The glacial history of the Maritime Alps, from the Last Glacial Maximum to the Little Ice Age

Federici Paolo Roberto[1], Ribolini Adriano[1*], Spagnolo Matteo[2]

[1]*Dipartimento di Scienze della Terra, University of Pisa, via S. Maria 53, Pisa, Italy*
[2]*School of Geosciences, University of Aberdeen, Elphinstone Road, Aberdeen, Scotland*

** Corresponding author (email: ribolini@dst.unipi.it)*

Abstract

A complete sequence of glacial deposits and moraines within a same valley system in the Maritime Alps, spanning from the Last Glacial Maximum (LGM) to the Little Ice Age (LIA) is described and discussed. The sequence is geomorphologically and morphostratigraphically coherent, while most stadials are chronologically constrained thanks to cosmogenic exposure ages, lichenometry, and by correlation with radiocarbon-dated moraines in neighboring valleys. The shape, extent and thickness of the palaeoglaciers at each stadial have also been reconstructed and their Equilibrium Line Altitude (ELA) calculated.

The LGM moraine of the Gesso Basin bears a similar ELA and age to that of other LGM moraines across the Alps. The recognized Lateglacial stadials show strict similarities with corresponding stadials of the central-eastern Alpine valleys, i.e. Gschnitz, Bühl, Daun and Egesen. The recalculation of exposure ages of moraine boulders with a new production rate better defines the LGM (24.0 ka) and the Egesen stadial (13.0 ka), while the Bühl stadial (18.5 ka) is here dated for the first time in the Alps. Three early Holocene glacial advances are defined and correlated to the Kartell, Kromer and Göschenen I stadials, widely recognized in other Alpine sectors. Lichenometric dates indicate a three-fold oscillation during the LIA (13th, 17th and 19th centuries).

Introduction

In their pioneering work, Penck and Brückner (1909) recognized that a rapid deglaciation of the Alps occurred after the Last Glacial Maximum (LGM) or Würm (following the original definition), the period when glaciers reached their maximum extent during the last glacial cycle, about 23-27 Ka BP (Hughes & Gibbard, 2015 and references therein). However, the presence of moraines upvalley from the LGM terminus indicates that the retreat was not continuous, but interrupted by still-standings and even some relevant re-advances. These latter are the so called glacial *Stadials*, whose temporal succession in the ~18-11 ka BP interval defines the *Lateglacial* period. Penck and Brückner (1909) compiled a frontal moraines chronological sequence and a nomenclature that has represented a paradigm to all future studies dealing with the evolution of Alpine glaciers. Namely, a three-fold glacial stratigraphy was proposed (Bühl, Gschnitz and Daun stadials, from older to younger), defined in the field by prominent moraines. The Equilibrium Line Altitude (ELA) of the palaeoglaciers that deposited these stadial moraines has been widely used to discuss palaeo-climatic implications (e.g. Kerschner *et al.* 2000; Kerschner & Ivy-Ochs 2008 and references therein). During the 20th century several proposals of modification and integration of the original scheme have been advanced, and today a five-fold Lateglacial stratigraphy (Gschnitz, Bühl, Clavadel/Sender, Daun and Egesen stadials, from older to younger) is commonly accepted (Ivy-Ochs *et al.*, 2008).

The Holocene is also punctuated by a series of minor Alps glacier re-advances, both in the Early Holocene (at ~11.7, 9.2 and 8.2 ka ago) and the Late Holocene (at ~3 ka and in the past few centuries) (Kerschner *et al.* 2006; Ivy-Ochs *et al.* 2006; Ivy-Ochs *et al.* 2009; Nicolussi & Schlüchter 2012; Schimmelpfenning *et al*. 2012; Schindelwig *et al.* 2012). The latter includes a series of recent oscillations that are commonly called the Little Ice Age (LIA), and which historical and geochronological data indicate to have occurred between the 14th and 19th centuries (Schimmelpfenning *et al.* 2014).

The recognition of these stadials and glacial re-advances within a same valley system is usually based on the geomorphology, stratigraphy and relative position of the various identified moraines and the corresponding ELA. However, issues related to moraine preservation as well as to uncertainty in palaeoglacier reconstruction and their ELA often make this task difficult. Furthermore, when the recognition process is based on comparisons between nearby valleys, further complications arise due to the influence of local factors that are sometimes able to completely inhibit the glacial response to a small climatic fluctuation (Lukas &Benn, 2006; Ivy-Ochs *et al.* 2008; Cossart *et al.* 2010). The recognition process has recently been greatly improved by the development and application of various dating techniques, including that of surface exposure dating with cosmogenic radionuclide isotopes. Ideally, these should be combined with the geomorphological, stratigraphical, geographical (i.e. relative position) and ELA-based approaches to provide a comprehensive understanding of the glacial stadials/re-advances that goes beyond a mere chronological constraint.

In this paper we present such an example, where within a same valley system (a rare occurrence in the Alps) multiple local-LGM to Holocene moraines have been (i) indentified (i.e. mapped), (ii) geomorphologically and sedimentologically characterized, (iii) used to infer the ELA of the corresponding palaeoglaciers, and, where possible, (iv) dated. This work summarizes the results of a multi-decadal effort aimed at understanding the glacial history of the SW Alps (e.g. Federici *et al.*, 2003). It assembles and partly revisits the key findings of several publications relative to the Gesso Valley, in the Maritime Alps (Italy), only 40 km away from the Mediterranean Sea. Results are discussed in relation to other chronologies and climatic proxies in the Alps and the wider Mediterranean region.

Setting

The Maritime Alps form the most part of the SW end of the Alps. They are almost totally constituted by the crystalline rocks of the Argentera Massif, outcropping from the Colle della Maddalena to the Colle di Tenda and culminating in the Argentera peak (3297 m a.s.l.). This Massif is one of the external crystalline massifs of the Alps and it is structured as a mega-antiform with a N120-oriented axis (Malaroda *et al.* 1970; Fry *et al.* 1989). It is composed of a metamorphic basement, an autochthonous sedimentary cover (Delfinese facies), and stacked tectonic units (Subrianzonese, Brianzonese and Piemontese facies). The crystalline basement constitutes the central nucleus of the Massif and it is composed of high-grade metamorphic and granitoid rocks involved both in the Ercynian and Alpine tectonic (Bogdanoff *et al.* 1991; Ribolini 2000; Musumeci *et al.* 2003; Ribolini & Spagnolo 2008). Sedimentary rocks crop out in the peripheral sectors of the Massif and compose tectonic units. Most moraines in the Maritime Alps are constituted by crystalline rock boulders generally rich in quartz, thus making it particularly easy to date their exposure by mean of cosmogenic isotope such as ^{10}Be.

The Gesso basin is one of the most important fluvial catchments in the Italian side of the Maritime Alps (Fig. 1). It is predominantly sculptured in the basement rocks of the Argentera, with only the terminal part eroded in the sedimentary covers. The topography and the general variety of rock types even within the crystalline basement (Malaroda *et al.* 1970), enable us to easily disentangle the source area for the boulders found on various moraines. It also gives the opportunity to understand the genesis of an uncertain landform, for example by making it easy to distinguish between a glacial deposit with its far-sourced boulders and a rock avalanche with its locally sourced sediment. The Gesso basin (Fig. 1) is composed of two large sub-basins, the Gesso della Valletta to the West and the Gesso di Entracque to the East. This latter is, in turn, composed of three valleys, the Gesso della Rovina, the Gesso della Barra-Coulomb and the Bousset. The sequence of moraines described in this paper is found in various locations from near the main watershed of the Maritime Alps down along the Gesso della Barra first and the Gesso di Entracque after. The oldest moraine discussed here is found at an elevation of 700 m a.s.l., further downvalley from the point where the two Gesso della Valletta and Gesso di Entracque sub-basins meet.

Due to their geographic position, at the southern end of the Alps, the Late Pleistocene-Holocene glaciers of the Maritime Alps have been sensitive to climate variations dominated not only by the interplay between N-S polar front oscillations and W-E directed atmospheric perturbations generated in the North Atlantic ocean, but also by the cyclogenesys phenomena occurring in the north-western Mediterranean and rapidly investing the south-western end of the Alps (Federici *et al* 2012). Today, some glacierets (7) and small glaciers (6) still survive within the Gesso basin, although now limited to only the uppermost parts of the cirque slopes (Fig. 2). They are mainly concentrated in the areas of the Clapier (2835 m a.s.l.), Maledia (3061 m a.s.l.) and Gelas (3143 m a.s.l.) peaks (Fig. 2), the latter being part of the Gesso basin. A vast documentation exists on these glaciers (Federici & Pappalardo, 2009 and references therein) and their retreat rate is still monitored on a yearly basis by the Italian Glaciological Committee (e.g. Baroni *et al.* 2014).

Methods

The criteria adopted to define the glacial stadials of the Gesso Basin are: i) the morphology of the frontal moraine systems and their position relative to other moraines along the valleys, ii) the correspondent ELA values, absolute and relative to the local modern ELA, and, where available, iii) the age of the deposits, determined by ^{14}C, cosmogenic radionuclides or lichenometry.

Our work largely benefitted from a detailed geomorphological map covering the entire study area (Federici *et al.*, 2003). This map is based on a series of dedicated fieldwork seasons, which have spanned over a period of almost two decades, and relevant remote sensing surveys. The work provides the necessary detailed morpho-stratigraphic elements of the glacial deposits along the Gesso basin (Fig. 3) that allow for a comprehensive understanding of their relative positions and for the reconstruction of their corresponding palaeoglaciers.

A GIS approach, based on the numerical technique of Benn and Hulton (2010), has been used to semi-automatically reconstruct the thickness and partly the extent of the palaeoglaciers at each moraine. Further GIS tools (Pellitero *et al.* 2015) have been adopted to automatically derive the ELA values of each reconstructed glacier, by applying the classic Area Altitude Balance Ratio (AABR) method (Osmatson 2005), with a ratio value of 1.6, as recommended by Rea (2009) for the Alps. This effort of homogenization is necessary because different methods and/or different key variables were adopted in the past to calculate the ELA of Maritime Alps palaeoglaciers, including the Höfer (Schweizer, 1968, Hannss, 1970), Accumulation Area Ratio (Federici *et al.* 2000) and Balance Ratio (Finsinger & Ribolini 2001; Ribolini & Fabre 2007). Both the absolute ELA value and the one relative to the present-day and to the Little Ice Age (LIA) (1850 AD)'s ELAs, 2900 m a.s.l. and 2800 m a.s.l. respectively (Federici *et al.* 2000), were evaluated and discussed.

