Available online http://amq.aiqua.it
ISSN (print): 2279-7327, ISSN (online): 2279-7335

Alpine and Mediterranean Quaternary, 30 (1), 2017, 51-67

REAPPRAISAL OF LATEGLACIAL STADIALS IN THE EASTERN ALPS: THE CASE STUDY OF VALPAROLA (EASTERN DOLOMITES, ITALY)

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ABSTRACT: This study aims to be a reappraisal of the Lateglacial stadials of the Dolomites. This has been accomplished by investigating the stadial moraine deposits in the pilot area of Valparola, in the light of the most recent techniques to reconstruct paleo-glaciers and to calculate their Equilibrium Line Altitude (ELA). The use of these techniques in Valparola could rely on a detailed geomorphological survey, in turn aided by the analysis of a LiDAR DEM. The results obtained, in terms of stadial attribution, have been compared to those obtained by a previous author, the last one to study the Lateglacial of the area already half a century ago. The comparison has allowed to verify how much improvement these techniques may offer to the knowledge of the local Lateglacial and their feasibility to extend the analysis to wider areas. Some knowledge gaps have also been highlighted, which should be taken into account in further studies. The analysis procedure tested in Valparola is proposed as a possible reference for the reappraisal of the Lateglacial over the whole Dolomites. Possibly, this could stir up new attention towards the study of the Lateglacial over the Alps, for which a comprehensive picture is still lacking.

Keywords: Glacial landforms, Lateglacial stadials, paleo-ELA, Dolomites, Italy.

1. INTRODUCTION

Half a century has passed since the publication of the milestone study on the stadial moraine deposits of the Dolomites by G.B. Castiglioni (1964). The study had the great merit to give a first overall framework of the Lateglacial of a large portion of the Alpine region, with important implications for its paleo-environmental reconstruction. The scale of the study, however, did not enable the detailed identification of glacial landforms and reconstruction of the respective paleo-glaciers. Despite progresses of methods to reconstruct paleo-glaciers and to calculate Equilibrium Line Altitudes (ELA) of current and former glaciers, the study has never been updated. The detailed reconstruction of paleo-glaciers (Sissons, 1974; Porter, 1975; Porter & Orombelli, 1982; Carr & Coleman, 2007; Ben & Hulton, 2010; Pellitero et al., 2016) has become increasingly important for calculating the respective ELA, the essential element for the relative dating of Lateglacial readvances. Also the approaches to obtain the ELA of current and paleo-glaciers have undergone a remarkable evolution (Sissons, 1974; Porter, 1975; Sissons & Sutherland, Gross et al., 1977; Meierding, 1982; Furbish & Andrews, 1984; Kerschner, 1990; Torsnes et al., 1993; Benn & Gemmell, 1997; Benn & lehmkuhl, 2000; Benn et al., 2005; Osmaston, 2005; Rea; 2009). Lastly, the possibility to assign absolute dates to the glacial deposits through 14C and, increasingly in the last decades, through cosmogenic nuclides, allows to constrain the classic stadials – in turn frequently modified through time (Penck & Brückner, 1909; von Klebelsberg, 1948; 1950; Maisch, 1982; van Husen, 1997; 2000; Ivy-Ochs et al., 2008; Heiri et al., 2014) – within gradually more precise temporal bounds (Ivy-Ochs et al., 2006; 2008; 2009).

The aim of this study is to investigate the stadial moraine deposits of the Dolomites within the pilot study area of Valparola, in the light of the most advanced techniques to reconstruct paleo-glaciers and paleo-ELAs (Benn & Hulton, 2010; Osmaston, 2005; Rea, 2009; Pellitero et al., 2015; 2016), which can also be easily implemented within Geographical Information Systems. The research, by comparing the outputs achieved with Castiglioni's interpretations, has also allowed to test how much improvement these techniques may offer to the reconstruction of the local Lateglacial and to highlight the knowledge gaps still to be filled for their full applicability. Some considerations will be made on the use of absolute dating in the specific geological and geomorphological conditions of the study area, which apply to other areas in the Dolomites.

The comparison with Castiglioni's results within this small pilot area aims to be an attempt to stir up a renewed attention towards the study of the Lateglacial, for which a comprehensive picture is still lacking over the Alpine region. The procedure adopted here, along with the uncertainties that have come out from its application in Valparola, is proposed as a possible reference for the reconstruction of the Lateglacial in other areas.

