±43	-15 ±2	15288 ±43
OST2-148	785.9 ±0.8	68 ±3	24705 ±975	-13.0 ±1.5	0.1290 ±0.0004	15284 ±53	15282 ±53	-14 ±2	15212 ±53
OST2-150	8896.1 ±11.2	879 ±26	21355 ±633	-14.4 ±1.5	0.1280 ±0.0003	15172 ±45	15169 ±45	-15 ±1	15099 ±45
OST2-152	8432.8 ±11.7	1573 ±38	11215 ±270	-10.3 ±1.5	0.1269 ±0.0003	14963 ±49	14957 ±49	-11 ±2	14887 ±49
OST2-154	5790.2 ±8.8	1390 ±29	8642 ±178	-7.8 ±1.4	0.1258 ±0.0003	14791 ±39	14784 ±40	-8 ±1	14714 ±40
OST2-156	19857.7 ±27.2	979 ±28	41481 ±1201	-12.7 ±1.3	0.1241 ±0.0003	14650 ±38	14649 ±38	-13 ±1	14579 ±38
OST2-158	9150.5 ±12.6	1084 ±28	17173 ±452	-13.1 ±1.4	0.1234 ±0.0003	14572 ±43	14568 ±43	-14 ±1	14498 ±43
OST2-159.5	12707.2 ±16.7	672 ±25	38115 ±1416	-20.6 ±1.2	0.1222 ±0.0003	14537 ±40	14535 ±40	-21 ±1	14465 ±40
OST2-170	7862.1 ±11.6	539 ±12	28933 ±654	-11.3 ±1.2	0.1203 ±0.0003	14154 ±37	14152 ±37	-12 ±1	14082 ±37
OST2-183	6584.3 ±9.1	612 ±15	20511 ±505	-12.3 ±1.4	0.1156 ±0.0003	13580 ±42	13577 ±42	-13 ±1	13507 ±42
OST2-200	13287.3 ±25.3	3513 ±81	6911 ±161	-7.8 ±1.3	0.1108 ±0.0004	12917 ±52	12910 ±52	-8 ±1	12840 ±52
OST2-202	5138.8 ±6.4	333 ±9	28084 ±742	-7.0 ±1.1	0.1104 ±0.0002	12852 ±31	12850 ±31	-7 ±1	12780 ±31
OST2-204	6619.7 ±12.3	268 ±39	44587 ±6509	-7.1 ±1.3	0.1096 ±0.0005	12762 ±66	12760 ±66	-7 ±1	12690 ±66
OST2-215	10442.1 ±15.5	365 ±10	50260 ±1383	-5.7 ±1.3	0.1066 ±0.0002	12370 ±33	12369 ±33	-6 ±1	12299 ±33
OST2-222	25413.3 ±51.7	1275 ±47	33859 ±1246	-6.9 ±1.3	0.1031 ±0.0003	11949 ±42	11947 ±42	-7 ±1	11877 ±42
OST2-230	15824 ±30.7	1078 ±45	24977 ±1039	-3.1 ±1.2	0.1032 ±0.0004	11916 ±46	11914 ±46	-3.2 ±1.2	11844 ±46
OST2-235	18403 ±36.2	1298 ±47	23934 ±875	-5.2 ±1.2	0.1024 ±0.0005	11846 ±62	11844 ±62	-5.3 ±1.3	11774 ±62
OST2-244	6525 ±12.1	891 ±43	12251 ±594	-3.0 ±1.2	0.1014 ±0.0005	11699 ±66	11695 ±66	-3.1 ±1.3	11625 ±66
OST2-247	7320.0 ±11.3	517 ±12	23749 ±540	-3.2 ±1.3	0.1016 ±0.0002	11727 ±31	11725 ±31	-3 ±1	11655 ±31
OST2-249	11260 ±21.3	900 ±43	20961 ±1005	-2.7 ±1.1	0.1016 ±0.0004	11715 ±49	11713 ±49	-2.8 ±1.2	11643 ±49
OST2-258	8664.5 ±10.9	467 ±12	30290 ±785	-3.0 ±1.2	0.0990 ±0.0002	11407 ±31	11405 ±31	-3 ±1	11335 ±31
OST2-272	5535.4 ±6.1	243 ±9	35821 ±1328	-3.1 ±1.2	0.0953 ±0.0003	10957 ±41	10955 ±41	-3 ±1	10885 ±41
OST2-292	4103.4 ±4.3	1310 ±27	2231 ±48	15.4 ±1.3	0.0432 ±0.0002	4738 ±25	4729 ±25	16 ±1	4659 ±25
OST2-306	2998.8 ±2.9	372 ±10	4839 ±132	21.7 ±1.4	0.0364 ±0.0002	3960 ±26	3957 ±26	22 ±1	3887 ±26
OST2-314	2315.4 ±3.1	1400 ±28	805 ±17	21.8 ±1.2	0.0295 ±0.0001	3198 ±13	3181 ±18	22 ±1	3111 ±18