Details about methodologies and laboratory procedures employed to get exposure, radiocarbon and lichenometric ages can be found in the original papers (Federici & Stefanini 2001; Finsinger & Ribolini 2001; Ribolini *et al.* 2007; Federici *et al.* 2008; Federici *et al.* 2012). With regards to the exposure ages, these were recalculated adopting the North America production rate using LM as time-dependent adaptation scaling scheme (Balco *et al.*, 2009)

Results

Last Glacial Maximum - the Andonno and Tetti del Bandito moraines

At the lower elevation of the Gesso basin, not far from where its main valley trunk reaches the Po Plain, frontal moraine deposits can be found near the villages of Andonno and Tetti del Bandito

(Fig. 4). The moraine deposit of Tetti del Bandito covers the valley flank between 710 and 850 m a.s.l. Here, beside the abundant coarse sandy matrix and pebbles of crystalline rocks, some large blocks were found standing on the surface. These blocks yielded an exposure age of 24.0 ka (average value recalculated from Federici *et al.* 2012) (Table 1). The Andonno moraine shows a matrix-supported deposit composed of pebble and blocks of crystalline nature and variable dimensions (10-70 cm of max diameters) dispersed in a sandy sediment. Some erratic blocks are present on the surface, but the vast part of the deposit is now covered by paraglacial alluvial fans and its original preservation has been further degraded by century-long anthropogenic reworking; especially block removal for farming/grazing purposes. Thus, this glacial deposit is not suitable for cosmogenic exposure dating and its chronology remains, to date, uncertain. However, its elevation comparable to that of the Tetti del Bandito deposit and its similar position along the main valley trunk suggest that the two could belong to a same frontal moraine system, now almost entirely eroded by the Gesso River that drains the basin. As no other moraines or glacial deposits are found downvalley of the Tetti del Bandito and Andonno deposits, these deposits are interpreted as the preserved accumulation of the maximum advance of the Gesso Glacier, i.e. the local LGM (Fig. 4). The ELA of this moraine apparatus yielded a value of 1845 m a.s.l. (Table 2), and corresponds to a depression of 1055 m and 996 m in respect to the ELA of the modern and LIA glaciers respectively.

Slightly upvalley (2.5 km) from the LGM moraines, on the left side of the Gesso Valley and near the village of Valdieri another moraine, about 250 m long, is found (Fig. 4). It is composed of a coarse sandy matrix that supports pebbles and blocks of crystalline composition and also, although less frequently, of limestone and sandstone, which outcrop locally. Large sectors of the moraine have been reworked by farming, e.g. terracing. The moraine terminates downvalley overlapping onto a geomorphologically poorly defined (i.e. no crest) glacial deposit that extensively infills a lateral tributary valley. This deposit is, in turns, largely covered by an alluvial fan.

On the opposite side of the valley, a glacial deposit is outcropping near the La Bastia area. It presents the same internal structure and composition of the Valdieri moraine and it is superimposed over limestone bedrock.

Valdieri and La Bastia deposits could be the relict of a single frontal moraine (Fig. 4), the main and central body of which was largely removed by the erosive power of the downcutting Gesso River. The anthropogenic modification of the original deposit makes these moraines unsuitable for cosmogenic dating. Since the ELA is the same as that of the Andonno-Tetti del Bandito phase (Table 2), it is possible that the Valdieri-La Bastia complex represents another still stand within the LGM (Kerschner & Ivy-Ochs, 2008; Ivy-Ochs *et al.* 2009).

Bühl *Stadial - Ponte Murato Moraine*

A few kilometers upvalley from the Valdieri-La Bastia complex, the two Gesso della Valletta and

Gesso di Entracque valleys separate. In the Gesso di Entracque Valley, the left handside portion of a prominent frontal moraines is well preserved in the locality of Ponte Murato at 820-880 m a.s.l. (Fig. 5, see also Fig. 3a). The moraine is up to 25 m high, and exhibits a well preserved arch shape transverse to the valley main axis. The central and right–hand side portion of the moraine must have been largely eroded by the action of the main river, and only a small remnant of the original deposit is still preserved on the valley flank opposite to where the Ponte Murato's moraine is found. The internal composition of the moraine deposit is quite similar to that described for the downvalley glacial deposits: abundant coarse sandy matrix, pebbles and blocks of crystalline lithology. Many large blocks (up to 4-5 m in diameter) of high-grade metamorphic and granitoid lithology are present on the moraine surface. The recalculated exposure ages (^{10}Be) of four of these blocks yielded an average age of 18.5 ka (recalculated from Federici *et a*l., 2012; Table 1), that is consistent with the Bühl stadial. It is worth to be noted that this stadial is rarely constrained in the Alps (van Husen, 1977). The ELA value of the Ponte Murato moraine is 1873 m a.s.l. (Table 2), 1027 m and 968 m less than the modern and LIA glaciers respectively.

Gschnitz *(?) stadial - the Entracque deposits*

The Gesso della Barra and Bousset valleys join together near the village of Entracque forming the main Gesso di Entracque Valley. The Gesso della Barra is here characterized by an overdeepening carved in bedrock and hosting the La Piastra Lake. The lake is partly natural and artificial, being closed downvalley by a dam located on the sill of the overdeepening, right before a considerable drop in elevation (Fig. 5). The sill itself is made of methomorphic bedrock, polished and shaped into whalebacks by glacial abrasion. The bedrock at the bottom of the overdeepening, today under water, is also sculpted by glacial abrasion and discontinuously covered by a glacial deposit which extends for 150-200 m and reaches the sill, at 950 m a.s.l., where it forms a substantial deposit on the left valley flank (the La Piastra deposit) (Bortolami *et al.* 1967). Part of this deposit is still visible near the top of the artificial dam. On the opposite valley flank at 1120 m a.s.l., a clear moraine ridge extends prominently for several hundreds of meters (Fig. 5). On the basis of the crest elevation and deposit dimension, it is disputable if this accumulation was built at the same time of the La Piastra deposit, shaping a continuous frontal arch, or it represents the remnant of a previous glacier expansion (LGM or Bühl).
In the terminal part of the Bousset Valley two > 3 km-long lateral moraines are found. The spectacular (>100 m high) left lateral moraine, called "*Serrera dei Castagni*", is well preserved and extends up to the nearby Entracque village terminating approximately at the same altitude of the La Piastra moraine (950-1000 m a.s.l.) (Fig. 3b). The internal slope of this moraine shows the existence of some breaks, suggesting a polycyclic formation via lateral aggradation caused by different phases of deposition. The maximum height of this landform appears compatible with the ice thickness reconstructed for the LGM and the Bühl stadial. A glacial deposit is also present on

the right side of the Bousset Valley, although poorly preserved because the glacier was here interacting with the rocky dorsal of the Mt Viver.

The overall poor preservation of the La Piastra and Bousset deposits, and the lack of a clear morphology make it difficult to interpret them as remnants of one (or more likely) two (one for each main valley) frontal moraine systems. However, it is interesting to notice that, should they indeed be interpreted as frontal moraines, the corresponding glacier ELA is 1964 m a.s.l., 877 m and 936 m below that of the LIA and present day ELA respectively. These figures are remarkably similar to those found in the Swiss Alps, for moraines attributed to the Gschnitz stadial (~ 16-17 ka) (Ivy-Ochs *et al.* 2006).

Clavadel/Sender-*Daun (?) stadials – the San Giacomo deposits*

A conspicuous glacial deposit covers the terminal part of the Gesso della Barra Valley at 1260 m a.s.l., at the confluence with the Gesso di M. Colombo Valley (S. Giacomo locality) (Fig. 6). It is composed of a massive diamict with large blocks (diameters up to 5 m) supported by a brownish silty matrix. Many large blocks are present on the surface. The deposit is partly reworked by agricultural terracing and laterally eroded by the river that has completely removed the last portion on the left-hand side deposit. Another glacial deposit, with similar sedimentological characteristics, is also present along the Gesso di M. Colombo Valley near the confluence between the two valleys. The overall San Giacomo deposits setting is therefore very similar to the La Piastra-Bousset one, with two distinct glacial deposits found on two separate valleys right at the confluence between the two and it remains unclear whether these were two separate frontal moraines or a single one.

As the San Giacomo glacial deposits are bracketed between the dated Egesen moraine upvalley (Piano del Priaet moraine, see hereafter) and the hypothetical Gschnitz deposits downvalley (La Piastra moraine), it is likely that they correspond to the Clavadel/Sender or Daun stadial. The ELA of the corresponding glacier(s) is 2016 m a.s.l., 884 m and 825 m below the present day and LIA ELA respectively. These latter values are higher than those found elsewhere in the Central and Eastern Alps for the Daun stadial (13-13.5 ka) (Maisch 1992; Maisch *et al.* 1999), but similar to those calculated in the South Western French Alps for an early Lateglacial stadial preceding the Egesen (Cossart *et al.* 2012) (*Table* 2). Thus, the San Giacomo deposit could be tentatively attributed to the Daun stadial. However, it is worth noting that in many localities of the Alps the distinction between Clavadel/Sender and Daun moraines is difficult because they were deposited close to each other (Ivy-Ochs *et al.* 2006). Thus, it cannot be excluded that the complex of glacial deposits in San Giacomo may be the morphological expression of both stadials.

Egesen I (?) stadial – Peirastretta moraine

Upvalley from the S. Giacomo deposits, a moraine is present at 1650 m a.s.l. (Peirastretta moraine) along the Gesso della Barra Valley, (Fig. 7). The deposit is predominantly composed of large boulders (with a maximum diameters of 3-4 meters) aligned transverse to the main valley axis. The moraine terminates upvalley against a fluvial and fluvio-glacial coarse sand deposit that overlays a periglacial aeolian sandy layer of a few decimeters. Despite the presence of suitable boulders, a lack of resources has not allowed yet for this moraine to be dated. However, the moraine rests right upvalley from a considerable valley step (about 150 m rise in elevation), which was at least in part carved by the erosive power of the glacier, as demonstrated by the common presence of polished bedrock. It is possible that the position of the Peirastretta moraine is related to that of the step, as glaciers will normally slow down once they have retreated above a step along the longitudinal profile of the valleys they occupy. However the glacial deposit is thick and exhibits small subdued ridges and boulders alignments. Consistently, the Peirastretta deposit could represent a climatically driven stadial which, given the close proximity and the similar ELA to the dated Egesen moraine upvalley (see next paragraph), could be interpreted as the lowest pulsation within a multiphase Egesen stadial (Maisch 1992; Maisch 1999).

Egesen (II) stadial – Piano del Praiet moraine

The Piano del Praiet moraine (1800 m a.s.l.) (Federici *et al.*, 2008) is organized in three nested ridges, partly overlapped and arch-shaped (Fig. 3c and 7). The deposit presents large blocks (up to 5-6 m in diameters) sustained by a coarse sandy-gravel matrix. Numerous large blocks stand on the surface of the moraine ridges. The general shape of the moraine system is slightly asymmetric, because the west portion of the moraine has been undercut by the main valley channel. An extensive deposit of fluvial and fluvio-glacial sands alternated with silty horizons is present upvalley from the moraine arch, partly covering its full height. This deposit overlaps a 10-12 cm thick layer of fine aeolian deposits.

