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We are indebted to Jean-Louis Edouard (Aix-Marseille Université) for pointing us to archival Albert Bezinge/Friedrich Rothlisberger's samples and allowed tree-ring measurement on it, as well as to Fritz Schweingruber (WSL, Birmensdorf) and Martin Schmidhalter (Dendrosuisse, Brig-Glis) for making early measurements of Röthlisberger's samples available. We warmly thank Conradin Zahno (Geotest AG, Zürich) for useful information about former mapping and dating efforts carried out at TN in the early 2000s, and Andreas Österreicher (Universität Innsbruck) for help in the field and some tree-ring measurements. We are grateful for comments made by Philippe Schoeneich (Université Grenoble Alpes) on an earlier version of the manuscript and to the two anonymous reviewers for their relevant remarks.

Introduction

1 Characterisation of the preindustrial Holocene climate variability baseline is of special interest in the context of rapid anthropogenic climate change, which has made the Alps one of the regions losing the most ice in the last two decades (Hugonnet *et al.*, 2021). Glacier variations were early linked to climate evolution in the region (e.g., Venetz, 1833). Later, improved knowledge about the climate sensitivity of Alpine glaciers has made them appear as the best suited proxies to reconstruct climate variability over a wide range of timescales during the Holocene (Oerlemans, 2005; Lüthi, 2014; Le Roy *et al.*, 2024).

2 The Little Ice Age (LIA) spanned most of the last millennium, between 1260 and 1860 CE (Nicolussi *et al.*, 2022). Based on historical sources and tree-ring dating three main periods of glacier maxima (14th, 17th and 19th centuries) have been identified in the Alps (Zumbühl and Holzhauser, 1988; Holzhauser *et al.*, 2005; Nicolussi *et al.*, 2022). As the most recent period of sustained glacier activity during the Holocene (Le Roy *et al.*,

2024), the LIA can be used as an analogue to understand the triggers responsible for previous cold periods. Proposed main forcings for the LIA multi-secular cooling include solar activity and clusters of volcanic eruptions (Brönnimann *et al.*, 2019). LIA moraine systems are clearly visible in the Alpine landscape and are generally referred to as "1850 moraines" (Maisch *et al.*, 2000), although not often properly dated. Accurate determination of glacier maxima during the LIA is nevertheless of great interest to deconvolving the different forcings that led to the observed maximum glacier extent. Despite early scientific interest (from the late 18th century) and systematic surveys (from the late 19th century), the respective timing of glacier maxima during the LIA is not accurately known for all major glaciers in the Alps. At the largest and most visited glaciers, length variations have been accurately reconstructed thanks to a rich pictorial corpus (Nicolussi, 2013; Zumbühl and Nussbaumer, 2018). However, at most sites historical sources are rather sparse and cannot be used to constrain glacier history.

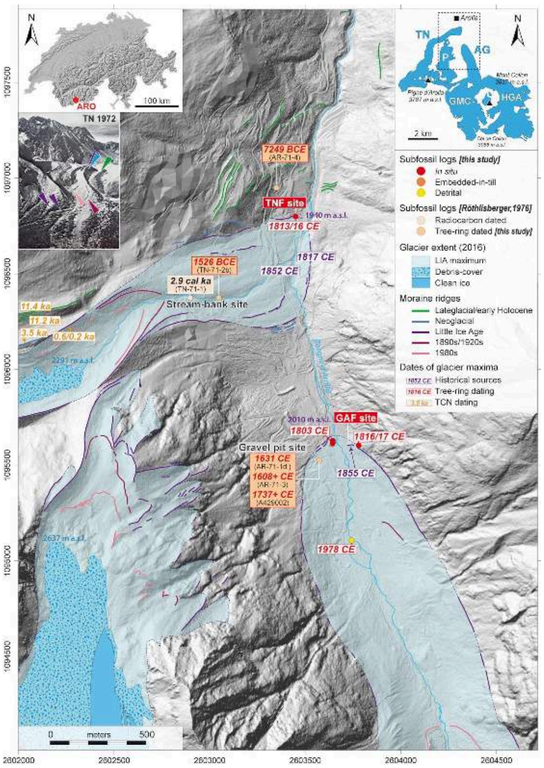
3 Tree-ring dating is a powerful tool to assign calendar date to any geomorphical or climatic event recorded in trees annual growth increment. Under favourable conditions, this method can provide spatially distributed information with high resolution, and even outperform historical dating from a chronological point of view, by reaching a seasonal resolution. Its use in palaeoglaciology has led to considerable progress with respect to the Alpine Holocene glacier chronology, which is the most accurate terrestrial record available to date globally (Pelfini, 1999; Nicolussi and Patzelt, 2001; Holzhauser *et al.*, 2005; Le Roy *et al.*, 2015; Solomina *et al.*, 2016; Nicolussi *et al.*, 2022; Le Roy *et al.*, 2024).

4 The aim of this paper is (i) to accurately map the late Holocene maximum extent at two neighbouring Alpine glaciers, and foremost (ii) to derive precise tree-ring dates for this advance. The accuracy of the obtained dates is then assessed against the historical information available.

Study Area and Previous Work

5 Arolla (2009 m a.s.l.) is located at the upper reach of the Val d'Hérens western branch, approximately 30 km south of the Rhône Valley. Despite its remoteness, accounts of travellers visiting the area are evidenced since the late 1830s. The Col Collon, 3068 m a.s.l. (Fig. 1), has long been used, especially for regular trade and grazing exchanges with Valpelline (Aosta Valley, Italy) during the last millennium (Gaspoz, 1950; Eschmann Richon, 2014). Glacio-archaeological artefacts from the Late Iron Age found near Col Collon highlight the age of this crossing route (Curdy and Nicod, 2020). Recreational use of the Arolla site increased with the opening of the Mont Collon Hotel in 1862 (Fig. 2c), which coincided with the rise of mountaineering in the region. From the 1950s, the construction of several roads for hydroelectric works allowed rapid access to the glaciers and promoted glaciological studies in the area (Bezinge, 1986).