Sample Number	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th/ ²³² Th (atomic x10 ⁻⁶)	δ ²³⁴ U* (measured)	²³⁰ Th/ ²³⁸ U (activity)	²³⁰ Th Age (yr) (uncorrected)	²³⁰ Th Age (yr) (corrected)	δ ²³⁴ U _{initial} ** (corrected)	²³⁰ Th Age (yr BP)***
OST3-0	29186.0 ±73.5	1460 ±30	50200 ±1042	-7.6 ±1.4	0.1523 ±0.0005	18171 ±69	18169 ±69	-8 ±2	18099 ±69
OST3-5	26192.5 ±52.6	1994 ±56	32258 ±913	-6.5 ±1.3	0.1489 ±0.0004	17714 ±61	17712 ±61	-7 ±1	17642 ±61
OST3-9	42178.0 ±86.1	1100 ±45	98238 ±4021	-10.1 ±1.2	0.1554 ±0.0004	18620 ±63	18620 ±63	-11 ±1	18550 ±63
OST-17	54149.9 ±114.6	878 ±43	151284 ±7394	-9.2 ±1.2	0.1487 ±0.0004	17737 ±62	17736 ±62	-10 ±1	17666 ±62
OST3-25	30498.0 ±88.8	891 ±20	81869 ±1802	-6.4 ±1.7	0.1451 ±0.0005	17214 ±69	17213 ±69	-7 ±2	17143 ±69
OST3-32	22635.9 ±54.6	5894 ±119	9121 ±186	-5.7 ±1.5	0.1441 ±0.0005	17069 ±67	17061 ±67	-6 ±2	16991 ±67
OST3-41	21421.6 ±47.1	1065 ±23	46071 ±989	-6.4 ±1.5	0.1389 ±0.0004	16425 ±56	16424 ±56	-7 ±2	16354 ±56
OST3-47	17283.3 ±40.0	503 ±12	69356 ±1722	-9.1 ±1.5	0.1225 ±0.0004	14392 ±52	14391 ±52	-9 ±2	14321 ±52
OST3-60	9861.8 ±18.1	604 ±15	32049 ±793	-9.0 ±1.6	0.1191 ±0.0003	13969 ±45	13967 ±45	-9 ±2	13897 ±45
OST3-70	7803.6 ±12.6	506 ±13	29520 ±732	-7.1 ±1.6	0.1162 ±0.0003	13574 ±42	13572 ±42	-7 ±2	13502 ±42
OST3-94	6989.3 ±9.8	7901 ±159	1621 ±33	-6.3 ±1.4	0.1111 ±0.0003	12936 ±39	12903 ±45	-7 ±1	12833 ±45
OST3-100	12121.5 ±26.7	1570 ±33	12782 ±267	-2.8 ±1.7	0.1004 ±0.0003	11570 ±40	11566 ±40	-3 ±2	11496 ±40
OST3-122	12030.7 ±25.8	464 ±12	42498 ±1068	-2.3 ±1.6	0.0995 ±0.0003	11452 ±38	11451 ±38	-2 ±2	11381 ±38
OST3-138	9366.1 ±17.6	404 ±12	37557 ±1092	-1.6 ±1.6	0.0982 ±0.0003	11294 ±37	11293 ±37	-2 ±2	11223 ±37
OST3-145	7115.4 ±13.7	485 ±14	23515 ±659	-4.2 ±1.8	0.0972 ±0.0003	11202 ±41	11200 ±41	-4 ±2	11130 ±41
OST3-151	6482.9 ±10.1	496 ±11	20719 ±478	-5.1 ±1.4	0.0961 ±0.0003	11081 ±36	11079 ±36	-5 ±1	11009 ±36
OST3-157	7661.7 ±15.4	2644 ±54	4541 ±92	-3.0 ±1.7	0.0951 ±0.0003	10927 ±37	10917 ±38	-3 ±2	10847 ±38
OST3-162	5432.6 ±6.4	1674 ±34	4805 ±99	-1.9 ±1.3	0.0898 ±0.0002	10280 ±32	10271 ±32	-2 ±1	10201 ±32
OST3-171	4434.4 ±7.8	769 ±16	8170 ±176	0.1 ±1.6	0.0859 ±0.0003	9797 ±37	9792 ±37	0 ±2	9722 ±37
OST3-180	1857.2 ±1.9	1125 ±23	2192 ±46	2.8 ±1.3	0.0806 ±0.0003	9132 ±43	9114 ±44	3 ±1	9044 ±44
OST3-192	3852.3 ±4.4	4024 ±81	1139 ±23	6.7 ±1.3	0.0722 ±0.0003	8112 ±36	8082 ±42	7 ±1	8012 ±42
OST3-201	3252.9 ±5.0	1525 ±31	2211 ±46	10.2 ±1.5	0.0629 ±0.0003	7005 ±36	6992 ±37	10 ±2	6922 ±37
OST3-212	3259.3 ±3.2	1331 ±27	2253 ±47	14.3 ±1.1	0.0558 ±0.0002	6170 ±26	6158 ±27	15 ±1	6088 ±27
OST3-216	5119.0 ±9.7	411 ±10	4947 ±125	27.1 ±1.6	0.0241 ±0.0001	2590 ±15	5121 ±37	27 ±2	5051 ±37
OST3-220	3727.6 ±4.9	2127 ±43	1248 ±26	21.1 ±1.3	0.0432 ±0.0002	4713 ±23	4697 ±26	21 ±1	4627 ±26
OST3-229	2828.3 ±2.7	1137 ±25	1461 ±33	19.8 ±1.3	0.0356 ±0.0003	3879 ±31	3867 ±32	20 ±1	3797 ±32
OST3-232	2881.0 ±4.0	878 ±19	2537 ±56	20.2 ±1.4	0.0469 ±0.0003	5129 ±36	2588 ±15	20 ±1	2518 ±15
OST3-247	4162.2 ±5.9	604 ±14	2260 ±53	23.9 ±1.4	0.0199 ±0.0002	2139 ±17	2135 ±17	24 ±1	2065 ±17
OST3-258	3623.6 ±9.8	3340 ±68	122 ±3	21.3 ±1.6	0.0068 ±0.0000	730 ±5	703 ±19	21 ±2	633 ±19