The large blocks on the moraine surface yielded an average exposure age of 13.0 ka (recalculated from Federici *et al.*, 2008; Table 1), consistent with the Egesen stadial of the Alps (Ivy-Ochs *et al.* 2009). This age marks the end of the Lateglacial in the southern flank of the Alps.

The ELA of the Piano del Praiet moraine is 2368 m a.s.l., with a lowering of 510 m and 473 m with respect to the modern and LIA glacier ELAs respectively (*Table* 2).

Kartell (?) stadial – the Ricovero Lombard moraines

Near the Ricovero Lombard (IInd world war installation), an irregular/complicated accumulation of glacial deposits covers the main valley bottom at 2070 m a.s.l. (Fig. 3d). It is composed of two moraines with crests running approximately parallel to the main valley axis, and bending in their downvalley portion to outline a, non-fully preserved, frontal closure (arch) (Fig. 8).The deposit of this moraine system is clast-supported with boulders up to 3 m in diameters, and a coarse gravel matrix isolated in pockets (Fig. 3d).

The moraine system of the Ricovero Lombard is the first glacial deposit upvalley from the Egesen stadial of the Piano del Praiet, and provides an ELA of 2411 m a.s.l., 489 m and 430 m lower than the modern and LIA glacier ELAs respectively. The ELA is notably higher than that of the Egesen stadial, although much lower than that of the LIA. The ELA and relative position are indeed compatible with those of the Kartell stadial in the Kartell valley of the northern Tyrol (Austria), where the moraines have an exposure age (^{10}Be) of 10.1 ± 1.1 ka (Ivy-Ochs *et al.* 2006). Hence, the Ricovero Lombard moraine system most likely marks the first Holocene glacial stadial in the Gesso Valley system, and could be tentatively attributed to the Kartell stadial.

Kromer (?) stadial - Ricovero Malariva moraine

A glacial deposit is evident at 2160 m a.s.l. near the Ricovero Malariva (also a IInd world war installation), just a few hundred metres upvalley from the Lombard moraine (Fig. 8). It is only a few meters high, but it forms a continuous, 200 m long ridge that bends downvalley outlining a frontal arch (Fig. 3e). The deposit is composed of blocks with a maximum diameter of 0.5-1 m and a very scarce matrix confined to distinct pockets.

This moraine testifies a glacial standstill with an ELA of 2464 m a.s.l., 436 m and 377 m lower than that of modern and LIA glaciers respectively. The ELA value is lower than that of LIA glaciers, but close to that of the Ricovero Lombard. Similar ELA differences and relative positions are found in the Kromer valley in Tyrol (Austria) (Gross *et al.* 1977), where moraines have an exposure age of 8.4 ± 0.5 ka (Kerschner *et al* 2006). Thus, the Ricovero Malariva moraine could be tentatively attributed to the Kartell stadial.

Göschenen I (?) stadial- the Vallette moraine system

Glacial deposits composed of angular blocks of up to 60 cm and sporadic pockets of coarse gravel matrix are found at an elevation of 2480 m a.s.l., immediately upvalley from a valley step dominating the Kromer moraine (Fig. 8 and 3f). The deposits form a series of frontal arches and longitudinal ridges 2-2.5 m high that here refer to as the Vallette moraine system. The average ELA of these moraines is 2640 m a.s.l., 260 m and 201 m lower than modern and LIA glaciers respectively. The Vallette moraines ELA is then slightly lower than that of the LIA. This stadial has also been identified in nearby valleys. On the basis of palynological, palaeobotanical and chronological evidences (De Beaulieu *et al.*, 1994; Finsinger & Ribolini 2001; Gandouin & Franquet 2002; Ribolini *et al.* 2007), these moraines are attributed to a Late Subboreal age as described elsewhere in the Alps and in the Apennines (Orombelli & Pelfini 1985; Baroni & Carton 1991; Nicolussi & Patzelt 2000; Ravazzi *et al* 2001; Deline & Orombelli 2005; Giraudi 2005; Nicolussi *et al* 2006; Holzhauser 2007; Schimmelpfenning *et al.* 2012), corresponding to the Göschenen I stadial in the chronology of Central and Eastern Alps (Maisch 1992; Maisch *et al.* 1999).

Little Ice Age - Gelas moraines

The glacial cirques incised in the upper flanks of the Gelas crests still host small glaciers (Gelas W, Gelas N, Gelas NE, Gelas E and Gelas S) (Fig. 2). A series of frontal festoon-shaped moraines are placed immediately downvalley (2500 m a.s.l.) from the cirque glaciers (Fig. 8). The deposit of these moraines consists of angular blocks (up to 60 cm of max diameter).

Some of these moraines have been dated with lichenometry to the LIA (Federici & Stefanini 2001). Specifically, the age of the LIA moraine in the area of Gelas North Glacier was lichenometrically determined at 1640 AD, similarly to other moraines in the area of the Gelas glaciers and in other valleys of the Gesso basin (Fig. 2a, e). This is the most prominent advance within the LIA stadial. One later (1780 -1820 AD) and one earlier (13th century) LIA phases have been identified and dated by lichenometry, thus overall suggesting a 3 oscillations LIA in the Maritime Alps (13th, 17th and 19th centuries).

Discussion

Reconstructions of the LGM to Holocene glaciers in the Gesso basin

During the LGM the Gesso Glacier extended down to the Andonno-Tetti del Bandito area with a total length of more than 22 km, a maximum width of 3 km in the area of the Entracque village, and a thickness up to 450 m (Fig. 9a; Fig. 10).

Following the LGM, the glacier retreated slightly up to the area of the village of Valdieri, then retreated again and divided into two large branches, e.g. the Gesso della Valletta and the Gesso di Entracque glaciers (Fig. 9b; Fig. 10). The position in the valley of the Ponte Murato moraine (ELA 1873 m a.s.l.) indicates that the two glaciers were already divided during the Bühl stadial. A further retreat divided and confined the glaciers into three tributaries, the Gesso della Valletta, Gesso della Barra and Bousset-Sabbione glaciers.

During the Daun (?) stadial (ELA 2016 m a.s.l.) (Fig. 10) the Gesso della Barra glacier may have already split into its two main tributaries, the Mt Coulomb and Gesso della Barra glaciers, although the two frontal positions could have been very close during this time (Fig. 6). Frontal moraines possibly related to this stadial have also been recognized in the nearby area of the Terme di Valdieri village in the Valletta Valley (Federici *et al.* 2003), and in minor, lateral hanging valleys (Serani 1995; Ribolini 1996, Pappalardo & Ribolini 1998).

The deglaciation was interrupted again during the Lateglacial with the advances testified by the Egesen moraines of the Piano del Praiet (ELA 2368 m a.s.l.) (Fig. 9c). During this phase the glacier was up to 3 km long, 900 m wide and 130 m thick(Fig. 10).

The early Holocene is characterized by three glacial advances older than the LIA and which can be correlated to the Kartell, Krömer and Göschenen I stadials of other Alpine settings (Ivy-Ochs *et al.* 2009). During these phases the glaciers were up to 1400 m long, 850 m wide and 80 m thick (Fig. 9d; Fig. 10).

Finally, three glacial advances occurred during the LIA (13^{th}, 17^{th}, and 19^{th} century), and the glaciers became relatively small and essentially concentrated in the cirques of the Gelas, Argentera, Asta and Matto peaks (Fig. 8; (Fig. 10).

Correlations with climate proxies and Alpine glacier fluctuations

The reconstructed glacial phases will be here discussed in relation to climatic events of hemispheric and Alpine/Mediterranean scale relevance as recorded by various proxies, e.g. Greenland ice cores, other Alpine glacial fluctuations, speleothems, lake geochemistry and Mediterranean marine sediments.

The age of the Andonno-Tetti del Bandito moraine (24.0 ka) frames the LGM phase of the Maritime Alps at the Marine Isotope Stage 2 (MIS 2, 18-30 ka) (Fig. 11), consistent with the GS-2c substadial registered in Greenland ice cores (GRIP) (Björck *et al.* 1998). Moreover, the recalculated age fits well with the recent definition of the global LGM as 23-27 ka (Hughes & Gibbard 2015). This confirms that the MIS 2 was the period of maximum expansion of the glaciers in the Alps (Monegato *et al.* 2007; Gianotti *et al.* 2008; Ravazzi *et al*. 2014), unlike other Mediterranean mountains, e.g. the Balkans, Iberia and Morocco ranges, and part of the Pyrenees (García-Ruiz *et al.* 2003; Hughes & Woodward 2008; Hughes *et al.* 2014). The importance of the MIS 2 climatic signal in the Western Alps is further confirmed by offshore sediments in the Mediterranean Sea, for example near the mouth of the Var River that drains the French side of the Maritime Alps. Here, the frequency of deep-water turbidity current overflows reaches the maximum during the MIS 2 (Bonneau *et al*. 2014), thus suggesting humid conditions and high debris availability that have favored the occurrence of river floods with high suspended-sediment concentration.

The recalculated age of Ponte Murato to the Bühl stadial (18.5 ka) is a novelty for the Alpine chronology, where only a few constraints are reported for this Lateglacial phase. The Bühl stadial corresponds chronologically to the hemispheric cold event (GS-2b substadial) detected in the GRIP (Björck *et al.* 1998). The Gesso glacier responded to the cold event of the Younger Dryas (~13.0-11.5 ka) with the readvance of the Egesen stadial at Piano del Praiet (13.0 ka). This response was relatively synchronous (+/- 690 years) to many other glaciers in the Alps and other mountains of Europe and the Near East, and matches well with the chronology of the same climatic event as recorded by other Arctic (GS-1 Greenland stadial) and European proxies (von Grafenstein *et al* 1999; Heiri *et al* 2014; Brisset *et al* 2015) (Fig. 11).

The cold phases responsible for the deposition of the Lombard and Malariva moraines (respectively Kartell and Kromer (?) stadials) are most likely correlated with the Pre-Boreal

Oscillation (11.3-11.6 ka) (PBO) and to the 8.2 ka cold event (8.1-8.4 ka) (Rasmussen et al, 2007), similar to other glaciers advances in the Alps (Kerschner *et al.* 2006; Nicolussi & Schlüchter 2012). However, in light of recent studies in the Alps (Schindelwig *et al.* 2012), a potential correlation with the 9.3 ka cold event (Fig. 11) cannot be excluded *a priori* for one of these advances. These climatic phases are also visible in other alpine and sub-alpine terrestrial proxies, i.e. decrease in $\delta^{18}O$ composition in speleothems and lake cores, lake level high-stands and increase in detritical input in Alpine lakes (i.e. increase in magnetic susceptibility of lake sediments) (Holzauser 1997; von Graftenstein *et al.* 2008; Boch *et al.* 2009; Debret *et al* 2010; Leutscher *et al.* 2011) (Fig. 10). The regional relevance of these cold phases goes well beyond the Alps, as documented by the fact that they are also found in Greenland and North Atlantic proxies (Rasmussen *et al.* 2007; Kobashi *et al.* 2008).

