Out-of-phase Late Pleistocene glacier maxima in the Western Alps reflect past changes in North Atlantic atmospheric circulation

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I. Geomorphic context and sedimentology

Geomorphic terrace and moraine classification

Previous studies have been conducted in the Lyon area and distinguished several substages associated with the IMC, based on glaciofluvial and moraine ridges stratigraphic correlations.

Mandier (1988) identified four Late Pleistocene glacial stages, from A to D, within the IMC, based on geomorphology and morphostratigraphy relationships between moraine ridges and glaciofluvial terraces. Stage A corresponds to the maximum ice extent (outermost and highest moraine ridge connected with the highest terrace level), and stage D corresponds to the smallest ice extent (inner and lowermost moraine ridge connected with the lowest terrace level).

Roattino et al. (2021) identified three main glaciofluvial terraces, from FgW1(highest) to FgW3 (lowest), connected with moraine ridges from the IMC, based on remote sensing cross checked with borehole data and on field sedimentological and geomorphological investigations.

In the present study, we mainly followed the classification of Roattino et al. (2021), such as terrace levels FgW1, FgW2 and FgW3 correspond to the high, middle and low terrace levels (T1/T2, T3 and T4), connected with the external, middle and internal moraine ridges (M2, M3 and M4). We however do recognise the presence of a fourth moraine ridge (M1) clearly visible in the NW part of the study area, uncovered by Roattino et al. (2021). As a consequence, we propose two possible (and geomorphologically very similar) high terrace levels T1/T2 for the rest of the study area, connected to the most external moraine ridge (M2, possibly including some remnants of M1 deposits).

In total, eight samples were collected in six sampling sites distributed across the study area, and from glaciofluvial geomorphic units representative of the different substages identified in the area (Table S1).

OSL sampling sites: detailed geomorphic and sedimentological context

For each sampling site, detailed information about the geomorphological and sedimentological context are provided in the Figures S2 to S7, as follow:

- 1) Geomorphological map (zoom locations as red boxes in the general geomorphological map below);
- 2) Representative longitudinal and transect profiles. These profiles do not directly intersect with the sampling site as they were first selected to best illustrate the general topographic/geomorphic context of the sampling area. However, the approximate location of the logged sedimentary section is indicated in the most relevant longitudinal/cross profile (note: the logged section symbol is not scaled and its absolute top elevation does not always fit within the elevation range of the topographic profile);
- 3) Detailed sedimentological log at the sampling site. Main sedimentary facies and sample location within the sedimentary section are indicated. The absolute elevation of the top of the log corresponds to the terrace surface at the sampling site.

Table S1: Sample locations and geomorphological information

Sample ID	Sampling site locality	Latitude/ Longitude (°N/°E)	Elevation (m a.s.l.)	Depth (m below surface)	Geomorphic unit (<i>Mandier, 1988</i>)	Geomorphic unit <i>Roattino et al. (2021)*</i>	Geomorphic unit This study***
EYP1	Eyzin Pinet (EYP)	45.496/5.009	262	5	Terrace level B	FgW2	T3
OYT1	Oytier (OYT)	45.575/5.030	265	3.2	Terrace level B/C	FgW2	T3
SPC5	St Pierre de Chandieux (SPC)	45.666/5.015	250	5	Terrace level B	FgW1	T1/T2
ART1	Artas (ART)	45.537/5.182	430	3	Terrace level D	FgW3	T4
ART2	Artas (ART)	45.536/5.182	420	12	Terrace level C	FgW2/3	T3 or T4
PEN1	Penol (PEN)	45.363/5.186	313	12	Terrace level A	FgW1	T1/T2
PIZ1	Pizay (PIZ)	45.876/5.088	250	13	Underlying till from the outermost moraine subset (stage A)	-	underlying M1
PIZ2	Pizay (PIZ)	45.876/5.088	256	2	Underlying till from the outermost moraine subset (stage A)	-	underlying M1

*This study was conducted across the area covering EYP, OYT, SPC, ART and PEN sampling sites.