Figure 1. Glacio-geomorphological map of the Tsijiore Nouve (TN) and Glacier d'Arolla (GA) sampling sites with dating results



The left inset shows the location of Arolla in Switzerland and the right inset shows the LIA extent of both glaciers. P: Pièce Glacier, GMC: Glacier du Mont Collon, HGA: Haut Glacier d'Arolla. Terrestrial Cosmogenic Nuclide (TCN) dating results are taken from Schimmelpfennig et al. (2012). The lower left inset shows TN in 1972 CE (i.e., the first year of the 1970–1990s re-advance) with moraine colour coding as in the main map. The innermost moraine (which will be later overridden by the 1990s moraine) dates from 1948 CE here (Röthlisberger, 1976). The hillshade background layer is based on the swissALTI^{3D} DEM at 50 cm resolution (courtesy of Swisstopo). Map coordinates are in metres of the Swiss Grid system (CH1903+/LV95).

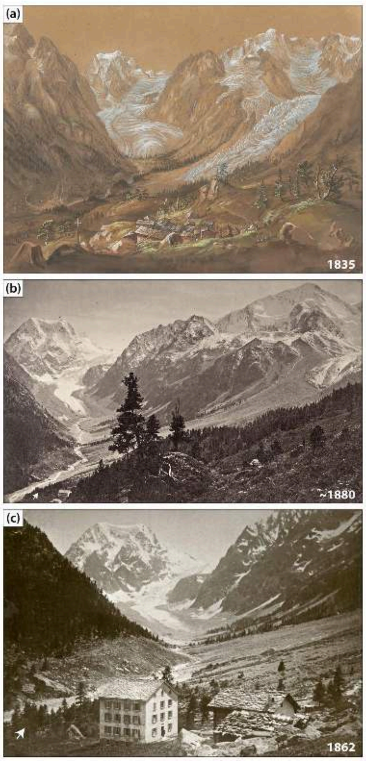
6 The glacial geomorphology of the upper Val d'Hérens is fairly well established (Bucher *et al.*, 2004; Lambiel *et al.*, 2016; Lambiel, 2021), especially regarding the Lateglacial period (Coutterand *et al.*, 2011; Scapozza, 2013). However, the late Holocene glacier extent of the Arolla area is only partially known (Röthlisberger, 1976; Abbühl *et al.*, 2002; Abbühl, 2004). We found previously available outline of the LIA extent (Maisch *et al.*, 2000) to be incorrectly delineated in the glaciers front area. We therefore propose herein a new interpretation of Holocene moraine mapping and dating based on precise DEM analysis and a synthesis of existing chronological data (Fig. 1).

Tsijiore Nouve Glacier

7 Tsijiore Nouve Glacier ("new stable/dairy" in local dialect, hereafter "TN") is a small-sized Alpine glacier (3.8 km² in 1817, this study, and 2.8 km² in 2016, Linsbauer *et al.*, 2021) (Fig. 1) flowing down Pigne d'Arolla north face (3787 m a.s.l.) to a debris-covered tongue through a 500 m-high icefall. It is characterised by a simple shape, without tributary, and had a maximum thickness of 190 m in 1950 (Bezinge, 1986). This makes it highly sensitive to climate variations, as early noted (Engelhardt, 1840; Forel *et al.*, 1897; Kinzl, 1932). This is borne out by a calculated response time of ~25 years

(Zekollari *et al.*, 2020) and above all by the frequency and scale of the four post-LIA re-advances that culminated in 1896 (+749 m), 1923 (+129 m), 1948 (+23 m) and 1995 (+268 m) (GLAMOS 1881–2022). The magnitude of the TN 1890s advance (spanning 1879–1896) stands out in the Alps. However, the reported number seems at odds with measurements made at other comparable glaciers (e.g., +411 m at Bossons Glacier) and with field evidence (this would imply an advance exceeding the LIA maximum). As the data prior to 1885 seems dubious, we chose to consider the series only from that date onwards (i.e., +426 m). Fig. 2b shows the state of the glacier in ~1880, i.e., during the relative minimum before the beginning of this advance.

Figure 2. Overview of Tsijiore Nouve (right), Pièce (center right) and Glacier d'Arolla (left) Glaciers and forefields during the 19th century, with Pigne d'Arolla and Mont Collon peaks in the background



(a) "Glacier Arolla en Val Arolla (Valais)" painted by Johann Rudolf Bühlmann on 1st August 1835 CE (Watercolour, gouache, graphite, chalk, Inv.-Nr. 376, Graphische Sammlung of ETH Zürich),
(b) Overview of Tsijiore Nouve and Glacier d'Arolla ~1880 CE. The picture date is bracketed between 1872 and 1884 (Unknown author, Ans_06373, ETH-Bibliothek Zürich, Bildarchiv, http://doi.org/10.3932/ethz-a-000239431). Mont Collon Hotel (having already undergone its first extension) can be seen at the bottom left close to our TNF sample site (white arrow),
(c) Forefield of Tsijiore Nouve Glacier taken in (or eventually shortly after) 1862 CE (https://ebibalpin.unil.ch/document/Arolla-1862-001/). The maximum date is given by the presence of Mont Collon Hotel, whose opening dates from 1862 CE. This photograph appears to be one of the first known pictures of Glacier d'Arolla (in the background). TNF sample site is shown with white arrow.

8 Importantly, the date of the LIA maximum is accurately known at TN and fixed to 1817 CE (Forel, 1886). During this advance, it dammed the valley and destroyed the forest on the right bank of the Borgne d'Arolla, resulting in the formation of a small temporary lake (Forel, 1886). However, no sedimentological evidence of this lake was later found (Abbühl *et al.*, 2002). The dam must have been shallow and easily cut by Glacier d'Arolla (hereafter "GA") meltwater. After a retreat phase starting as early as 1817, renewal of activity is evidenced in 1834 or slightly before (Fröbel, 1840) (Fig. 2a). A secondary

maximum then occurred between 1844 and 1852 when the tongue only reached the path to GA, building a small moraine there around the latter date (Forel, 1886) (Fig. 1). TN is also known to have triggered water pocket outbursts, especially in the early 1980s (1981 and 1986) (Raymond *et al.*, 2003).