The Vallette moraine system (Göschenen I (?) stadial) was deposited during the cold and wet Late Subboreal climatic fluctuation, which corresponds to the Iron Age (2500-4200 yr BP) in Europe (Haas *et al.* 1998; van Geel & Renssen 1998; van Geel *et al.* 1996). This is a time when many other alpine glaciers advanced, e.g. Ghiacciaio dei Forni (Italy) (Orombelli & Pelfini 1985), Great Aletsch and Stein glaciers (Switzerland) (Holzhauser *et al.* 1997; Schimmelpfenning *et al.* 2014) (Fig. 11). This cold phase can be framed inside the climate deterioration that characterized the second half of the Holocene as registered by the Arctic and North Atlantic proxies (Bond *et al.* 1997; Kobashi *et al.* 2013), and discontinuously by other Alpine terrestrial proxies (Holzhauser *et al* 2005; Vollweiler *et al* 2006, Debret *et al* 2010 (Fig. 11).

Similar to the majority of the Alpine glaciers, the Maritime Alps glaciers reacted to the SubAtlantic LIA cold phase with three advances (13^{th}, 17^{th} and 19^{th} century). However, and unlike other glaciers in the Alps (Röthlisberger & Schneebeli, 1979; Holzhauser *et al.* 2005), the LIA expansion of the Gesso basin glaciers was not the most important glacial phase of the Holocene, i.e. the LIA glaciers did not overrode antecedent Holocene moraines. Only in a few cases, the LIA and Late Subboreal Maritime Alps moraines interacted with each other, resulting in an undistinguishable Holocene ablation complex (Finsinger & Ribolini, 2001, Ribolini & Fabre, 2007). It is worth to notice that in some cases both the LIA and Subboreal moraines underwent post depositional deformative events caused by permafrost creep (Ribolini *et al* 2007; Ribolini *et al.* 2010), thus complicating their identification in the field and potentially leading to an incomplete reconstruction of stadial sequence. Interestingly, of all LIA pulsations, the geomorphological and lichenometric data indicate that the 17^{th} century's was the most important phase, unlike what it has been commonly found in most other Alpine sectors, where the 19^{th} century's is the strongest phase. This different behavior could be related to the enhanced mitigation effect of the nearby Mediterranean Sea on later cold pulsations, combined with the role played by glaciers size, bed steepness and hypsometry (Kuhn, 1985; Oerlemans *et al.*, 1992). According to the authors (Oerlemans 2005; Schindelwig *et al.* 2012), steep and small glaciers such as the ones in question may react to climatic solicitations with decade-annual fluctuations of low amplitude.

Following the second half of the 19th century, a continuous and inexorable contraction affected the already small glaciers of the Maritimes Alps (Federici & Pappalardo 2010). In many cases, the small cirque glaciers became debris-covered and generally stopped reacting to any climatic change. Hence, it is no surprise that these disappearing glaciers did not record the positive pulses described in the Alps in the 1920s and during the 1960-1985 interval (Camoletto, 1931; Zanon, 1985). Nor did they react to the inter-annual variability of climatic conditions of the last decades, thus suggesting that their complete exhaustion could be imminent.

Conclusions

The attempts carried out in the past to define the LGM to Holocene glacial history of the SW Alps (Peretti 1935; Trevisan 1939; Malaroda 1948; Castiglioni 1961; Mayr & Heuberger 1968) suffered the lack of a continuous and chronologically constrained sequence of frontal moraines. In this paper we have presented a complete sequence of glacial phases/stadials within a same valley system in the Maritime Alps, at the southern end of the Alpine chain.

The sequence is geomorphologically and morphostratigraphically coherent, and most phases/stadials have been chronologically constrained. The LGM found at Tetti Bandito bears a similar age to that of other LGM moraines across the Alps and further highlight the different behavior of the Alps glaciers in comparison with other mountain chains across Europe. The recognized Lateglacial stadials of Ponte Murato, Entracque, S. Giacomo, and Piano del Praiet, show strict similarities (age and ELA) with corresponding stadials of the centre-eastern Alpine valleys where the Lateglacial stratigraphy has been defined, i.e. Gschnitz, Bühl , Daun and Egesen. Although the Clavadel/sender stadial was not documented, the Bühl stadial is chronologically constrained here for the first time in the Alps. Lichenometry provides ages of the Little Ice Age moraines, whereas the chronology of the other Holocene moraines is argued by correlation with nearby valleys in the studied area and other Alpine sectors. Three early Holocene glacial advances are defined in our stadial sequence (Ricovero Lombard, Ricovero Mallariva and Vallette moraines), that can be correlated to the Kartell, Kromer and Göschenen I stadials widely recognized in the centre-eastern Alps. Following the second half of the 19th century, a continuous and inexorable contraction characterized the Maritime Alps glaciers. In the past few decades, these glaciers have essentially stopped responding to the inter-annual variability of climatic conditions, sign of an imminent exhaustion.

Overall, the reconstructed sequence of glacial advances/standstills indicates that the SW Alps recorded a non-linear trend of deglaciation, analogously to the rest of the Alps. However, some palaeoglaciological differences (i.e. ELA) can be noted, partly related to the particular geographic setting (proximity to the Mediterranean Sea) and partly to the dynamic behavior of relatively small and steep glaciers, especially during the Holocene.

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Table 1 - Synoptic panel of the moraines (Mor) and glacial deposits (Dep) composing the Lateglacial-Holocene sequence of stadials of the Maritime Alps. Moraine average exposure ages after (a) Federici *et al.* 2008 and (b) Federici *et al.* 2011. The ages were recalculated adopting the North America production rate using LM (Balco *et al* 2009). Moraine lichenometric ages (c) after Federici & Stefanini 2001.

Moraine/deposit name	Type	Lat (UTM 32T)	Long (UTM 32T)	Elevation (m asl)	Age (yrs)	External error (yrs)	Average Age (yrs)
Tetti del Bandito	Dep	4905246	374942	710-730	23,956 21,571	1,610 1,443	22,764[a]
Valdieri-La Bastia	Dep	4903736	371703	780-830			
Ponte Murato	Mor	4901204	371109	820-880	16,871 18,723 12,875 19,757	1,336 1,201 1,098 1,246	18,450 [a]
La Piastra sx La Piastra dx Serrera castagni	Dep Mor Mor	4898343 4898100 4896931	371299 372477 373831	930-950 1060-1120 1150-1330			
San Giacomo	Dep	4892584	370959	1260-1300			
Peirastretta	Dep	4889477	369520	1650			
Piano del Praiet	Mor	488826	369069	1800	13,930 13,668 13,055 12,043 12,627	903 1,046 847 801 801	13,174[b]
Ric.Lombard	Mor	4887169	368975	2050-2085			
Ric. Malariva	Mor	4886815	369220	2160-2260			
Vallette	Mor	4886419	369435	2480-2540			
Gelas	Mor	4886949	370263	2690-2745			13th, 17th, 19th [c]

Table 2 - ELA values for Lateglacial and Holocene moraines in the Gesso Valley of the Maritime Alps (a), South -Western French Alps (b) (Cossart et al, 2012) and Central-Eastern Alps (c) (Ivy-Ochs et al, 2006 and references there in). AABR is Accumulation Area Balance Ratio method (ratio 1.6); AAR is the Accumulation Area Ratio method (ratio 0.67). ΔELA is the ELA depression in respect to the Little Ice Age value. Alpine stadial terminology after Maisch *et al.*, 1999.

	Maritime Alps (a)					SW Alps (b)	Central and Eastern Alps (c)
Alpine stadial	**Moraine name**	**ELA (m a.s.l.) AABR meth**	**ELA (m a.s.l.) AAR meth**	**ΔELA (m) AABR meth**	**ΔELA (m) AAR meth**	***ΔELA (m) AAR meth***	**ΔELA (m) AAR meth**
LGM	Tetti del Bandito Valdieri-La Bastia	1845 1845	1685 1703	996 996	1125 1107	*-980*	-1200 to 1000
Bühl	Ponte Murato	1873	1733	968	1077		-1200 to -800
Gschnitz	La Piastra sx La Piastra dx Serrera Castagni	1964	1809	877	1001		-700 to -650
Daun	San Giacomo	2016	1956	825	854	*-560 to -700*	-400 to -250
Egesen	Peirastretta Piano del Praiet	2217 2368	2207 2305	624 473	603 505	*-390 to -490*	-450 to -180
Kartell	Ric.Lombard	2411	2358	430	452	*-210 to -250*	-120
Kromer	Ric. Malariva	2464	2436	377	374		-75
Göschenen I	Vallette	2640	2617	201	193	*220*	?
Little Ice Age	Gelas	2841	2810	0		*0*	0

Figure captions

Figure 1 - Geographic sketch map of the South Western Alps. The Gesso basin in the Maritime Alps is indicated, along with the Gesso della Barra river.

Figure 2 - Some of the glaciers of the Maritime Alps. a) Gelas North East glacier; b) Gelas North glacier; c) Clapier glacier; d) Maledia glacier; e) Peirabroc glacier; f) Lorousa glacier. Lichenometry ages of Little Ace Age moraines by Federici and Stefanini (2001).

Figure 3 - Moraines defining the principal Lateglacial and Holocene stadials in the Maritime Alps: Ponte Murato (a), Serrera dei Castagni (b), Piano del Praiet (c), Ricovero Lombard (d), Ricovero Malariva (e), Vallette and Gelas (f) moraines. White arrows indicate possible ice flow direction.

Figure 4 - Sketch map of the area of LGM glacier front (Andonno-Tetti del Bandito). 1) glacial deposit; 2) debris cone; 3) trace of possible moraine front. It is outlined the possible position of a sub-stadial referable to Valdieri-La Bastia deposits. Average value of exposure ages as recalculated after Federici *et al.* (2012).

Figure 5 - Sketch map of the area of the Ponte Murato and Entracque village. 1) glacial deposit; 2) lacustrine deposit; 3) moraine ridge; 4) trace of possible moraine front; 5) polished and striated rock surface; 6) scarp of glacial origin. It is outlined the position of the Bühl glacier front (Ponte Murato moraine) and the possible position of the Gschnitz glaciers front (La Piastra and Serrera dei Castagni moraines). Average value of exposure ages as recalculated after Federici *et al.* (2011).

Figure 6 - Sketch map of the area of San Giacomo village, with the glacial deposits possibly drawing the glacier front of the Daun stadial. 1) glacial deposit; 2) debris cone; 3) rockfall.

Figure 7 - Sketch map of the area of the Piano del Praiet area, with the frontal moraine drawing outlining the glacier front during the Egesen stadial. Note the Peirastretta deposit, potentially referable to an early Egesen phase. 1) glacial deposit; 2) debris cone; 3) moraine ridge. Average value of exposure ages as recalculated after Federici *et al.* (2011).