2. THE STUDY AREA

The study area is located within the Upper Badia Valley, at the boundary between the Autonomous Province of Bolzano and the Belluno Province (Veneto Region), in the Eastern Dolomites, Italy (Fig. 1) (see Marchetti et al., 2017). The main orographic features bounding the area are, to the north, Piz dles Conturines (3064 m), to the south, Mount Setsas (2571 m) linked to the Valparola Pass (2187 m), to the east Monte de Lagazuoi (2718 m) and, to the west, peak Les Pizades (2255 m) and the torrent Rü de Störes. The minimum altitude is at locality Armentarola (1615 m) while the maximum is at Piz dles Conturines (3064 m). The extent is about 20 km^2.

The area lies within the basin of the Adige River, next to the watershed of the Piave River basin. The drainage network is composed by two main torrents, the Rü Sciarè and the Rü de Col dai Furns, receiving inputs from many ephemeral streams.

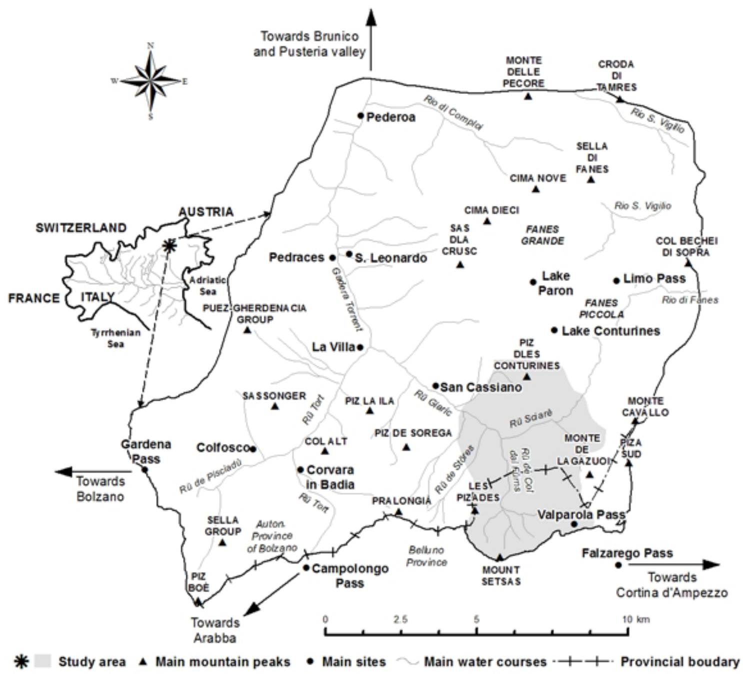

Fig. 1 - Location of study area, between the Autonomous Province of Bolzano/ South Tyrol and the Belluno Province (Veneto Region), Dolomites, Italy.

Water courses are principally fed by rainfall and snowmelt waters and, at the contact between highly fractured dolomite rocks and the underlying marly and clayey rocks, numerous springs originate, scattered all over the basin at a mean altitude of 2000 m.

The climate can be classified as "temperate-cold" (class "Dfc" according to Köppen, 1931, as modified by Pinna, 1970) through the series of mean monthly air temperatures and precipitations recorded from 1994 to 2014 at the meteorological station of San Cassiano (1545 m). The station can be assumed as representative for the Valparola's climate, as the San Cassiano valley is the continuation towards north-west of Valparola and the distance between the village and the study area about 3 km. Winter months have the lowest values of mean precipitations, around 25 mm, and they coincide with the period of snow cover.

The rocks outcropping in the area are of sedimentary origin and range from the Upper Ladinian to the Norian. The depositional environments are coral reefs and back-reefs, deep-sea basins, marine margins (paralic) and carbonaceous tidal planes (cf. Bosellini, 1996). The mountain groups of Mount Setsas, Piz dles Conturines and Monte de Lagazuoi are mainly formed by massive or stratified dolomites from the Medium-Upper Triassic (Dolomia Cassiana and Dolomia Principale formations), with brittle mechanical behaviour and, secondarily, by marls and silts from the Ladinian and Carnian (Pordoi, Heiligkreutz and Travenanzes formations), with ductile behaviour. The slopes at the cliff-base of the previously cited groups are formed by complex lithologies, composed by pyroclastic sandstones and siltstones from the Medium Triassic (Wengen Formation) and by sequences of calcarenites, marls and silts form the Medium-Upper Triassic (S. Cassiano Formation) (cf. Brandner et al., 2007).