9 TN is framed by large Holocene composite lateral moraines whose formation has been studied in detail (Röthlisberger and Schneebeli, 1979; Small; 1983; Schimmelpfennig *et al.*, 2012; Scapozza, 2013). They are one of the best examples of unconstrained moraines in the Alps (see the "TN 1972" inset in Fig. 1). Glacier surface elevation between these landforms has not depressed notably during the 20th century (up to 1990 CE). This is due in part to the low sediment export capacity which causes the predominantly sedimentary bed (Bezinge, 1986) to progressively rise and narrow (Abbühl, 2004). Increasing debris cover during the 20th century through steady emergence of the medial moraines also insulated the tongue (Wetterauer and Scherler, 2023). Partly as a result, the northern Holocene composite lateral moraine was overtopped during each post-LIA re-advance. This occurred over an 800 m-long portion during the 1970–1990s advance (Small, 1983; Small *et al.*, 1984; Bezinge, 1986), leading to the formation of ice cored lenses at the top of the moraine (Whalley, 1973; Small, 1983). Photographic evidence shows similar lateral moraine overtopping processes during the 1920s advance (picture 006ph-00745, https://xml.memovs.ch/006ph-00803.xml). This unusual behaviour for an Alpine glacier has been suggested to arise from the sharp turn in the flow of the glacier at this location and of a kinematic wave travelling the glacier (Whalley, 1973). Erosion rates in the catchment were studied with a terrestrial cosmogenic nuclide (TCN)-based approach by sampling sediments along its medial moraine (Wetterauer and Scherler, 2023). This has shown that sediments near the front are less than 100-yr old and that surface velocities experienced a marked drop since the 1980s (from 20 $m.a^{-1}$ to 4 $m.a^{-1}$ in the distal area). In recent years, following marked downwasting of the tongue, a sliding of the left lateral moraine crest occurred on its internal face.

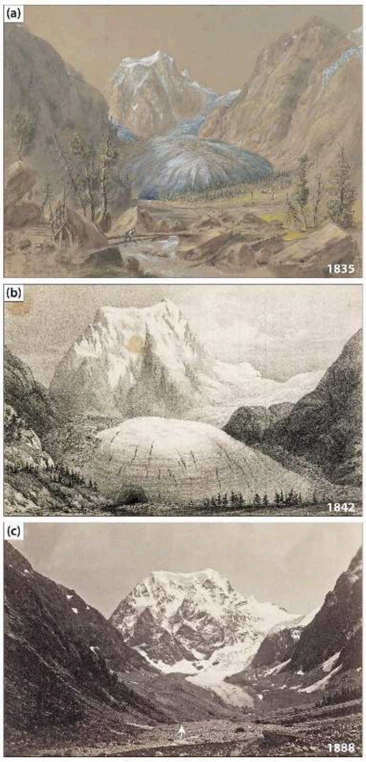
10 TN Holocene lateral moraines were exhaustively sampled for TCN dating. The results show three periods of moraine deposition during the Holocene prior to the late LIA: at ~11.4 ka, ~3.5 ka and ~0.55 ka (Schimmelpfennig *et al.*, 2012). They occurred during the Preboreal Oscillation (PBO), the Bronze Age Advance Period (BAAP) and the early LIA (eLIA), respectively (Le Roy *et al.*, 2024). In addition, tests carried out on the most recent moraines show that boulders are devoid of inherited nuclides at this site (Abbühl, 2004; Abbühl *et al.*, 2009; Schimmelpfennig *et al.*, 2012). A further period of glacier advance was proposed by Röthlisberger (1976) after 2940 ± 150 BP (~2.9 cal ka), based on radiocarbon dating of subfossil wood material (TN-71-1) found in a stream-bank till exposure ("Stream-bank site", Fig. 1). It would have been in the order of the 1890 CE extent (Röthlisberger, 1976). About ten other wood pieces were found in this area in 1971, among which TN-71-2b (Fig. 1; Supplementary Table). Further downstream and slightly outboard the LIA extent (c. 100 m), a buried larch woodland (10–15 meters long trees) was found at a depth of 12 m below till, boulders and sand deposits during an excavation in 1971. The trunks were parallel to the slope and were interpreted as having been buried by the glacier. One of the logs was sampled (AR-71-4) (Fig. 1) and radiocarbon dated to 8400 ± 200 BP (~9.4 cal ka), which was at that time the oldest subfossil wood dated in the Alps (Röthlisberger, 1976) (Supplementary Table). Finally, in 2002, two subfossil trunks were sampled in the LIA outermost moraine southeast of

Mont Collon Hotel (TNF site, Fig. 1) and dated to 245 ± 40 BP (~1660 cal CE) (Abbühl, 2004; Bucher *et al.*, 2004) and 240 ± 50 BP (~1675 cal CE) (unpublished dating) (Supplementary Table).

Glacier d’Arolla

11 Glacier d’Arolla (here short “GA”) was a large glacier system with compound basins during the LIA maxima (16.6 km^2, this study) (see Fig. 1 right inset). The two tributaries, Glacier du Mont Collon and Haut Glacier d’Arolla (hereafter “GMC” and “HGA”) flowed northwards from extensive and flat firn basins to the tongue below Mont Collon (3637 m a.s.l.) through two icefalls, of which the 500 m-high GMC’s was the most notable (Fig. 3). During the early 1940s, GMC and HGA split up. Bas Glacier d’Arolla (which is the geographical name of the valley glacier tongue without HGA inflow) got this designation around 1949. It was previously known as Mont Collon Glacier (name later used only for the upper part, above the icefall). Today, the valley tongue no longer exists and GMC and HGA cover respectively 5.1 and 3.6 km^2 (2016 data, Linsbauer *et al.*, 2021). Maximum thickness was in the order of 180 m for HGA in 1990 (Sharp *et al.*, 1993). Compared to TN, GA shows only moderate post-LIA re-advances as explained by a response time of ~65 years (Zekollari *et al.*, 2020). These weak still-stands/re-advances peaked in 1894 (+14 m), 1928 (+24 m) and 1987 (+140 m) (GLAMOS 1881–2022).