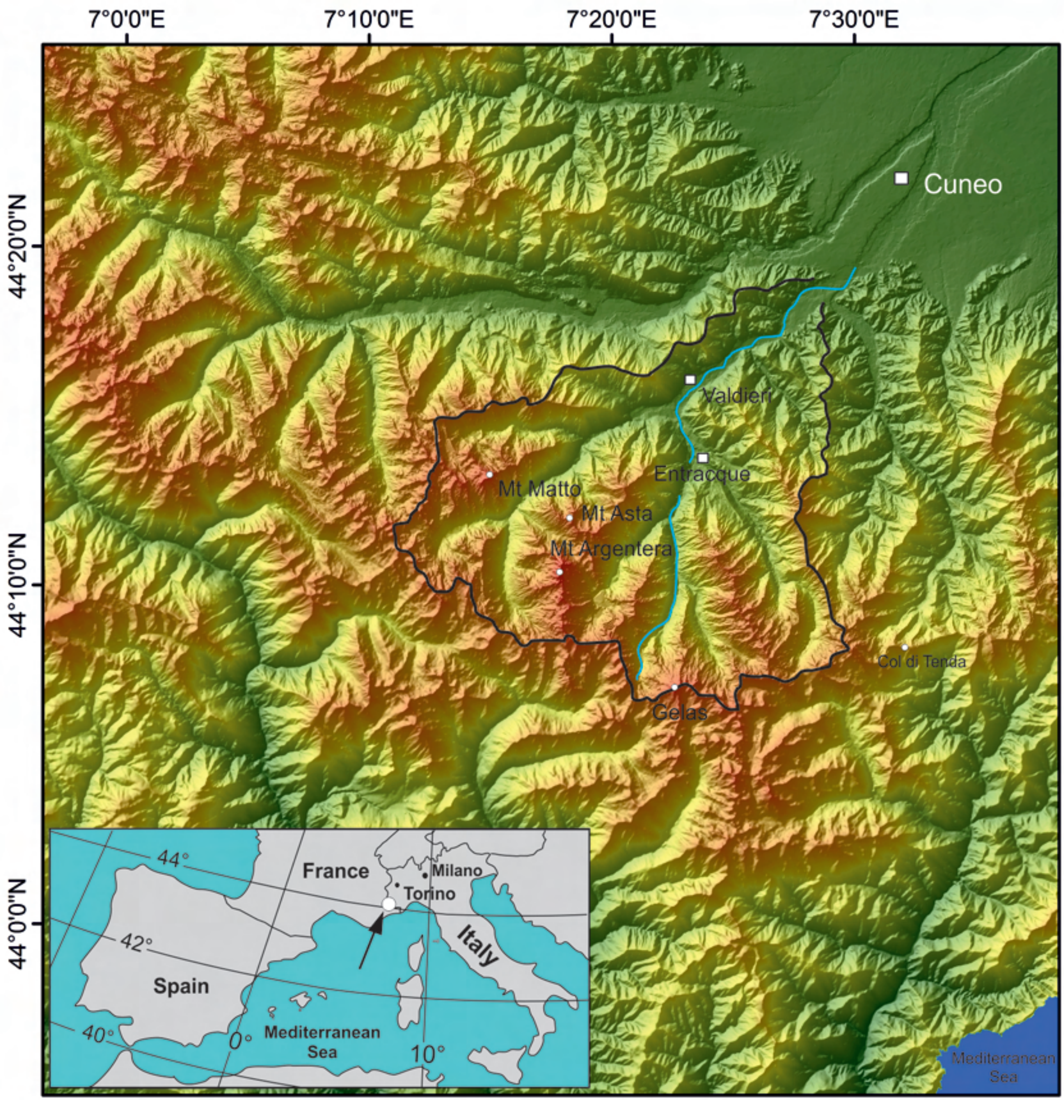
Figure 8 - Sketch map of the uppermost Gesso della Barra river catchment, with the frontal moraines outlining the Kartell, Kromer and Göschenen I stadials, corresponding to the Ricovero Lombard, Ricovero Malariva and Vallette moraines respectively. 1) glacial deposit; 2) rock glacier; 3) glacier; 4) debris cone; 5) moraine ridge; 6) scarp of glacial origin. LIA moraines of the Cima del Gelas crest are indicated with the available lichenometric ages (after Federici & Stefanini 2001).

Figure 9 - Reconstructions of the stadial glaciers of the Maritime Alps for the Last Glacial Maximum (a), Bühl (b), Egesen (c) and Kartell (d) stadials.

Figure 10 – Longitudinal profile of the Gesso Valley with the stadial moraines and glacial deposits discussed in the text (a). ΔELA is the ELA depression with respect to the Little Ice Age ELA value, calculated with AABR methods (see Table 2). The position of the longitudinal profile trace and the discussed moraines within the Gesso basin are shown in (b). Red squares correspond to the valley portions depicted in Figs 4, 5 , 6 , 7 and 8

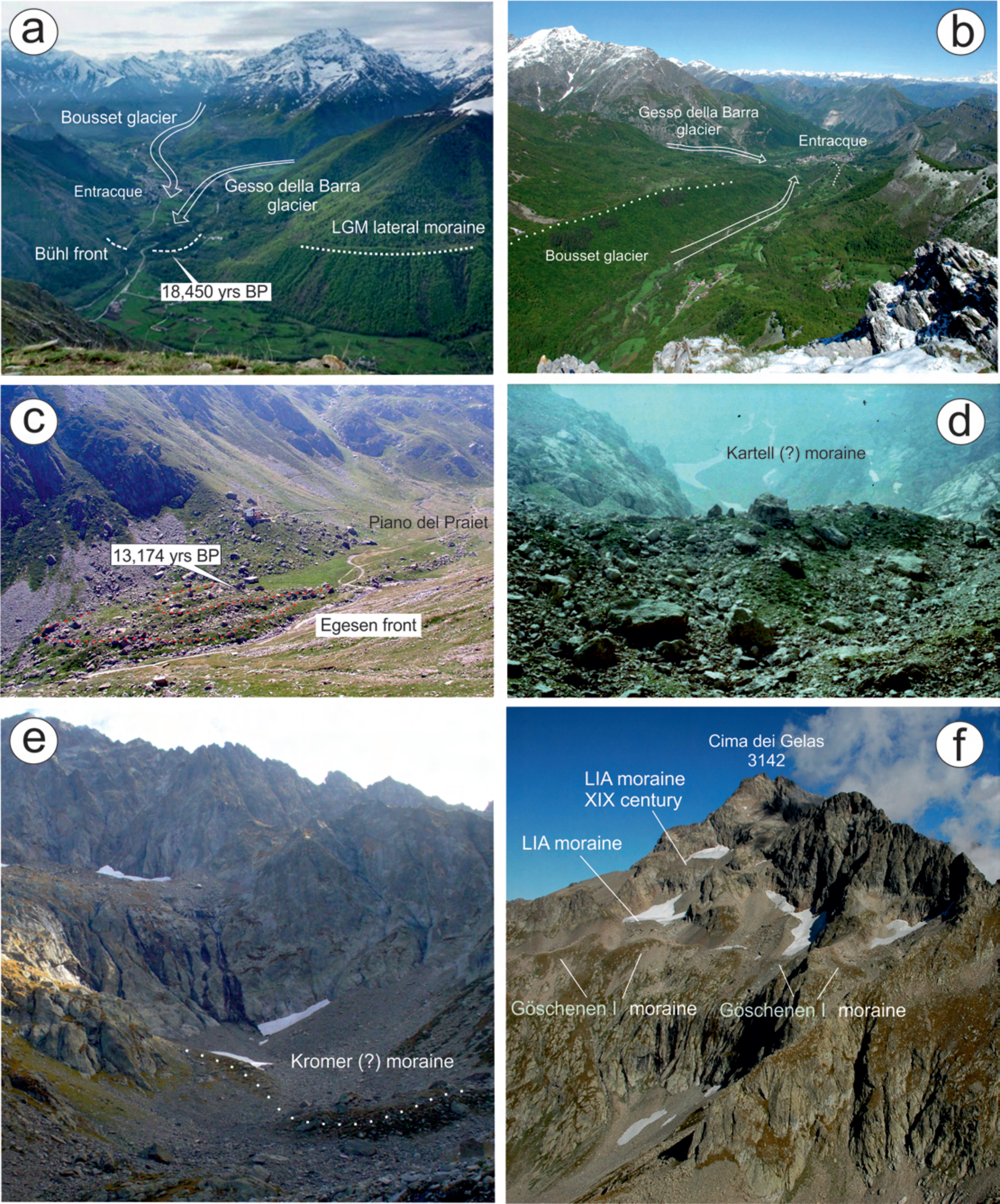
Figure 11 - Comparison between climate proxy data and glacial advances. a) δ^{18}O isotope GRIP ice core (Rasmussen *et al*. 2007); b) record of atmospheric residual δ^{14}C as proxy of solar activity (positive/negative values mean high/low solar activity) (Stuiver *et al.* 1998); c) ice-rafting events in the north Atlantic (Hienrich and Bond events) (Bond et al. 1997); d) δ^{18}O combined record of speleothems from the Spannagel Cave (Austria) (Volleweiler *et al.* 2006); e) δ^{18}O record from benthic organisms from Lake Ammersee (Germany) (von Grafenstein *et al.* 2000); f) lightness signal (L*) (sediment color used as a proxy of carbonate/silica ratio,