From the geomorphological point of view, Valparola has well preserved Lateglacial moraine deposits, despite slope processes have partly hid the till and the glacial landforms since the retreat of the last glaciers (cf. Soldati et al., 2004, 2006; Soldati & Borgatti, 2009; Borgatti & Soldati, 2010; Panizza et al, 2011; Ghinoi et al., 2014; Marchetti et al., 2017). The oldest traces left by glaciers can be attributed to the LGM, when all valleys of the Dolomites were covered by ice until high elevations, sometimes even greater than the current mountain passes (Penck & Brückner, 1909; Mutschlechner, 1933; B. Castiglioni, 1940; von Klebelsberg, 1948; G.B. Castiglioni, 1964; Cantelli & Vai, 2004). The rounding of Mount Setsas crest, in the tract from Mt. Castello to Valparola Pass, and the saddle-like form of the pass itself represent the most evident traces of a glacier transfluence from the Upper Badia Valley towards south, to the Andraz valley and the confluence with the Cordevole paleo-glacier. Mutschlechner (1933) sustained the hypothesis that during the LGM the Upper Badia Valley

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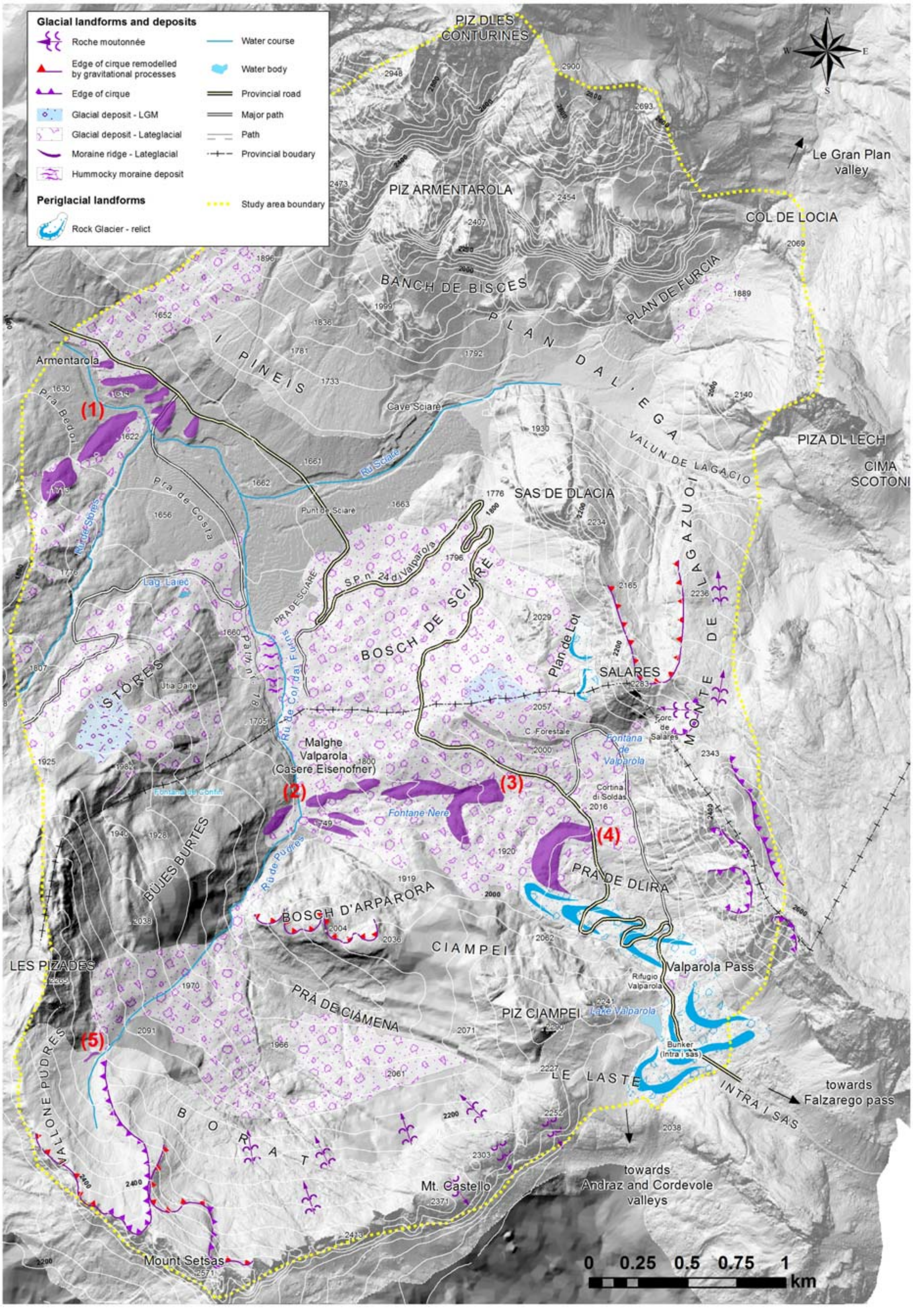
Fig. 2 - Distribution of glacial and periglacial landforms and deposits in the study area. 1: Armentarola frontal moraine complex; 2: Malghe Valparola lateral-frontal moraine; 3: Dlira I frontal moraine; 4: Dlira II frontal moraine; 5: Pudres frontal moraine. White lines: isolines (50 m equidistance).