Figure 3. Views of Glacier d'Arolla front during the 19th century



(a) "Glacier de la Arolla dans la vallée d'Erin (d'Hérens, Valais)" painted by Johann Rudolf Bühlmann on 1st August 1835 CE (Watercolour, gouache, graphite, chalk, Inv.-Nr. 374, Graphische Sammlung of ETH Zürich),
(b) "Mont Collon and the glacier of Arolla, Vallée d'Erin" drawn from nature by Professor James David Forbes, lithograph by T. Picken (Forbes, 1843),
(c) "Mont Collon und der Arolla-Gletscher" taken by Friedrich Gottlieb Stebler and Carl Schröter in ~1888 CE (Hs_1360-0076, ETH-Bibliothek Zürich, Bildarchiv, http://doi.org/10.3932/ethz-a-000067965). The white arrow points to the remnant of the LIA right latero-frontal inner ridge (shown with a black arrow in Fig. 5a). Since 1842 CE, the glacier tongue has flattened, and the front has retreated by c. 600 m, while the two medial moraines have expanded considerably.

12 The first descriptions of TN and GA are from the mid to late 1830s. The first detailed representation of Arolla glaciers is due to J.R. Bühlmann who painted GA with a bulged tongue, typical of an advancing glacier, on 1st August 1835 (Fig. 2a; Fig. 3a). The close-up view was interpreted by Röthlisberger (1976) as an advancing tongue "touching" trees, but likely not overriding them as all trees are clearly standing upright (Fig. 3a). In contrast to the bulged but smoothed GA tongue, the lower section of TN was depicted by Bühlmann in the 1835 painting with a series of ice towers typical of dynamic flow behaviour and suggesting that the 1834 advance was still in progress (Fig. 2a).

13 The Arolla glaciers were visited in 1837 CE by Engelhardt (1840, pp. 110–114) who reported that TN would be a very sensitive glacier, repeatedly advancing and melting back. Godeffroy (1840, p. 44) has crossed Col Collon from the north in August 1838 and has therefore observed GA before. He mentions that "the Aroles glacier [...] has three perfect alignments of moraines on either side, which attest to a reduction in the duration of the growths [i.e., shorter advance periods], or a reduction at the bottom of the flow [i.e., tongue length and/or thickness reduction]". Fröbel (1840), who was in the Arolla Valley in summer 1839, mentions an advance of TN in 1834 which, according to

local reports, was accompanied by thunder, indicating a rapid, surge-like advance. Finally, Forbes (1843) crossed Col Collon from the south and painted the GA front a few years after Bühlmann, in August 1842, showing the same dynamic features of an advancing tongue (Fig. 3b). He also mentions a woodland a short distance from the glacier composed of “stunted and desolate Cembran pines (*Pinus cembra*) many (of which) are dead and some fallen”. This Cembran pine forest with many dead but still upright trees in the lower area was already described by Fröbel (1840, p. 71). Although the exact date of the 19th century maximum is not known at GA, the tongue was found to be first retreating from the LIA moraine in 1855 according to historical accounts (Forel, 1886).

14 Unlike at TN, very few numerical dates have been produced at GA in order to get insight into its Holocene evolution. In contrast, setting aside the paleoclimate issue, HGA has been a popular field site for glaciological experiments as the target of 100+ studies in recent decades (e.g., Sharp *et al.*, 1993), making it one of the most studied glaciers in the world. The GA forefield has been significantly altered by successive works since one of the pumping stations of the Grande Dixence S.A. power scheme was established in 1965, only 100 m outboard the LIA maximum moraine (Fig. 1). During excavations, subfossil wood material was found 10 metres deep in a gravel pit in 1971 (Bezinge, 1976; Röthlisberger, 1976) (“Gravel pit site”, Fig. 1). Finally, the recent marked paraglacial evolution of GA composite Holocene lateral moraines has been studied by Tonkin (2023).

Methods

15 Tree-ring methodology applied here was previously fully described in various papers (Nicolussi and Patzelt, 2001; Le Roy *et al.*, 2015; Nicolussi *et al.*, 2022). Absolute dating was achieved by crossdating measured tree-ring width series against the Eastern Alpine Conifer Chronology (EACC, Nicolussi *et al.*, 2009; 2015). In the field, the living trees (n=5) were cored with an increment borer and the subfossil samples (n=6) were cut with a chainsaw. For the latter, care was taken to target the best-preserved outer part of the logs. To do so, several sections were collected per sample, to ensure identifying the longest series and thus obtaining the closest estimate of the death date.

16 With regard to the additional archive resources (n=6), either physical samples or data (tree-ring measurements) were retrieved from two academic repositories (Service régional de l’archéologie 13, Aix-en-Provence, France and WSL, Birmensdorf, Switzerland). Archival samples came only with basic metadata (sample label, geographical coordinates) and no proper description of the stratigraphical context, nor field pictures. Sometimes original labels were missing and sample characteristics were matched to published lists dating back to the sampling period in order to identify them (e.g., Evin *et al.*, 1975; Röthlisberger, 1976; Röthlisberger *et al.*, 1980). For these reasons, the interpretation of archival samples in terms of glacier position must be made more cautiously than for the samples recovered as part of this study.