Detailed geomorphic and sedimentological context per sampling site

Main sedimentary facies identified in the sedimentary sections logged

- Sand-gravel, massive to coarsely stratified (horizontal bedding)
- Sand-gravel, coarsely stratified (trough/planar cross-bedding)
- Sand, trough/planar cross-bedded
- Sand, ripple cross-laminated
- Diamicton

Figure S1: Up: Geomorphological map of the study area. The red boxes correspond to the zoomed areas for each sampling site, and for which a detailed sedimentological log was also recorded in the field. Down: Legend of symbols used to record lithological and structural data (see sedimentological logs after; *SE* indicates observed erosion surfaces).

Eyzin-Pinet

Figure S2: Eyzin-Pinet (EYP) sampling site: detailed geomorphological map (up), longitudinal and cross profiles representative of the glacial/glacio-fluvial geomorphological context (down left), and sedimentological log (down right) with sample measured feldspar (IR₅₀) and quartz (green OSL) single-grain ages.

Oytier

Geomorphological map

Topographic profiles

Sedimentological log

Figure S3: Oytier (OYT) sampling site: detailed geomorphological map (up), longitudinal profile representative of the glacial/glacio-fluvial geomorphological context (down left), and sedimentological log (down right) with sample measured feldspar (IR_{50}) and quartz (green OSL) single-grain ages.

St Pierre de Chandieux

Figure S4: Saint Pierre de Chandieux (SPC) sampling site: detailed geomorphological map (up), longitudinal profile representative of the glacial/glacio-fluvial geomorphological context (down left), and sedimentological log (down right) with sample measured feldspar (IR_{50}) and quartz (green OSL) single-grain ages.

Figure S5: Artas (ART) sampling site: detailed geomorphological map (up), longitudinal and cross profiles representative of the glacial/glacio-fluvial geomorphological context (middle), and sedimentological logs (down) with sample measured feldspar (IR₅₀) single-grain ages.

Penol

Geomorphological map

Topographic profiles

Sedimentological log

Figure S6: Penol (PEN) sampling site: detailed geomorphological map (up), longitudinal and cross profiles representative of the glacial/glacio-fluvial geomorphological context (down left), and sedimentological log (down right) with sample measured feldspar (IR_{50}) single-grain age.

Pizay

Geomorphological map

Topographic profile

Sedimentological log

Figure S7: Pizay (PIZ) sampling site: detailed geomorphological map (up), longitudinal profile representative of the glacial/glacio-fluvial geomorphological context (down left), and sedimentological log (down right) with sample measured feldspar (IR_{50}) single-grain ages.

Figure S8: DEM observations (5-m resolution, confirmed by field observations) of overridden moraines (right panel), in the NW of the study area (red box in the left panel), indicated by the presence of subtle lines (straight red lines on the right panel) cross-cutting perpendicularly sinuous positive topographic features (dark blue lines on the right panel) that are aligned with the general IMC ridges pattern (although more discrete). We interpret the latter as older moraine ridges (M1) which have been overridden by subsequent glacier advance.

II. Optically stimulated luminescence dating

Sample preparation, instrumentation and measurement protocols

Coarse-sand samples were collected in black tubes and prepared in the laboratory under red-light conditions following standard procedures (e.g. Lowick et al., 2015). The 200-250 μm fraction was sieved and treated with HCl and H_2O_2 to remove carbonates and organic components, respectively. Heavy-liquid density separation (sodium heteropolytungstate solution) was applied to isolate feldspar and quartz minerals, and the quartz fraction was etched using HF (40% for 40 min). Individual feldspar and quartz grains were placed in separated holes (100 holes of 300 μm diameter) drilled in a 9.8 mm diameter aluminium disk for single-grain luminescence measurements, or mounted on 4-mm aliquots for large-aliquot measurements.