Glacial landforms and deposits
Roche moutonnée
Edge of cirque remodelled by gravitational processes
Edge of cirque
Glacial deposit - LGM
Glacial deposit - Lateglacial
Moraine ridge - Lateglacial
Hummocky moraine deposit
Water course
Water body
Provincial road
Major path
Path
Provincial boudary
Study area boundary
Periglacial landforms
Rock Glacier - relict
PIZ DLES CONTURINES
PIZ ARMENTAROLA
BANCH DE BISCES
PLAN DE FURCIA
PLAN DAL EGA
COL DE LOCIA
Le Gran Plan valley
I PINEIS
Armentarola
Pra Bedoi
(1)
Cave Sciare
Ru Sciare
Pra de Costa
Punt de Sciare
SAS DE DLACIA
VALUN DE LAGACIO
PIZA DL LECH
CIMA SCOTONI
LAGAZUOI
MONTE DE LAGAZUOI
S.P. n° 24 di Valparola
PRA DE SCIARE
BOSCH DE SCIARE
Lag. Laiec
STORES
Utia Daite
Plan de Lot
SALARES
Forc de Salares
C. Forestale
Fontana de Valparola
Malghe Valparola (Casere Eisenofner)
(2)
(3)
Fontane Nere
Cortina di Soldas
(4)
PRA DE DLIRA
Fontana de Confin
BÜJES BURTES
BOSCH D'ARPARORA
CIAMPEI
LES PIZADES
Rü de Pudres
Valparola Pass
Rifugio Valparola
PRA DE CIAMENA
PIZ CIAMPEI
Lake Valparola
Bunker (Intra i sas)
(5)
VALLONE PUDRES
LE LASTE
INTRA I SAS
towards Falzarego pass
BORAT
towards Andraz and Cordevole valleys
Mt. Castello
Mount Setsas
0 0.25 0.5 0.75 1 km

was reached by a glacier tongue whose feeding area was within the Pusteria valley, extending with an E-W direction some 30 km north. According again to Mutschlechner (1933), the Mount Setsas ridge, perpendicular to the flow direction of the glacier tongue, may have acted as a main obstacle to the flow itself, together with the local ice masses on the Puez-Gherdenacia and Sella Groups on one side and those on the Fanes Grande, Fanes Piccola and Monte de Lagazuoi on the opposite side (Fig. 1).

Mutschlechner (1933) stated that the southernmost evident traces left by the Pusteria glacier tongue in the Badia Valley are represented by few scattered, small crystalline erratics found around the village of San Cassiano and in the main depression of Valparola, near Malghe Valparola (*Eisenofenalpe* in his map). In the latter locality, where a series of W-E trending humps of well-polished clasts of different lithology and size can still be visible (Fig. 2), Mutschlechner (1933) found a fist-size quartz stone that he took as a proof for the southernmost advance of the Pusteria glacier inside the Badia Valley. This may not necessarily imply the attribution of the deposit to an LGM glacier; more likely, its genesis can be related to a local valley glacier confined within the Valparola, which reworked former LGM deposits.