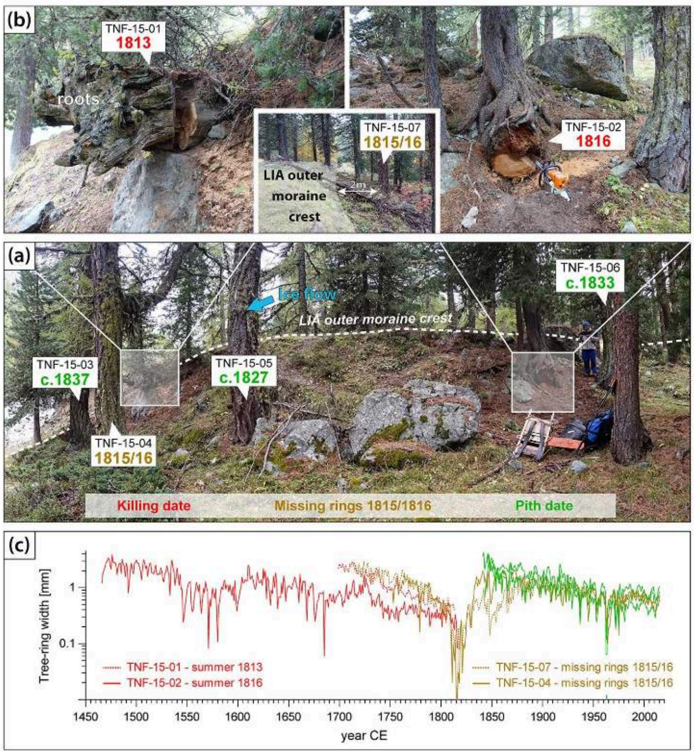
Results

17 In the following section, an extensive description of the samples retrieved at the two studied glacier sites is given along with their tree-ring dating results. For both sites, the last paragraph is dedicated to the archival samples, tree-ring-dated here for the first time.

Tsijiore Nouve Glacier

18 The TNF site (stands for “TN frontal”) sampled in 2015 lies at the outermost left latero-frontal LIA moraine, 80 m southeast of Mont Collon Hotel, at an altitude of 1942 m a.s.l. (Fig. 1; Fig. 2c; Fig. 4). We focused here on a segment of the distal face of the moraine which is 2 m-high at this location and single-crested (Fig. 4a). The sections of two embedded subfossil logs, one Cembran pine (TNF-15-01) and one larch (TNF-15-02), were retrieved in 2015 (Fig. 4b). Additionally, five living larches growing on the distal slope of the moraine were sampled (Fig. 4). The two subfossil logs had already been sampled for radiocarbon dating in 2002, and results proved a LIA age for the death of the trees (Supplementary Table).

Figure 4. Tree-ring dating results at the Tsijiore Nouve Glacier LIA left latero-frontal moraine site (TNF site)



(a) Overview of the sampling site with killing- (red, subfossil trees), growth suppression-(brown, surviving bordering trees) and minimum- (green, posterior colonisers) tree-ring dates for the TN LIA maximum,
(b) Close-up view of the two embedded subfossil wood sampled at the TNF site, TNF-15-01, which died in summer 1813 (left) and TNF-15-02, which died in summer 1816 (right). Central inset shows the second bordering tree that survived moraine deposition (TNF-15-07),
(c) Raw tree-ring width data (no detrending) for the trees sampled at the TNF site. Series are colour-coded according to the classification in (a).

19 The log TNF-15-01 is embedded with the rootstock facing outwards and is located in the upper part of the moraine wall (Fig. 4b). This proves a certain, but surely short (as the bark is still present), transport distance from the former growth site of the tree to the present deposition place. In contrast, TNF-15-02 is embedded at the foot of the moraine wall and had probably grown at this very site. It was finally overthrown and subsequently partly buried by the deposition of the moraine (Fig. 4b). The outer sections of the logs were still relatively well preserved at the time of sampling, i.e., the waney edge (last ring formed) was present in each case and bark remains were partially present. The inner sections, on the other hand, already showed decay, which only allowed the pith dates to be estimated. Both trees died during a summer season: TNF-15-01 during summer 1813 CE and TNF-15-02 during summer 1816 CE (Fig. 4c). These summer killing dates indicate that the advancing glacier buried the trees during moraine formation and that the ice margin was near-, and present-, at the TNF site in 1813 CE and 1816 CE, respectively. Interestingly, this site has been free of ice since at least the mid-15th century as shown by the long lifespan of the *in situ* larch TNF-15-02. Indeed, the pith date of TNF-15-02 (1462 CE) to which is added an estimated 20-yr ecesis interval yields a conservative germination date of ~1440 CE. Given the low growth of the TNF-15-02 tree during two intervals (1570–1580 CE and around 1685 CE) (Fig. 4c) we can assume that the glacier tongue was close to the site at this time, but not enough to endanger the tree. The early 19th century advance is therefore the TN LIA maximum, and other late LIA highstands were located significantly inboard.

20 Apart from the two subfossil samples, cores from five living trees were obtained at the TNF site (Fig. 4a). Tree-ring analysis shows that two of these trees germinated before the 1810s (TNF-15-04 and TNF-15-07), and therefore witnessed the 19th century maximum advance in very close proximity (Fig. 4a, 4b). They both show a distinct period of growth suppression between 1811 and 1821 CE (Fig. 4c), reflecting the very severe growth conditions in the immediate vicinity of the ice margin. This growth suppression resulted in two missing rings in both trees, most likely in 1815–1816 CE, in good agreement with the kill dates of the nearby subfossil samples (Fig. 4a). The relatively abrupt onset of the growth suppression phase in 1811 CE may indicate that TN was already close to the TNF site at that time and probably meltwater runoff and sediment flows affected the two larches (especially TNF-15-04). Conversely, the growth recovery of the trees from the early 1820s onwards indicates the rapid withdrawal of the glacier margin (historically evidenced since 1817 CE). The three remaining living trees all germinated after moraine deposition and are the first colonisers of the surface. Estimated pith dates (which give minimum ages for germination of the trees, and to which should be added a correction for sampling height on the trunk) on sampled cores span a narrow interval between ~1827 and 1837 CE (Fig. 4a). This demonstrates that the ecesis period (i.e., the time elapsed between moraine deposition and germination of viable larch saplings) was very short, around 10 years here.