3. Calcite fabrics of the speleothems, growth rates and their relationship with isotopic and chronological results

The age models show a common growth period during last deglaciation in OST1 and OST2 (from 18.5 kyr BP to around 10.5 kyr BP), interrupted by two hiatuses in OST3 (Fig. S4). Higher growth rates were observed in OST2 during part of GS-2.1b, GS-2.1a and the end of GS-1 (Fig. S4). OST3 grew between 18.1 and 10.2 kyr with two hiatuses between 16.3-14.3 kyr BP and 12.8-11.5 kyr BP, corresponding to part of GS-2.1a and GS-1 (Fig. S4). Three dates of OST2, one of OST1 and two of OST3 from these stalagmites are out of stratigraphic order (Fig. S4). The sector where this problem appeared is composed of microcrystalline fabric (Cm) (Fig. S3).

To evaluate the likelihood of kinetic/vadose zone processes in the δ¹⁸O profiles we cannot provide any Hendy test since sampling along a single growth layer was flawed on OST stalagmites. Contrarily, we can provide good results from the “replication test” (Dorale and Liu, 2009) since the three stalagmites show very similar δ¹⁸O profiles. Additionally, once studied the calcite fabrics, we are able to discard the only sector with microcrystalline fabric (Cm) (Fig. S3), where δ¹⁸O variations could have been diagenetically modified.