Although not of crystalline origin, highly rounded pebbles and small blocks of dolomite and calcarenite, found at elevations ranging from 1970 to 2000 m (Fig. 2), call for the presence of a glacier occupying the whole Valparola. The elevation of the deposits and the more rounded clasts compared to all the other moraine deposits of the valley, lead to hypothesize their chronostratigraphic attribution to the LGM. Their preservation seems to have been favoured by their position on top of two stable and gently sloping structural surfaces whose height was likely never reached by successive stadial glaciers.

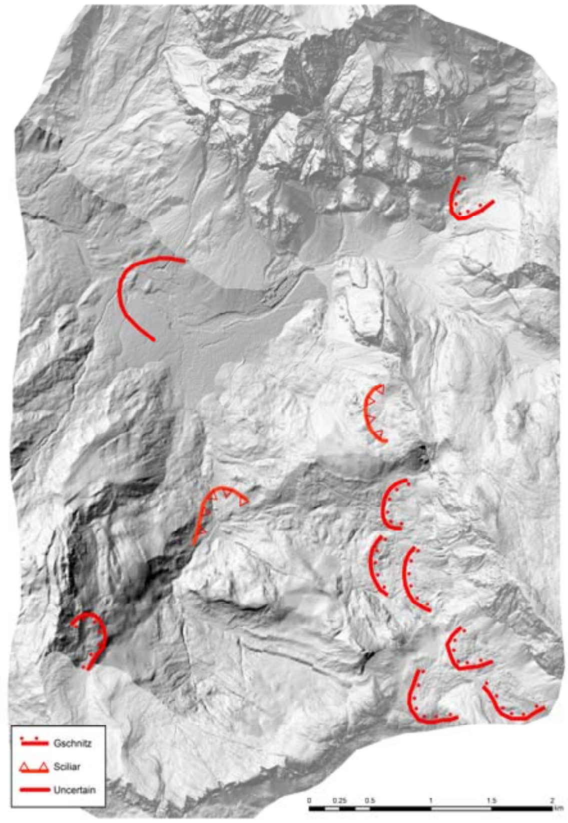


Fig. 3 - Frontal moraines and their stadial attribution as from G.B. Castiglioni (1964), drawn on the LiDAR DEM for this study.

At the onset of the Lateglacial, roughly around 19 ka (Klasen et al., 2007), the ice tongues within the main alpine valleys were essentially stagnant and down-

	$\Delta_{ELA\,(m)}$ Penck & Brückner (1909, Bd.1)	$\Delta_{ELA\,(m)}$ von Klebelsberg (1948)[1]	$\Delta_{ELA\,(m)}$ Castiglioni G.B. (1961)	$\Delta_{ELA\,(m)}$ Masini (1998)	$\Delta_{ELA\,(m)}$ Ivy-Ochs et al. (2008)	Chronostratigraphy Ivy-Ochs et al. (2008)
L.I.A.				-50/-200		
Lateglacial Stadial names						
KARTELL					-120	Preboreal oscillation?
EGESEN		-100/-120	-100/-200	-100/-400	$-180_{(smd)}$/-450	Younger Dryas mean ^{10}Be age: 11.2±1.1 ka[3]
DAUN	-300/-400	-300/-400	-300	-300/-500	-250/-400	Before Bølling
CLAVADEL/SENDERS					-400/-500	Before Bølling
GSCHNITZ	-500/-700	-600	-450/-750	-600	-650/$-700_{(t)}$ max. $-1000_{(s)}$	Before Bølling mean ^{10}Be age: 15.4±1.4 ka; oldest: 16.1±1 ka $_{(t)}$[2]
STEINACH		-600/-700				
BÜHL	-900/-1000	(*Sciliar*) -800/-900	(*Sciliar*) -800/-900	-900		Before Bølling (early Lateglacial ice decay)
Pre-Lateglacial						
LGM				-1200	-1200/-1500	Final deglaciation[4] Some 21 cal ka BP