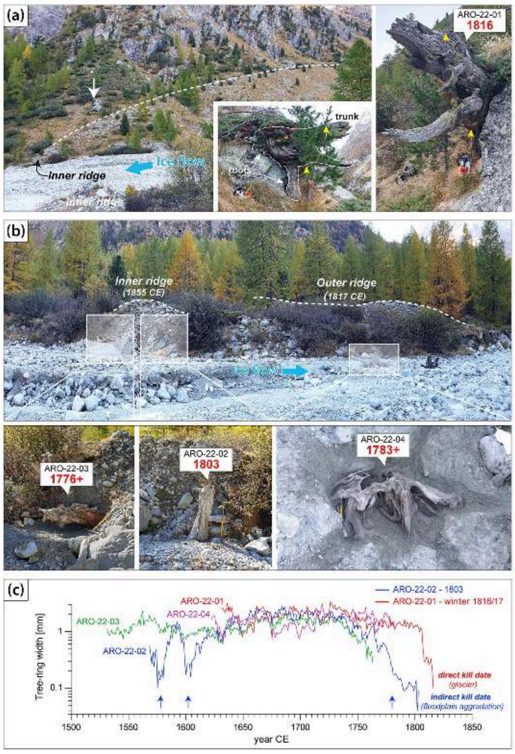
21 Aside from the LIA period, newly established tree-ring dates for the archival TN samples permitted some conclusions to be drawn. Wood found in the proglacial stream (TN-71-2b) shows that TN experienced an advance during the Bronze Age Advance Period (BAAP), which exceeded its 1890 CE extent, after 1526 BCE (Fig. 1; Supplementary Table). This confirms the timing of the BAAP dated by TCN at the left lateral moraine to ~3.5 ka (Schimmelpfennig *et al.*, 2012) (Fig. 1). Finally, the early Holocene sample (AR-71-4) excavated c. 100 m outboard the LIA extent was tree-ring-

dated here to 7249 BCE (Fig. 1; Supplementary Table). Following the interpretation by Röthlisberger (1976) this calendar date would indicate a LIA-like glacier advance around 9.25 ka, which has no equivalent in the Alps (Le Roy *et al.*, 2024).

Glacier d'Arolla

22 The two locations sampled in 2022 at GAF site (stands for "GA frontal") are situated on either side of the stream at the frontal margin reached during historical maximum, as shown by mapping of the sparse moraine remnants (Fig. 1; Fig. 5a, 5b). The GA forefield features few well-marked frontal moraines compared to TN.

Figure 5. Tree-ring dating results at the Glacier d'Arolla LIA frontal moraine site (GAF site)



(a) Situation at the right latero-frontal moraine of Glacier d'Arolla and location of the ARO-22-01 sampling site (white arrow). Insets show two different views of the ARO-22-01 dry-dead tree, looking south (left) and east (right) with the yellow arrows pointing to the two sampled sections,
(b) Situation at the left latero-frontal moraine and location of the ARO-22-02/03/04 sampling site. Insets show close-up views of the three subfossil wood samples before sampling. Representation of ARO-22-04 is a zenithal view based on a SfM (Structure from Motion) 3D model. Pick for scale is 55 cm long,
(c) Raw tree-ring width data (no detrending) for the Cembran pines subfossil and dry-dead samples at the GAF site. The blue arrows point to growth disturbances in tree ARO-22-02 caused by floodplain geomorphological changes, likely resulting from a glacier advance.

23 On the right bank, a well-defined lateral trimline can be traced down to the valley bottom where it ends with open work blocky deposits and a small ridge abutting the floodplain (Fig. 5a). Immediately outboard this drift, a large boulder (>5 m long) lies perpendicular to the valley axis, 27 m above the stream. On the distal side of this boulder rests a balanced stump (ARO-22-01) that appears to have been raised and tilted as part of the root system and the trunk point downstream, parallel to the slope (Fig. 5a). Only one of the original roots is still in contact with the ground (Fig. 5a). This

is a dry-dead tree, as it has not been covered by sediments and has remained exposed since its death. Sections were obtained at two distant locations on the trunk where bark patches were visible (Fig. 5a). Tree-ring analysis shows that this tree was killed in 1816 CE (winter season 1816/1817 as the latewood is complete), following adverse growth conditions during the last years, from 1808 CE onwards (Fig. 5c). The innermost part of the trunk was missing on the sampled sections, but a pith offset estimate shows this tree germinated immediately prior to 1600 CE (Supplementary Table).