All luminescence measurements were performed at the Institute of Geological Sciences of the University of Bern, Switzerland, on a Risø TL/OSL DA-20 reader equipped with an internal $^{90}\text{Sr}/^{90}\text{Y}$ beta-source, and with a single-grain attachment (Bøtter-Jensen et al., 2003). The OSL signal was stimulated with a green laser (single grain) or blue LEDs (large aliquot) and detected in the near-UV spectrum (Hoya U-340 filter). The infra-red stimulated luminescence (IRSL) signals were stimulated with at 140-mW with a 830-nm IR laser (90%) power (single-grain aliquot) or with IR LEDs (large aliquot) or and were detected in the blue wavelength (Schott BG-39 with a 410-nm interference filter and with an additional RG-780 filter for single-grain measurements).

Modified single-aliquot regenerative (SAR) protocols (Murray and Wintle, 2000) were applied to measure single-grain quartz (OSL; Table S2) and feldspar (post-IRIR₂₂₅; Buylaert et al., 2012; Table S2) equivalent doses (D_e). The OSL (quartz) signal was integrated over the first 0.1s minus a background averaged over the last 2s, and IR₅₀ and post-IRIR₂₂₅ (feldspar) signals over the first 0.5s minus a background averaged over the last 2s. Dose-response curves were reconstructed using an exponential fitting, including 2.5% instrumental uncertainty for single-grain D_e calculation. Single-grain D_e measurements were kept for further analysis with the following criteria: recycling ratio within 10%, recuperation ratio < 5%, and $D_e < 2D_0$. The suitability of each SAR protocol was checked by conducting dose-recovery and residual tests for each sample at the single-grain level for feldspar IRSL measurement, and for one representative sample using large aliquots for quartz OSL measurement (due to the very low proportion, i.e. $\leq 2\%$, of quartz grains, emitting suitable luminescence signal). For all samples, recovered dose after removal of the residual signal was within 10% of the given dose (within uncertainty), except for the post-IRIR₂₂₅ signal of one sample (PIZ2 within $19 \pm 5\%$; Fig. S9).

Data analysis: partial bleaching evaluation and burial dose determination

Quartz OSL single-grain data could be collected for only three out of eight samples (EYP1, OYT1, SPC5), due to the very low luminescence sensitivity of quartz. Feldspar (IR₅₀ and post-IRIR₂₂₅) single-grain data were collected for all samples. However, analysis for burial dose determination were conducted using the IR₅₀ signal only, as the post-IRIR₂₂₅ natural signal was systematically saturated for a large grain proportion (>30-50%; Fig. S14).

Burial doses used for age determination were calculated from single grain D_e distributions using the Central Age Model (CAM; Galbraith et al., 1999), or the Finite Mixture Model (FMM; Galbraith and Green, 1990) in case of partial bleaching (i.e. incomplete reset of luminescence signal prior deposition) diagnosis. The FMM was run for multiple components (testing 2, 3, and 4 components), assuming a sigma-b (σ_b) value of

0.25 (quartz) or 0.35 (feldspar-IR₅₀) for well-bleached sediments in glaciofluvial environments (Gaar et al., 2014; 2019; Gribenski et al., 2018; Smedley et al., 2016; 2019). Final selection of the FMM component and associated burial dose (FMM D_e) was based on statistical indicators (BIC and likelihood; Bailey and Arnold, 2006; Jacobs et al., 2008), the significance of the identified “youngest” D_e subpopulation ($p_0 > 0.05$), and on visual inspection of the single-grain D_e distributions. The robustness of the approach was investigated by testing the sensitivity of the FFM D_e to varying σ_b values (0.30-0.40; tests run on IR₅₀ distribution; Fig. S12) and by checking the consistency between burial doses obtained using the FMM and other sub-statistical models (e.g. Minimum Age Model - 4 parameters; Galbraith et al., 1999).

Samples collected in such proximal glaciofluvial environment (Fig. S1) are typically prone to partial bleaching issue, due to the characteristic sediment transport mode over short distances and in turbid waters, limiting the grain exposure to natural light (Duller, 2006; Fuchs and Owen, 2008). The significant increase in CAM D_e values and/or in the saturated-grain proportion between the signals with different bleaching rates (i.e. decreasing resetting probability going from quartz OSL, IR₅₀, to post-IRIR₂₂₅; Buylaert et al., 2012; Murray et al., 2012; Colarossi et al., 2015) suggest limited light exposure of grains prior deposition. Final partial bleaching diagnostic was established for all the quartz and feldspar single-grain dataset but one (quartz OSL signal for EYP1 sample), based on the complex (asymmetrical and multimodal) and largely-spread (overdispersion OD>30% for quartz and OD>40% for feldspar) single-grain D_e distributions.