Tab. 1 - Stadial classifications for the Alpine Lateglacial based on ELA-depression ranges (in metres) from different Authors. 1: limit values of ELA depressions partly revised by G.B. Castiglioni (1961). 2: in Ravazzi et al., (2014), for the Garda amphitheatre: 16.4±0.16 to 15.5±0.16 cal ka BP. 3: in Federici et al., (2008) for the Maritime Alps: mean ^{10}Be age of 11.3±0.4 ka. 4: for the Southern Alps the same age of 21 cal ka BP is taken as the end of the last LGM advance for the Tagliamento amphitheatre ("*Conodusso maximum advance*" in Monegato et al., 2007). (s): southern chains closer to the Adriatic sea (Kerschner et al., 1999; Kerschner & Ivy-Ochs, 2008); (smd): south of Alpine main divide (Kerschner et al., 2000); (t): at type locality (Ivy-Ochs et al., 2008).

wasting, while in the Eastern Alps only small local glaciers were active (Ivy-Ochs et al. 2008). It is likely that during this period the whole Valparola was still occupied by a local ice tongue, with LGM inherited ice just at the bottom of the ice mass.

The reconstruction of the valley's paleo-glacier evolution during the Lateglacial by G.B. Castiglioni (1964) (Fig. 3) shows that most of the frontal moraine arcs relate to the Gschnitz stadial and are quite close to the accumulation areas of the respective glaciers. Going further valleyward, two arcs were attributed to the Sciliar stadial, with which the Author replaced the Bühl stadial following von Klebelsberg (1948). The lowest arc in altitude was interpreted as not referable to any stadial (in this case probably comprised between the LGM and the Sciliar stadial). More recently, Masini (1998) identified, for the nearby Fanes Grande and Fanes Piccola areas, more moraine features than those present in the map of Lateglacial stadials by G.B. Castiglioni (1964) and classified them from the Gschnitz to the LIA, adding also the Egesen stadial which, according to G.B. Castiglioni (in Leonardi, 1967), is not present in the Dolomites.

3. MATERIALS AND METHODS

The Lateglacial evolution of Valparola has been reconstructed by calculating the ELA of the local paleo-glaciers. The difference between the assumed local-LIA ELA and the calculated paleo-ELA (the so called "ELA depression") allowed to attribute each paleo-glacier to a specific Lateglacial stadial, according to the most recent stadial classification suggested for the Alpine region (Ivy -Ochs et al., 2008; Heiri et al., 2014) and Italian Alpine valleys (Federici et al., 2008, 2012; Monegato, 2102; Colucci et al., 2014): "Gschnitz", "Clavadel/Senders", "Egesen" and Kartell" (see table 1). To accomplish this, a detailed geomorphological survey has been undertaken, focusing the attention to the glacial deposits and landforms, but also to the abundant landslide deposits which often mask the glacial landforms or sometimes mimic their shape. The survey has been aided by the interpretation of aerial photographs and the boundaries of mapped features could be refined by the analysis of a high-resolution (1.5x1.5 m) LiDAR Digital Elevation Model (DEM) made available by the Autonomous Province of Bolzano and of an even higher-resolution (1x1 m) LiDAR DEM freely made available for the Dolomites as WMS service by the Italian Ministry of Environment, Land and Sea.

3.1. Paleo-glacier surface and paleo-ELA reconstructions

The procedure used in this study to calculate the paleo-ELA of glaciers in the valley can be described as follows.

1) The theoretical longitudinal glacier surface profiles (from now on "longitudinal profiles") have been modelled using the method by Benn & Hulton (2010) within the GIS-integrated tool by Pellitero et al. (2016), implementing the steady-state model which assumes a "perfectly plastic" ice rheology. Altitude of the frontal moraine and topography derived from the DEM were used as input data, although having no lateral moraine to validate the output surface-profiles. As for the basal shear stress given by the sliding of the glacier on the bedrock surface, the value of 50 kPa has been assigned to the portion of the glacier over the flat and wide valley bottom, while the value of 100 kPa has been assigned to the remaining portion, as suggested by Pellitero et al. (2016). As Valparola's paleo-glaciers were valley glaciers, whose flow movement was therefore conditioned also by the side-drag along the valley sides, the "shape factor" was also introduced and calculated at several points along the longitudinal profile.
2) The hypsometry of each paleo-glacier tongue is then reconstructed thanks to the ice thickness calculated in step 1 and corrected by the "shape factor". Hypsometry is the primary input for the Osmaston (2005) method with which the paleo-ELA can be calculated in an iterative way with the "Area x Altitude Balance Ratio method" (AABR), assuming paleo-glaciers at hypothetical balanced state. The BR is the ratio between the linear slopes of the mass balance/altitude curves above and below the ELA. For our study area we have used a Balance Ratio (BR) of 1.6, which is the mean value found by Rea (2009) for current glaciers of the European Alps. The same ratio has been used also in the Maritime Alps by Federici et al. (2012).
3) We have also performed a parametric analysis, looking at the change of the reconstructed paleo-ELA varying the BR value within the confidence interval of the mean 1.6 found in Rea (2009) (i.e., ±0.6).