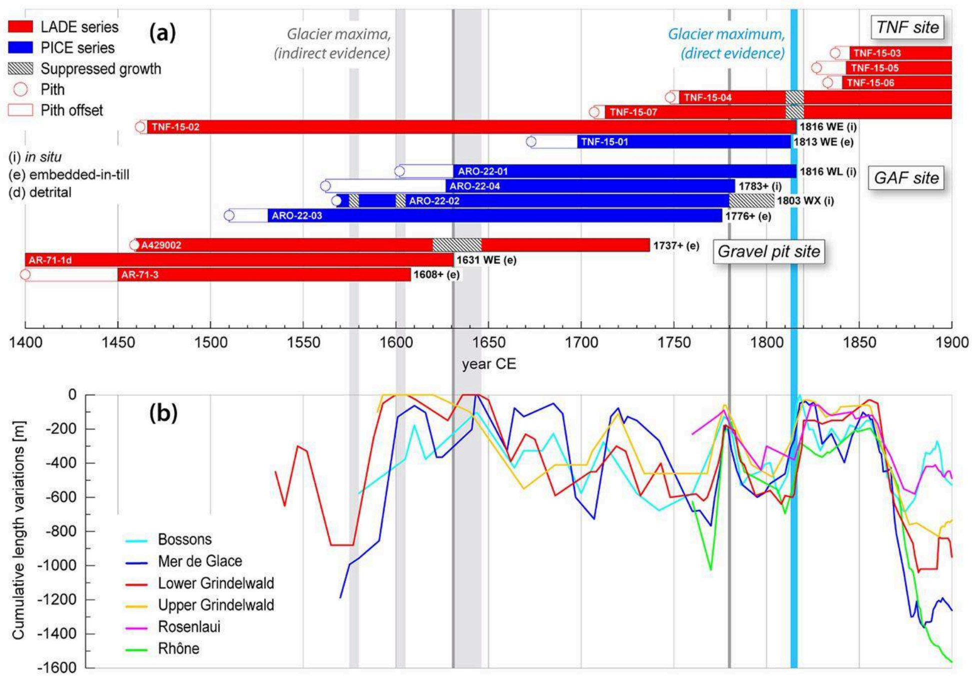
24 On the left bank, two subfossil *in situ* stumps (ARO-22-02 and ARO-22-04) firmly rooted in the floodplain were retrieved from an area lying immediately outboard the LIA (inner) frontal moraine, materialised here by a small and flattened ridge abutting the floodplain (Fig. 5b). A more marked (outer) moraine ridge located only 34 m downstream can be considered as the actual LIA maximum extent (Fig. 5b). However, this outer moraine can hardly be connected to a ridge on the right-hand side (unlike the inner moraine). This could be due to the alluvial fan located opposite at this location (Fig. 5a). The most distal *in situ* stump (ARO-22-04), located 23 m inboard the outer ridge and 11 m outboard the inner ridge, was barely protruding from the surface and had to be excavated (Fig. 5b). It was heavily weathered and severed at the root collar level, so the trunk was missing. No trace of bark could be detected. The most proximal *in situ* stump (ARO-22-02), located right from the inner ridge exposure, was preserved over a 1.2 m height (Fig. 5b). The outer surface is abraded and weathered, but a very limited sector displays a bark patch on the upstream side of the trunk. Finally, a detrital sample (ARO-22-03) was excavated directly outcropping from the inner moraine ridge exposure, only 3 metres upstream of ARO-22-02 (Fig. 5b). It was found perpendicular to the valley axis and the outer part was poorly preserved, suggesting that few outer rings may be missing. Tree-ring dating of the three samples yielded ages of 1783+, 1803 and 1776+ (ARO-22-04/-02/-03, distal to proximal), respectively. Based on the state of preservation of the last rings, only ARO-22-02 dating can be interpreted as an exact death date, ARO-22-03 could be lacking a few rings (c. 4), and ARO-22-04 is clearly the sample with the most rings missing (but no more than 33) (see the Supplementary Table). Interestingly, the ARO-22-02 tree-ring series displays (i) two periods of anomalous low growth during the late 16th to early 17th century (Fig. 5c), which are probably linked to geomorphological disturbances in the floodplain due to an advancing glacier (e.g., wandering of the proglacial stream), and (ii) more than 20 outermost rings on the upstream side of the trunk with a high resin content and a very low growth level (Fig. 5c), two features that can be interpreted as tracing a wound, probably caused by flooding or partial burying of the trunk around 1780 CE.

25 Archival GA measurements series and a sample can be ascribed, based on published descriptions (Röhtlisberger *et al*., 1980), to larch logs found in a gravel pit slightly inside the LIA moraine ("Gravel pit site", Fig. 1). Two of the sample series end in the early 17th century CE (AR-71-1d and AR-71-3) whereas another series covers the time interval 1460 to 1737+ CE (A429002). Noticeably, this latter tree-ring series demonstrates very low growth rates in the early 17th century (~1620–1647 CE) (Fig. 6a). It seems therefore likely that the two oldest trees were killed by a GA advance in the early 17th century, culminating in or shortly after 1631 CE (AR-71-1d), as evidenced by the only kill date available here (Fig. 6a). This advance would not have reached the third tree (A429002), causing only a significant reduction in growth.

Discussion

26 At both studied glaciers, we provide unambiguous evidence for a LIA maximum reached during the early 19th century, as early as the mid-1810s (Fig. 6a). At TN, the most advanced position of the tongue was reached around (or shortly after) summer 1813 CE and then occupied up to summer 1816 CE at least. At GA, the maximum extent was reached in winter 1816/1817 CE. Our dating results refer to the year when the ice margin reached and killed the trees, and cannot capture the duration of the subsequent front stagnation at the same location, which is partly known here from historical observations (e.g., retreat starting in 1817 CE at TN and 1855 CE at GA).

Figure 6. Comparison between (a) the tree-ring dated wood samples from Tsijiore Nouve (TNF site) and Glacier d'Arolla (GAF site) frontal moraines (see Fig. 1 for location) and (b) the length variations of six major Alpine glaciers reconstructed from historical sources during the late LIA period (Zumbühl and Nussbaumer, 2018; WGMS, 2022)



Vertical shaded panels represent the timing of glacier advances determined here based on direct (blue) and indirect evidence (grey). Dark grey shading means that the proposed glacier advance is based on different types of evidence from at least two samples (e.g., a death date coinciding with a growth suppression period). LADE: *Larix decidua*, European larch, PICE: *Pinus cembra*, Cembran pine. W: waney edge, i.e., the last tree ring formed before the tree died, is present; WL: latewood is formed on the last ring present, indicating tree death during autumn or winter following the formation of the last ring; WE: only earlywood is formed on the last ring present, indicating tree death during the summer period; the "+" after a date means that an unknown number of outer rings is missing.

27 At TN, a mid-19th century secondary maximum (during the 1850s) was found to be located clearly inboard the 1817 CE extent. Our evidence relies on (i) Bühlmann's 1835 CE painting (Fig. 2a) showing the glacier upstream the limit marked by the small moraine (located c. 150 m behind the 1817 maximum) that we have attributed to this last LIA re-advance (see Fig. 1) and on (ii) historical sources pointing to 1852 CE as the last LIA maximum (Forel, 1886). At GA, the front must have fluctuated in a narrower range than at TN during the early 19th century. After a limited retreat from the 1817 position (c. 35 m), the inner moraine could date from the 1850s (Fig. 5b), as the

beginning of the retreat started definitively in 1855 CE according to historical accounts (Forel, 1886).