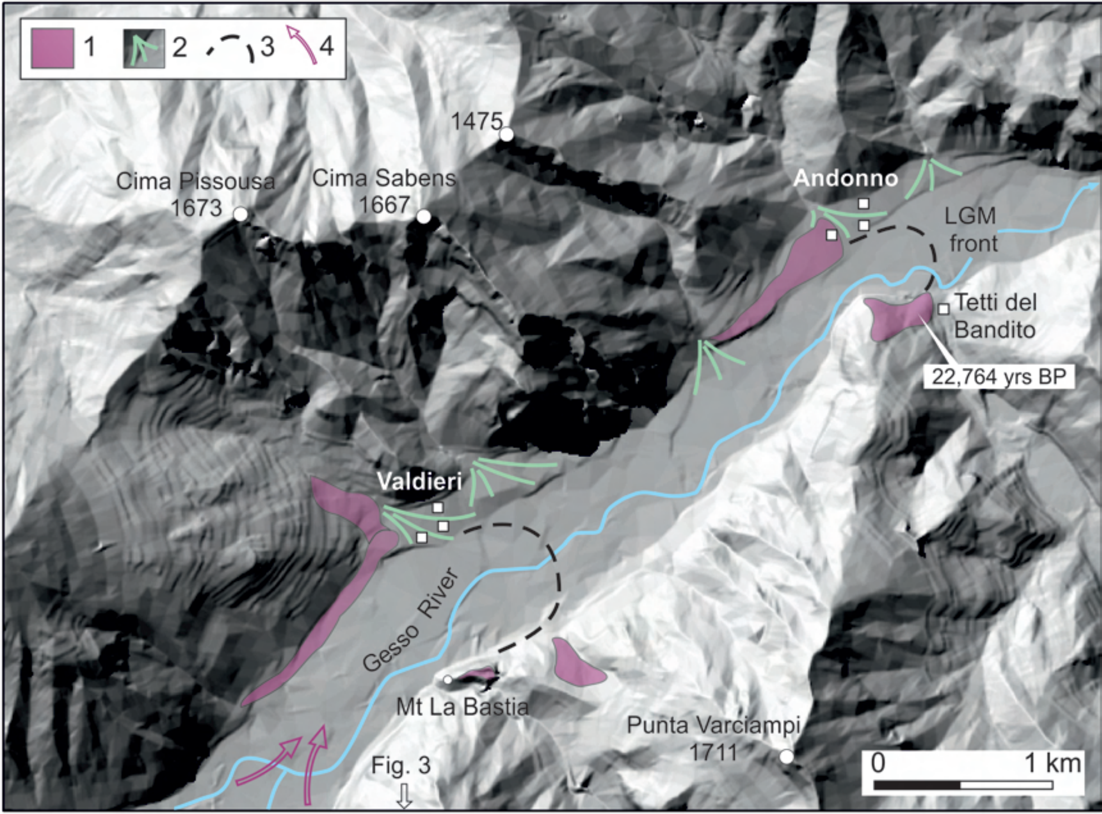
marker of detritism) from Lake Bourget (Western Alps, France) (Debret *et al*. 2010); g) magnetic susceptibility from the Lake Iseo record (North Italy) (Lauterbach *et al.* 2012); h) lake-level highstands in the NW Alps (Magny, 2004); i) main recognized glacial advances in the NW Alps (Mt Bianco and Southern French Alps) (Deline and Orombelli 2005; Gianotti *et al.* 2008; Cossart *et al.* 2012; Le Roy *et al.* 2015 and reference therein); l) main recognized glacial advances in the centre-eastern Alps (Ivy-Ochs et al. 2006; Ivy-Ochs et al. 2008; Ivy-Ochs et al. 2009); m) dated and inferred glacial advances in the Maritime Alps (this paper). LGM: Last Glacial Maximum; OldestD: Oldest Dryas, BO: Bolling; OlderD: Older Dryas; si è contebYD: Younger Dryas; PB: PreBoreal; BO: Boreal; AT: Atlantic; SB: SubAtlantic; H: Heinrich event.

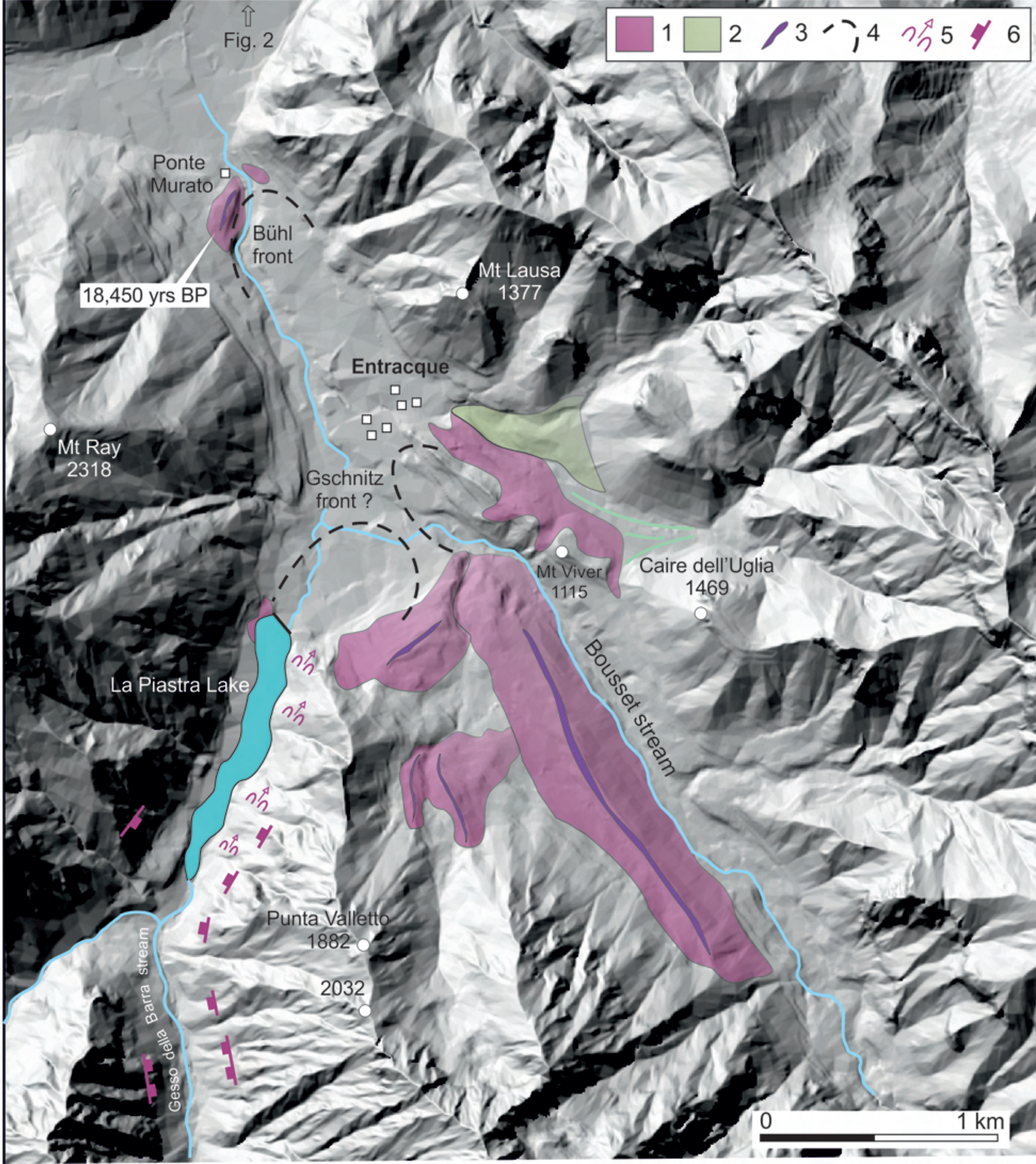


7°0'0"E
7°10'0"E
7°20'0"E
7°30'0"E
44°20'0"N
44°10'0"N
44°0'0"N
Cuneo
Valdieri
Entracque
Mt Matto
Mt Asta
Mt Argentera
Col di Tenda
Gelas
Mediterranean Sea
44°
42°
40°
0°
10°
France
Milano
Torino
Italy
Spain
Mediterranean Sea

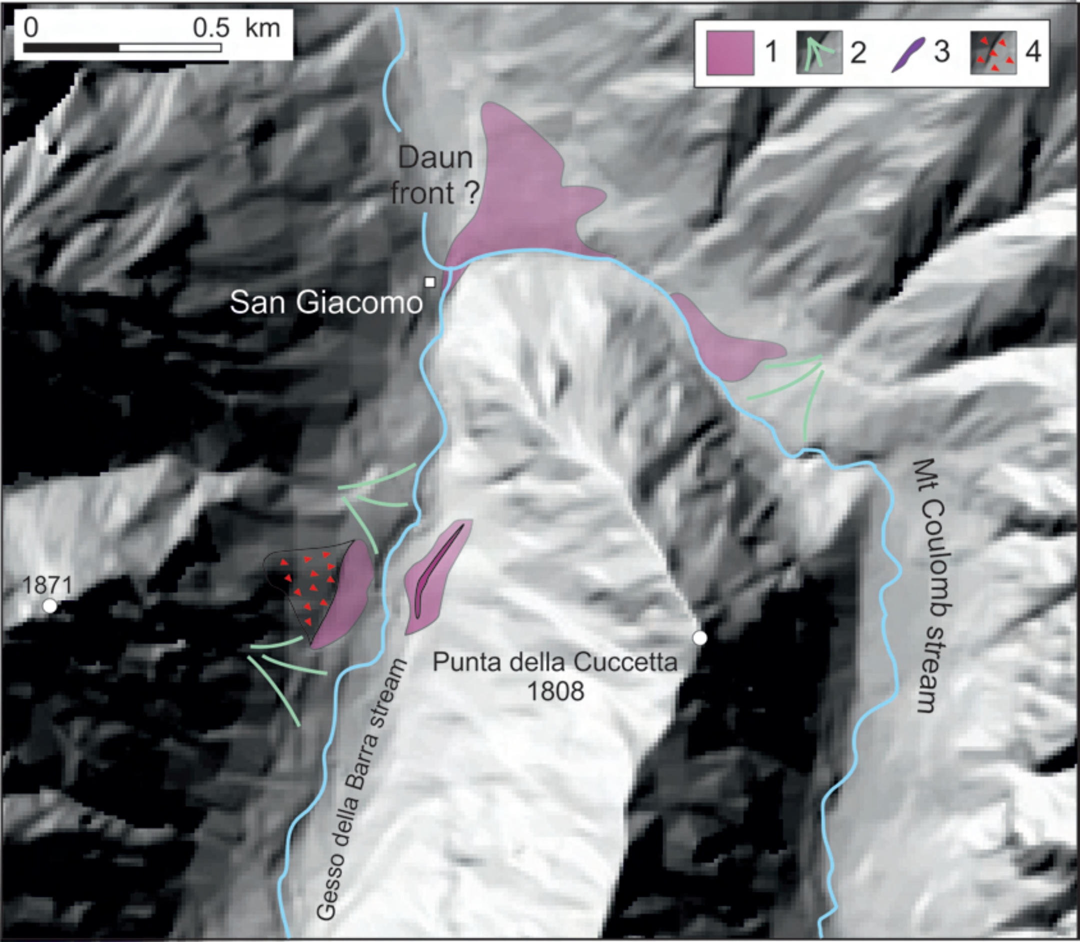
a
Gelas North East
Glacier
LIA moraine
XIX century
LIA moraine
~1685 AD
b
Gelas North
Glacier
c
Clapier Glacier
d
Maledia Glacier
LIA moraine
XIX century
e
Peirabroc Glacier
LIA moraine
~1690 AD
f
Cima Argentera
3297
Lorousa Glacier
LIA moraine
~1825 AD