Fading measurements (IR₅₀) were conducted following two different protocols: at the single-grain level and using 4-mm aliquots. Both approaches provided similar outcomes when comparing single-grain (weighted average) and 4-mm aliquots (arithmetic mean) g-values within two standard errors, except for PIZ1 (Fig. S10). No relationship could be identified between single-grain D_e and g-value (Fig. S11). Based on the lower inter-aliquot variability and the higher signal magnitude (better counting statistics), sample-individual g-values from 4-mm aliquot were used for correction of burial doses (following Huntley and Lamothe, 2001).

Sample-individual dose rates for age calculation were calculated using U, Th and K concentrations measured by high-resolution gamma spectrometry (Table S5) on bulk sediment using the online DRAC calculator (Durcan et al., 2015). A water content of 10±5% was assumed to take in account large variations over the considered time. For feldspar (IR₅₀) dose rate calculation, an internal K-content of 12.5±0.5% (Huntley and Baril, 1997) and an alpha efficiency value of 0.15±0.05 (Balescu and Lamothe, 1994) were used.

Figure S9: Dose recovery tests for feldspar IR₅₀ and post-IRIR₂₂₅ protocols (CAM recovery dose from single-grain measurements, 1 SG disc for each sample) with intrinsic overdispersion values (given in %).

Figure S10: Individual sample g-values (two standard error) for IR₅₀ feldspar from single-grain measurements (1-2 SG discs for each sample; weighted average, in red) and from 4-mm aliquot measurements (3 discs for each sample; arithmetic mean, in purple).

Figure S11: Individual single-grain IR₅₀ g-values plotted against corresponding single-grain D_e (black dots). Sample g-values from single-grain (weighted average; red line) and 4-mm aliquot (arithmetic mean; purple line) are also indicated. Some samples count significantly less single-grain g-values due to the non-measurable fading at an acceptable level of sensitivity and /or the absence of corresponding single-grain D_e .

Figure S12: IR₅₀ feldspar burial dose (one sigma error; non-fading corrected) obtained when applying the FMM model (FMM D_e) using σ_b values at 30, 35, 40%. In most cases, FMM D_e agree within 1 σ error using different σ_b values. For ART2 and EYP1, FMM D_e agree within 2 σ error. Only for SPC5, a significant difference persists between 30-35% and 40% σ_b values. However, IR₅₀ feldspar-age using 30-35% σ_b value agrees within error with the associated OSL quartz age, hence we selected σ_b of 35% for IR₅₀ feldspar age calculation. For PIZ1, the proportion of the minimum subpopulation extracted when applying the FMM model with 30% σ_b is not significant ($p_0 < 0.05$), hence no FMM D_e is provided.

Figure S13: Single-grain OSL quartz D_e distribution for EYP1, OYT1 and SPC5 samples (suitable signals/statistics), and burial doses obtained using the CAM (top circle) and FMM (vertical line/envelope) models. No FMM model was run for EYP1 due the limited overdispersion of this dataset (OD<25%).

Figure S14: IR₅₀ and post-IRIR₂₂₅ single-grain D_e distribution (non-fading corrected) for all samples. Probability distribution and burial doses (non-fading corrected) obtained using the CAM (top circle) and the FMM (vertical envelope) models are only provided for the IR₅₀ signal, as a large proportion of grains were saturated when considering the post-IRIR₂₂₅ signal.