The amplitude of δ¹⁸O in OST2 is around 5‰ with a mean of -5.3‰ (Fig. S4). OST1 and OST2 record the most negative values during GS-2.1 between 18.7 and 15 kyr BP with a negative spike at 16.2-16.0 kyr BP (-8.9 ‰), most positive values during GI-1 (14.9-12.9 kyr BP) and more negative values again during GS-1 (12.9-11.7 kyr BP). Less negative values are recorded at the onset of the Holocene (-4.02‰). The transition from GS-2.1b to GS-2.1a (17.5 kyr) is marked by a change from a variable drip rate (columnar microcrystalline [Cm]) to a more constant one (elongated columnar fabric 1 [Ce1]). GS-2.1a is recorded by more positive values with a mean of -4.23‰ (-3.5‰ uncorrected by ice volume change). After the large isotopic shift at 14.9 kyr the predominant fabric changes to elongated columnar type 2 (Ce2) with

a faster growth rate (from 10 $\mu\text{m}/\text{yr}$ in the end of the GS-2.1a, to 25-35 $\mu\text{m}/\text{yr}$ during the GI-1) (Fig. S3 and S4).

Figure S3. Slab of stalagmite OST2 and its microstratigraphic log (left side) showing changes in the type of fabric (Cm, columnar microcrystalline; C, columnar compact; Ce, columnar elongated [1 and 2]). Photomicrographs of thin sections are shown on the right side. [A] Hiatus in the upper area (serrated form) marking the base of the Holocene. [B] Compact columnar (C) fabric changing to the elongated type (Ce1) type. [C] Columnar elongate fabric with wide crystals (Ce2). [D] Columnar elongate fabric with small, thin, and elongated crystals (Ce1). [E] Microcrystalline fabric (Cm) with smaller crystals and irregular intercrystalline boundaries. Image A taken in plane-polarized light, and images B-E taken in cross-polarized light.

Figure S4. Depth-age models (gray lines and black dots with error bars), $\delta^{18}\text{O}$ data (red) and growth rate (light blue) of three stalagmites from Ostolo cave. A) OST1, B) OST2 and C) OST3. Red dots mark outliers.

Figure S5. $\delta^{18}\text{O}$ record of OST2 corrected for the global ice-volume effect following Bintanja et al. (2005).

4. Comparison with Greenland ice core (NGRIP) and regional speleothem records

Comparing OST2 speleothems with the NGRIP ice core record highlights the high synchrony among both records suggesting that the OST2 isotope signal is dominated by atmospheric temperature variability (Fig. S6).

Figure S6. Detailed comparison of the $\delta^{18}\text{O}$ records from NGRIP (Rasmussen et al., 2014) and Ostolo (OST2) cave for the last deglaciation. The time gap that exists between both records in the GI-1 onset is highlighted by a gray column.

There are slight differences in the timing between Ostolo and Greenland during GI-1. GI-1 starts in Ostolo 296 years before the onset in NGRIP, but this lag is almost included in the uncertainty of both age models. It is relevant to consider the low errors in OST2 U/Th dates for this abrupt change (± 40 yrs) in relation to the NGRIP chronology (± 186 yrs, Rasmussen et al., 2014). Additionally, the chronology of OST-2 for the onset of GI-1 interval is constrained by 9 dates allowing a robust age model for this part of the sequence.

Very few speleothem records are available for the last deglaciation interval in Europe. In Iberia, it is worth to highlight the record from Seso Cave in Central Pyrenees (Bartolomé et al., 2015; later improved by Cheng et al., 2020). The chronological control and high isotopic resolution of that record, in spite it only covers the GS-1 interval, indicates a high similarity with OST2 stalagmite (Fig. S7). Both records show a 2‰ $\delta^{18}\text{O}$ variation in GS-1, with more negative values in Seso cave (794 m a.s.l.) than in Ostolo cave (248 m a.s.l.). There is a clear synchrony in the timing of GS-1 and the onset of the Holocene with the NGRIP record (Rasmussen et al., 2014) (Fig. S6, S7 and S8) within their chronological uncertainties. The drop of nearly 2‰ at the start of the GS-1 and a similar rise at the onset of the Holocene (Fig. S7) is interpreted as a temperature change (see main text). A marked decrease in $\delta^{18}\text{O}$ values of 2.5‰ at the onset of GS-1 is also recorded in the Hölloch Cave of southern Germany (Li et al., 2020) (Fig. S8g).