28 Evidence for previous LIA maxima is only available at GA and is indirect. Growth disturbances identified within the ARO-22-02 *in situ* stump evidence high discharge and glacier proximity around 1575–1580 CE, 1600–1605 CE and again from 1780 CE, leading to the tree's slow death (Fig. 5c; Fig. 6). Secondly, based on the finding site of AR-71-1d/AR-71-3 ("Gravel pit site", Fig. 1) we can hypothesise that a 17th century advance reached c. 40–50 m from the 19th century LIA maximum and buried trees at that time, from 1631 CE (Fig. 6a). However, as evidence of the original growth site is lacking for these archival samples, it is not clear how long the glacier had been upstream from this location and what is the exact location reached during this advance. What is surprising at GAF site is that mature Cembran pine individuals grew during the coldest part of the LIA on the very margin of the forefield (germination dates span ~1510 to 1600 CE). These trees were only approached and buried by the ice during the early 19th century advance. Consequently, any previous advance during the 17th or 18th centuries would have necessarily been smaller by few tens of meters. This is consistent with length variations reconstructed at other very reactive glaciers (e.g., Bossons Glacier), showing they were slightly more retracted during the 17th and 18th centuries maxima than during the early 19th century (Nussbaumer and Zumbühl, 2012) (Fig. 6b).

29 Regarding the early 19th century maximum, our dates appear to be significantly earlier than at any other Alpine glaciers where this advance was dated with an annual resolution. For instance, the LIA maximum was dated to 1818 CE at Bossons, Brenva, Pré-de-Bar, Giétro and Fee Glaciers (Venetz, 1833; Forbes, 1843; Bircher, 1982; Nussbaumer and Zumbühl, 2012), to 1819 CE at Argentière, Grande di Verra and Sulden Glaciers (Forel, 1901; Pelfini, 1999; Savi *et al.*, 2021) and to 1821 CE at other large reactive glaciers, like Lys, Mer de Glace and Upper Grindelwald Glaciers (Monterin, 1932; Zumbühl and Nussbaumer, 2018) (Fig. 6b). The early dates obtained at TN are consistent with the fact that it is considered to be one of the most reactive glaciers in the Alps, but they seem more surprising for GA, which has a longer response time.

30 Drawn on above results, we can securely propose that Arolla Glaciers were close to their LIA maximum extent before the largest volcanic eruption of the last 500 years, the Mount Tambora (April 1815 CE), had any substantial effect on climate. Indeed, the most pronounced impact on temperatures occurred in the summer of 1816 (Brönnimann and Krämer, 2016), while the two glaciers were already occupying their LIA outer moraine. After a relative maximum around 1780 CE, the most important and best-known Alpine glaciers experienced a relative minimum centred on 1806/1808 CE, during which they retracted within 300–600 meters from their LIA maximum extent (Nicolussi and Patzelt, 2001; Zumbühl and Nussbaumer, 2018) (Fig. 6b). At these large glaciers, renewal of activity occurred between 1811 and 1814 CE (Fig. 6b), but it have most likely started earlier at smaller glaciers. This is an indication of the probable influence of the unattributed eruption of 1809 (Brönimann *et al.*, 2019; Timmreck *et al.*, 2021; Leland *et al.*, 2023) in triggering the first advance of the 19th century. At most sensitive glaciers, such as Arolla ones, most of this hundreds of meters scale advance was completed before the Tambora eruption. This shows that the summer cooling that followed the 1809 eruption, which was marked (in 1810, 1812 and especially 1813 CE), but not uniform (as 1811 was a mild year with a rather high snowline) (Venetz, 1833),

combined with persistently cool winter conditions starting in 1808/1809 CE (Reichen *et al.*, 2022) allowed for LIA glacier maxima to be reached.

Conclusion

31 This study shed new light on the timing of the LIA maxima at two climate-sensitive valley glaciers. Our results show—for the first time in the Alps—that early 19th century LIA glacier maxima were reached as early as 1813/1816 CE at Tsijiore Nouve and 1816 CE at Glacier d'Arolla, i.e. before the volcanic eruption of Mount Tambora had any actual impact on climate and was able to trigger these maxima. This has implications regarding forcing of the late LIA glacier advances. In addition, we are documenting at least two other LIA maxima at GA based on indirect evidence: during the early 1630s and around 1780 CE (Fig. 6a), both of which were slightly more restricted than the early 19th century one.

32 Apart from the LIA period, the tree-ring dates produced here for the archival detrital subfossil samples yielded possibly insights into two previous Holocene glacier advances, despite difficulties of interpretation arising from the lack of robust metadata (e.g., sample stratigraphy, original growth location). At TN, these two discussed advances could have reached a large extent (>1890 CE and >LIA maximum, respectively) around 1526 BCE and 7249 BCE. The youngest period of advance is already known (BAAP) and its culmination has been widely tree-ring-dated to ~1540 BCE in the Alps, reaching sometimes LIA-like extent. On the other hand, the oldest period— which would be contemporary with the so-called '9.3 ka event'—is not known to have resulted in advances exceeding the LIA extent in the Alps, but rather much smaller advances (Le Roy *et al.*, 2024). Confirmation of an advance with such magnitude at TN, which was originally proposed by F. Röthlisberger (1976), would therefore require further investigation.

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RÉSUMÉS

Little Ice Age (LIA) glacier variations are well constrained in the Alps, partly thanks to an unparalleled body of historical sources. When absent, tree-ring dating can be used to obtain accurate chronological information on glacier maxima. To do so, it is necessary to focus on the trees that immediately bordered the former maximum extent reached by the glaciers in historical times. Here, we present tree-ring dating results for newly sampled wood material and archival data from the forefields of two glaciers in the Pennine Alps, Tsijiore Nouve and Glacier d’Arolla. These sites have historical sources dating back to the early 19th century, i.e. slightly more recent than for the best known Alpine glaciers. At Tsijiore Nouve, the dating of trees embedded in the LIA outer moraine at the valley bottom and of bordering living trees both indicate the presence of the ice near this location as early as summer 1813 CE and of a maximum extent reached in 1816 CE. This is highly consistent with available historical sources pointing to a LIA maximum in 1817 CE. At Glacier d'Arolla we dated the outermost moraine to winter 1816/1817 CE, which is synchronous, despite different glacier response times. The dates we obtained are significantly earlier than available evidence at other Alpine glaciers during the same advance. Our results highlight the ability of tree-ring dating to derive accurate calendar dates for glacier maxima and show – for the first time in the Alps - that some glaciers were already at or near their LIA maxima when the cooling associated with the Mount Tambora volcanic eruption occurred.

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