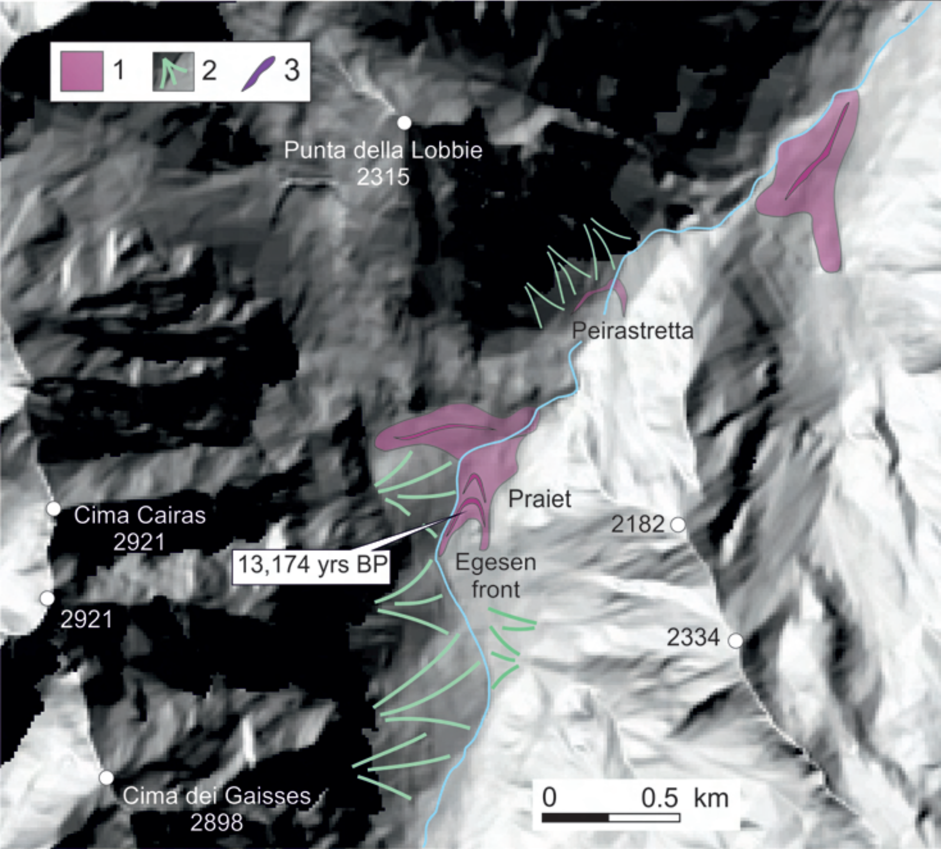

a
Bousset glacier
Entracque
Gesso della Barra
glacier
LGM lateral moraine
Bühl front
18,450 yrs BP
b
Gesso della Barra
glacier
Entracque
Bousset glacier
c
Piano del Praiet
13,174 yrs BP
Egesen front
d
Kartell (?) moraine
e
Kromer (?) moraine
f
Cima dei Gelas
3142
LIA moraine
XIX century
LIA moraine
Göschenen I moraine
Göschenen I moraine


1
2
3
4
1475
Cima Pissousa
1673
Cima Sabens
1667
Andonno
LGM
front
Tetti del
Bandito
22,764 yrs BP
Valdieri
Gesso River
Mt La Bastia
Punta Varciampi
1711
Fig. 3
0
1 km

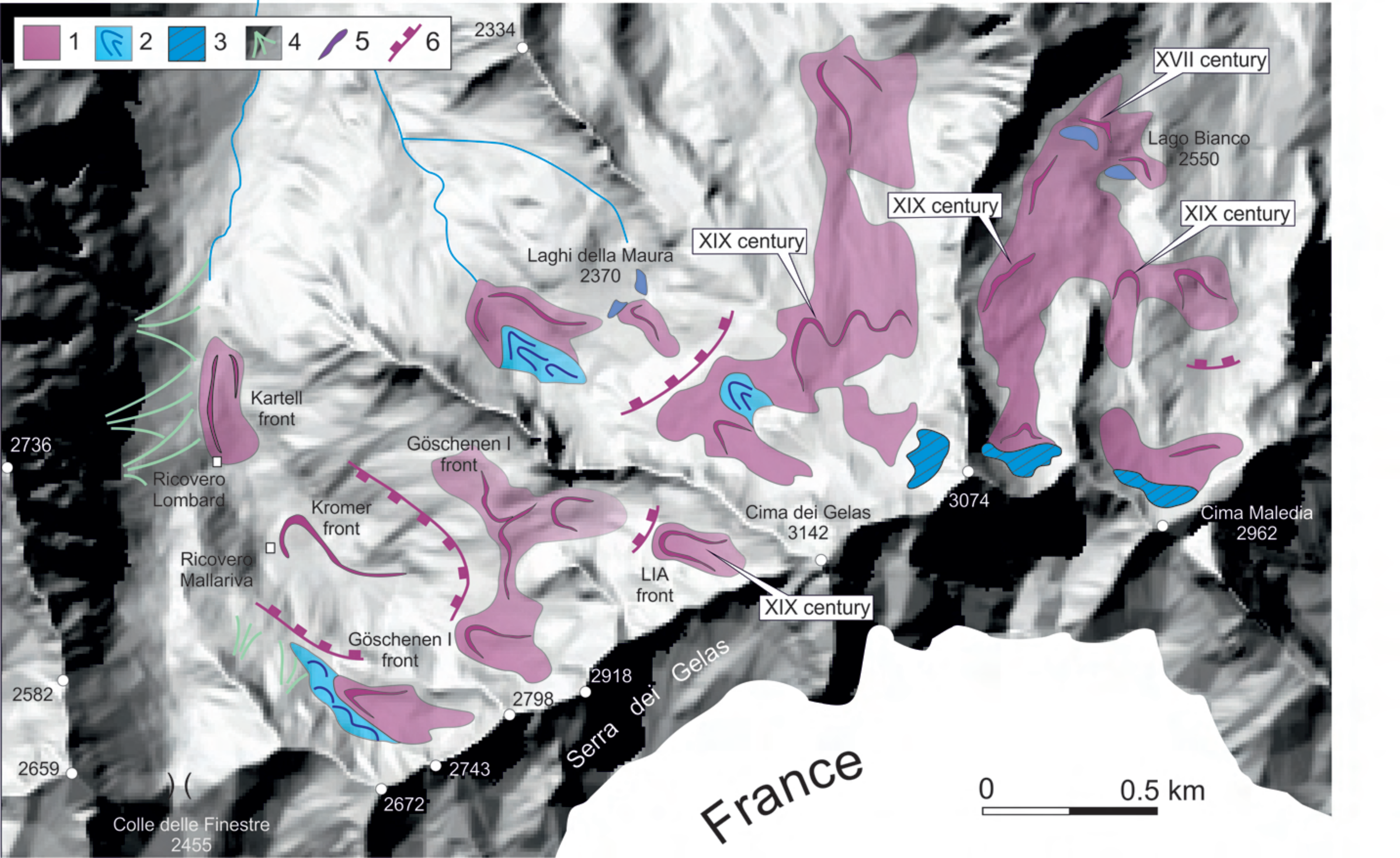


1
2
3
4
5
6
Fig. 2
Ponte Murato
Bühl front
18,450 yrs BP
Mt Lausa 1377
Entracque
Mt Ray 2318
Gschnitz front ?
Mt Viver 1115
Caire dell'Uglia 1469
La Piastra Lake
Bousset stream
Punta Valletto 1882
2032
Gesso della Barra stream
0
1 km

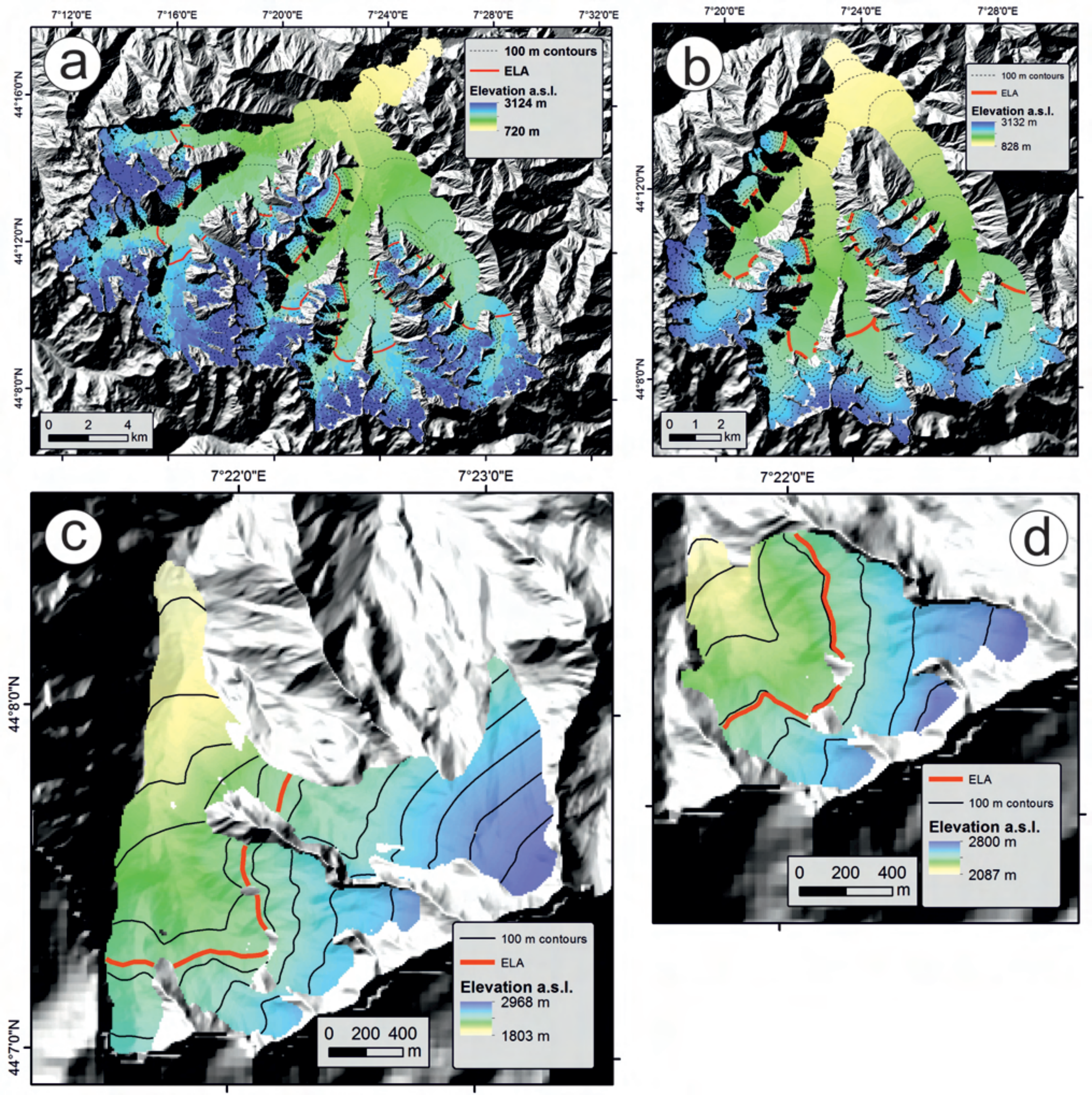

0
0.5 km
1
2
3
4
Daun
front ?
San Giacomo
1871
Punta della Cuccetta
1808
Gesso della Barra stream
Mt Coulomb stream