Figure S7. Detailed comparison of the $\delta^{18}\text{O}$ records from Seso cave (Cheng et al., 2020) and the global ice volume corrected $\delta^{18}\text{O}$ values of Ostolo cave (OST2) at the GS-1.

Fig. S8 shows the available speleothems records from W Europe covering at least partially last deglaciation interval (Fig. 1 for caves location). The GAR-01 $\delta^{18}\text{O}$ record from La Garma Cave in NW

Iberia reveals shifts in oxygen isotope values that are interpreted as temperature variability, modified by seasonality changes in temperature and precipitation (Fig. S8c - Baldini et al., 2019). The presence of similar $\delta^{18}\text{O}$ values during warm periods of the Holocene and during the cold GS-1 led the authors to suggest that seasonality changes were responsible for part of $\delta^{18}\text{O}$ variability. The record from El Pindal Cave in NW Iberia (Fig. S8e) shows a constant and less clear signal, making it difficult to identify drastic changes during the last deglaciation. In this particular case, and in speleothem record from Chauvet Cave (Genty et al., 2006) from southern France (Fig. S8d), the complexity of competing factors (temperature vs. precipitation) makes it difficult to obtain unambiguous information from $\delta^{18}\text{O}$ values. Most interpretations are hence based on other geochemical indicators, such as $\delta^{13}\text{C}$ (Moreno et al., 2010). It is worth to note that both El Pindal and Chauvet records display more negative $\delta^{18}\text{O}$ values during warm/wet interstadials, thus pointing to the potential role of precipitation (note the reversed y-axis for better comparison in Fig. S8). The Meravelles cave located in the NE of the Iberian Peninsula provides another interesting recently published speleothem record (Pérez-Mejías et al., 2020) (Fig. S8f), where $\delta^{18}\text{O}$ signal is mostly influenced by hydrology. A small negative excursion at 16 ka BP in $\delta^{18}\text{O}$ values was interpreted to be produced by the entrance of freshened Atlantic waters as a consequence of massive discharge from the ice sheets. To complete the regional overview, we show here two records from the Alps. First, a recently published Hölloch record where $\delta^{18}\text{O}$ variability during the deglaciation is large and closely follows the NGRIP record (Li et al., 2020) (Fig. S8g). Stalagmites from the 7H cave system (Luetscher et al., 2015) record a rapid rise in $\delta^{18}\text{O}$ at the end of the GS-2.1a synchronous with Greenland and a growth stop at the onset of GI-1 (Fig. S8h). Finally, two $\delta^{18}\text{O}$ records from Italian caves which have limited resolution for the last deglaciation period are also presented for comparison (Frisia et al., 2005; Zanchetta et al., 2007; Fig. S8i, j).

Figure S8. (next page) Ostolo $\delta^{18}\text{O}$ records (a) compared to other speleothems records for the last deglaciation. (b) $\delta^{18}\text{O}$ record of Seso Cave, Pyrenees (Cheng et al., 2020); (c) GAR-01 $\delta^{18}\text{O}_{\text{speleo}}$ record from La Garma Cave (micromilled samples and laser ablation (orange dots) spots - Baldini et al., 2015); (d) $\delta^{18}\text{O}_{\text{speleo}}$ from the southern France (Genty et al., 2006) and (e) northern Iberia (Moreno et al., 2010); (f) $\delta^{18}\text{O}_{\text{speleo}}$ from Meravelles Cave, NE Spain (Pérez-Mejías et al., 2020); (g) HÖL22 and HÖL1 $\delta^{18}\text{O}_{\text{speleo}}$ records from the southern Germany (Li et al., 2020); (h) The $\delta^{18}\text{O}$ record of the 7H cave system, Switzerland (Luetscher et al., 2015); (i) The $\delta^{18}\text{O}_{\text{speleo}}$ from Grotta Savi (SV1 record), NE Italy (Frisia et al., 2005); (j) $\delta^{18}\text{O}_{\text{speleo}}$ from Grotta Antro del Corchia, central Italy (Zanchetta et al., 2007). Note that the y-axis amplitude is the same in all records. The y-axis is reversed for Chauvet, El Pindal, Meravelles, Corchia and Savi speleothems (combined effect of temperature and precipitation) to facilitate comparison with records from the Alps and the Pyrenees (which are temperature dominated).

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