Table S2: SAR protocols used for feldspar and quartz single-grain equivalent doses

Feldspar post-IRIR ₂₂₅	Quartz OSL
Dose	Dose
Preheat at 250°C for 60s	Preheat at 220°C for 10s
SG IRSL (laser) at 50°C for 5s	IRSL (diodes) at 125°C for 40s
SG IRSL (laser) at 225°C for 5s	SG Green OSL (laser) at 125°C for 5s
Test dose (500s)	Test dose (500s)
Preheat at 250°C for 60s	Preheat at 220°C for 10s
SG IRSL (laser) 50°C for 5s	IRSL (diodes) at 125°C for 40s
SG IRSL (laser) at 225°C for 5s	SG Green OSL (laser) at 125°C for 5s

Table S3: Details of single-grain IR₅₀ feldspar measurements and age determination

Sample ID	n grains (n/N, % ¹)	Total OD (%)	CAM D_e (Gy)	skewness	kurtosis	FMM D_e ² (Gy; σ_b 0.35)	g-value ³ (% per decade)	Dose rate (Gy/ka)	Age (ka)
EYP1	106 (35%)	78	96.0±7.3	1.44	5.33	49.9±3.7 (FMM 2)	2.4±0.1	2.14±0.12	29.4±2.8
OYT1	120 (40%)	73	164.8±11.1	0.65	2.52	57.5±6.8 (FMM 3)	2.5±0.2	2.27±0.12	32.4±4.3
SPC5	123 (41%)	68	244.8±15.1	0.75	2.72	79.7±14.0 (FMM 3)	2.8±0.3	2.53±0.13	41.6±7.9
ART1	105 (12%)	68	228.6±15.4	0.37	2.29	55.2±11.1 (FMM 3)	2.3±0.4	2.03±0.12	33.8±7.3
ART2	123 (41%)	75	182.8±12.6	1	4.37	70.2±5.3 (FMM 3)	2.5±0.4	2.20±0.12	40.6±4.2
PEN1	173 (29%)	43	328.2±11.0	0.9	6.42	107.9±18.1 (FMM 2)	2.0±0.1	2.09±0.12	63.0±11.4
PIZ1	133 (22%)	48	325.9±13.9	0.75	3.49	148.6±29.5 (FMM 2)	1.9±0.1	2.94±0.14	60.8±12.3
PIZ2	133 (22%)	52	326.4±15.3	1.45	6.83	181.2±34.4 (FMM 2)	2.5±0.2	3.05±0.13	76.4±15.1

¹Percentage of grains used for analysis (n) compared to the total number of measured grains (N). ²FMM D_e used for age calculation. For each sample, the number of components of the selected FMM model is indicated; ³mean and standard error g-value from fading measurements using 4-mm aliquots.

Table S4: Details of single-grain OSL quartz measurements and age determination

Sample ID	n grains (n/N, %)	Total OD (%)	CAM D_e (Gy)	skewness	kurtosis	FMM D_e (Gy; σ_b 0.25) ¹	Age model	Dose rate (Gy/ka)	Age (ka)
EYP1	28 (2%)	24	39.4±2.3	0.11	2.48	-	CAM	1.20±0.05	32.9±2.3
OYT1	34 (2%)	36	60.2±4.1	0.67	2.45	48.7±4.6	FMM 2	1.34±0.06	36.4±3.8
SPC5	27 (2%)	39	74.6±6.3	1.38	4.77	60.2±6.4	FMM 2	1.56±0.07	38.6±4.5

¹using a σ_b of 0.3 results in FMM D_e with less than 5% difference.

Table S5: Element concentrations from high-resolution gamma spectrometry used for dose-rate calculation (see Tables S3 and S4 for output dose rates)

Sample ID	U (ppm)	Th (ppm)	⁴⁰ K (%)
EYP1	0.89±0.11	3.97±0.08	0.79±0.01
OYT1	0.53±0.17	3.02±0.02	1.07±0.01
SPC5	1.26±0.31	5.91±0.13	0.98±0.01
ART1	0.79±0.1	3.73±0.11	0.90±0.01
ART2	0.85±0.23	2.63±0.08	0.78±0.01
PEN1	0.6±0.11	2.34±0.08	1.01±0.01
PIZ1	1.27±0.16	7.1±0.24	1.43±0.02
PIZ2	1.20±0.13	6.16±0.2	1.57±0.02

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