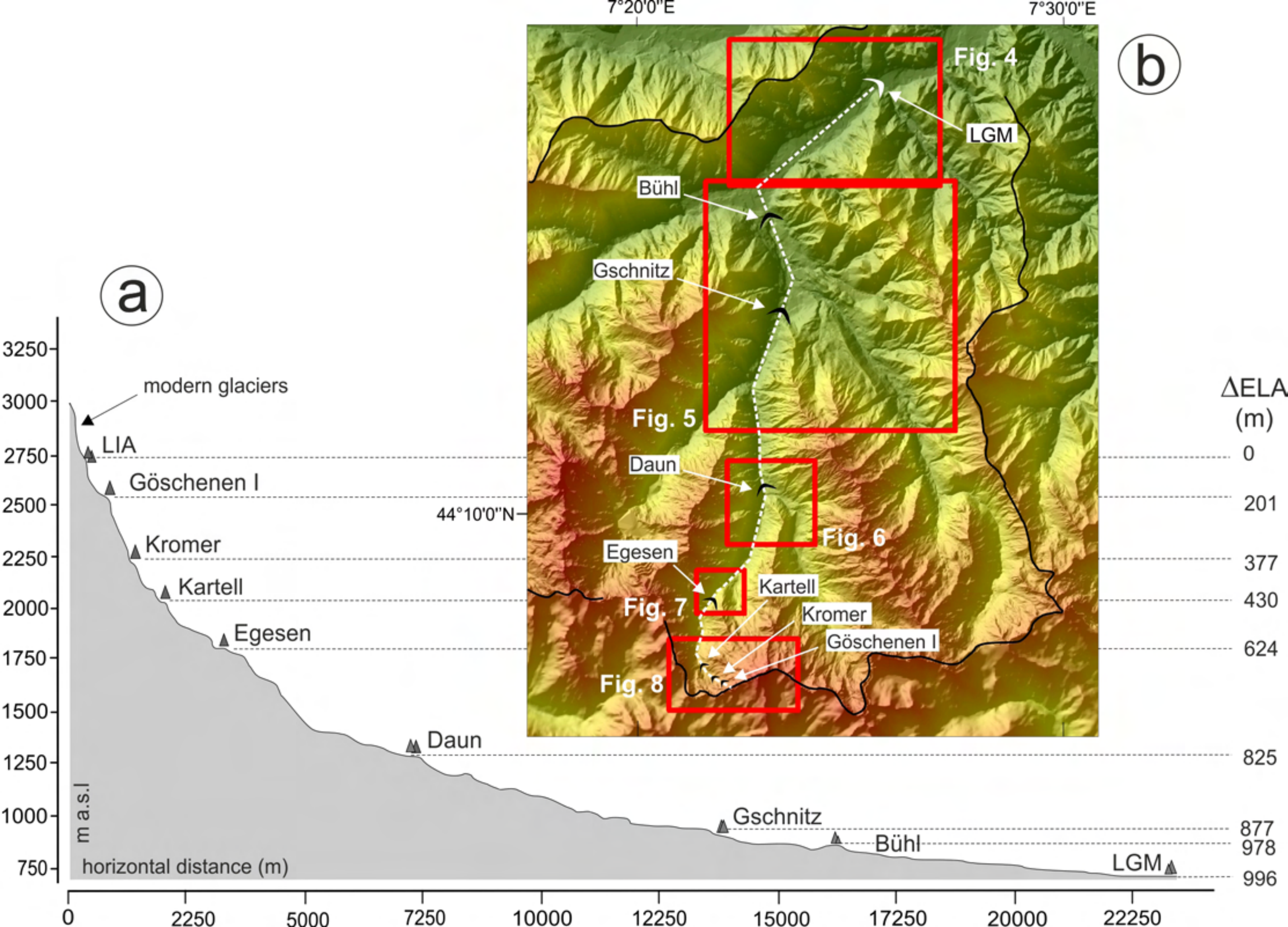
1
2
3
Punta della Lobbie
2315
Peirastretta
Praiet
Cima Cairas
2921
2182
13,174 yrs BP
Egesen
front
2921
2334
Cima dei Gaisses
2898
0
0.5 km



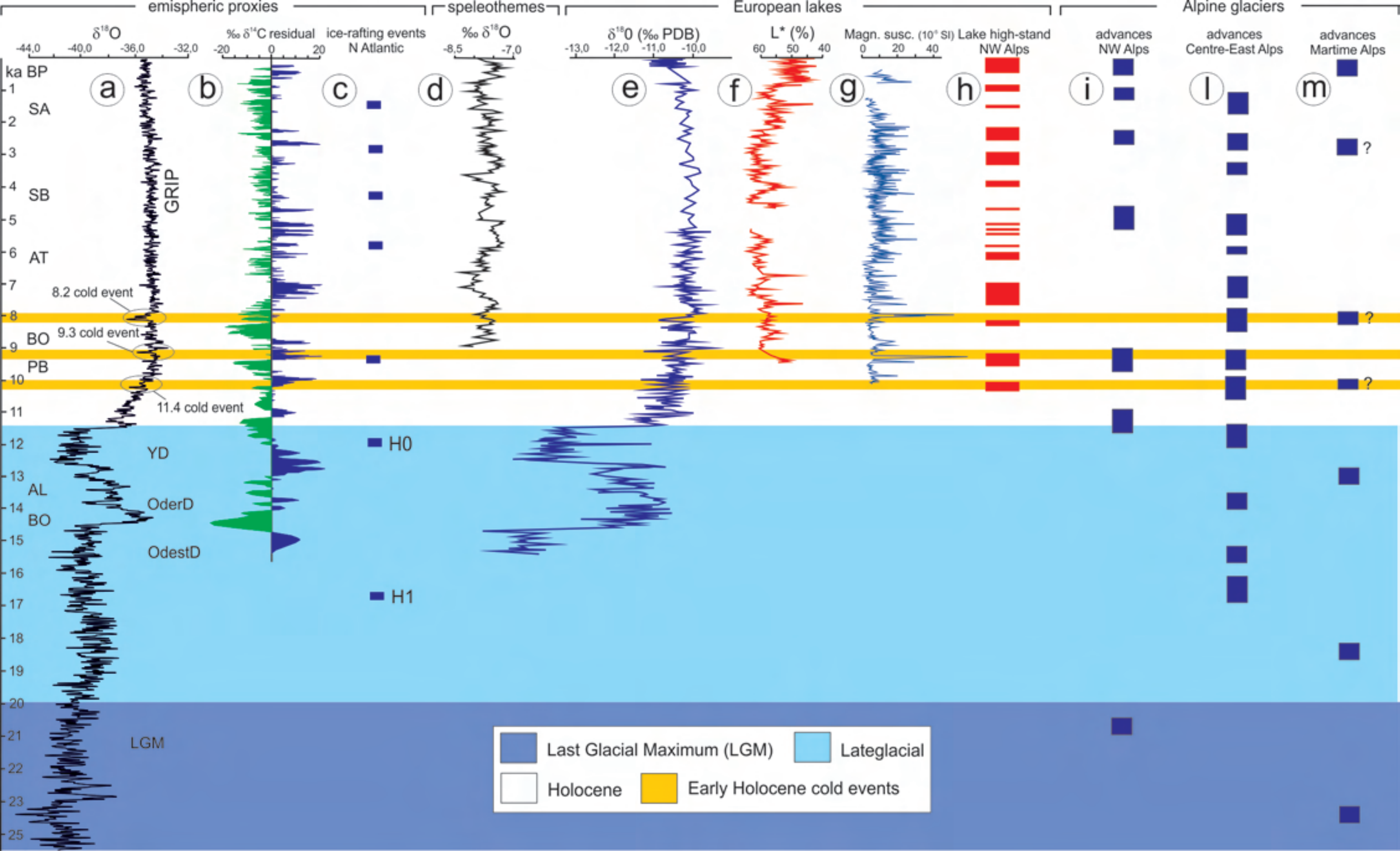
1
2
3
4
5
6
2334
XVII century
Lago Bianco
2550
XIX century
XIX century
XIX century
Laghi della Maura
2370
Kartell
front
2736
Ricovero
Lombard
Göschenen I
front
Kromer
front
Ricovero
Mallariva
LIA
front
XIX century
Cima dei Gelas
3142
3074
Cima Maledia
2962
Göschenen I
front
2918
2798
Serra dei Gelas
2582
2743
2659
2672
Colle delle Finestre
2455
France
0
0.5 km



a
100 m contours
ELA
Elevation a.s.l.
3124 m
720 m
7°12'0"E
7°16'0"E
7°20'0"E
7°24'0"E
7°28'0"E
7°32'0"E
44°16'0"N
44°12'0"N
44°8'0"N
0 2 4 km
b
100 m contours
ELA
Elevation a.s.l.
3132 m
828 m
7°20'0"E
7°24'0"E
7°28'0"E
44°12'0"N
44°8'0"N
0 1 2 km
c
7°22'0"E
7°23'0"E
44°8'0"N
44°7'0"N
100 m contours
ELA
Elevation a.s.l.
2968 m
1803 m
0 200 400 m
d
7°22'0"E
ELA
100 m contours
Elevation a.s.l.
2800 m
2087 m
0 200 400 m



7°20'0"E
7°30'0"E
b
Fig. 4
LGM
Bühl
Gschnitz
Fig. 5
Daun
Fig. 6
44°10'0"N
Egesen
Fig. 7
Kartell
Kromer
Göschenen I
Fig. 8
a
modern glaciers
LIA
Göschenen I
Kromer
Kartell
Egesen
Daun
Gschnitz
Bühl
LGM
ΔELA (m)
0
201
377
430
624
825
877
978
996
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
m a.s.l
horizontal distance (m)
0
2250
5000
7250
10000
12250
15000
17250
20000
22250



emispheric proxies
speleothemes
European lakes
Alpine glaciers
δ18O
‰ δ14C residual
ice-rafting events N Atlantic
‰ δ18O
δ18O (‰ PDB)
L* (%)
Magn. susc. (10-5 SI)
Lake high-stand NW Alps
advances NW Alps
advances Centre-East Alps
advances Martime Alps
-44,0 -40,0 -36,0 -32,0
-20 0 20
-8,5 -7,0
-13,0 -12,0 -11,0 -10,0
60 50 40
0 20 40
ka BP
a b c d e f g h i l m
SA
SB
AT
BO
PB
AL
BO
GRIP
8.2 cold event
9.3 cold event
11.4 cold event
YD
OderD
OdestD
LGM
H0
H1
?
Last Glacial Maximum (LGM)
Lateglacial
Holocene
Early Holocene cold events