3.2. Reconstruction of ELA depressions and stadial attribution

Since the seminal studies by Penck & Brückner (1909), different authors have tried to reconstruct, also for this sector of the Dolomites, the paleo-glacier evolution during the Lateglacial by calculating the difference between the ELA of paleo-glaciers and the "present-day" [1)] (or LIA's) ELA. The ELA is the altitude corresponding to a mass budget equal to zero. The method is clearly qualitative, but it has one main advantage: it allows to compare paleo-glacier reconstructions over large-scale areas. Like all models, it has also drawbacks: the uncertainties related to the reconstruction of paleo-glacier surfaces; the difficulty in selecting the reference ELA for certain areas with peculiar topographic and/or climatic conditions. The latter is the case of the Dolomites where, in our knowledge, no ELA calculation exists neither for the current time, nor for the LIA.

Up to now, the terminology of the Lateglacial stadials has undergone frequent changes and even their ELA -depression ranges have been revised, making it difficult to compare results achieved in different time periods. Looking at Tab. 1, it is possible to appreciate the differences between some stadial classifications selected from literature studies which are "geographically close" to our study area.

[1)] The term "present-day" is referred to the time period close to when the studies were carried out, therefore the reference ELAs are likely different from the current (2017) one.

As it can be argued from Tab. 1, most of the stadial names are persistent through time, while the range of their ELA depression shows sometimes strong differences. The term “Bühl stadial”, first introduced by Penck & Brückner (1909, Bd.1), was replaced by the “Sciliar stadial” (or “*Schlernstadium*”) in von Klebelsberg (1948) and never used again until now, except in Masini (1998). Von Klebelsberg (1950) added the “Steinach stadial” (still present in van Husen, 2000) between the Sciliar and the Gschnitz ones. The most recent classification, by Ivy-Ochs et al. (2008), has the “Clavadel/Senders stadial” between the Gschnitz and Daun ones, plus the “Kartell stadial” between the Egesen and the LIA.

Which ELA to select as reference for calculating the ELA depression is another critical issue for the comparison of stadials between different authors: most of them have used the “present-day” ELA (see annotation 1), and only recently the LIA’s ELA is becoming the standard reference (Gross et al., 1977; Maisch, 1982). Penck & Brückner (1909, Bd.1) used the “*heute*” *schneegrenze* (variable from valley to valley) as the reference ELA: considering the values they found in different valleys (in the north-eastern Alps), it could have ranged from 2500 to 2800 m. Von Klebelsberg (1947) identified the “present-day” ELA for the Sella Group and surrounding areas around 2950 m. G.B. Castiglioni (1961) used the “present-day” ELA that Marinelli (1910) calculated around the Sella Group, i.e., again 2950 m. Masini (1998), using three different methods for calculating the “present-day” ELA from the Veneto Region’s glaciers, obtained three different ELAs: 2820 m, 2760 m and 2580 m, although the ELA at year 1998 should have been in the 2800-2900 m range (as stated by Masini), somehow close to the ELAs estimated by von Klebelsberg (1947) and by Marinelli (1910). Ivy-Ochs et al. (2008) took as reference the LIA’s ELA, since it is considered the Holocene maximum glacier advance in most catchments of the Alps and more reliable to determine than the “present-day” ELA, mainly due to the scarcity of current glaciers in the Alps with known current ELA (Gross et al., 1977).

For this study we have selected the local LIA’s ELA as reference for the ELA-depression calculation, in order to compare the results with the most up-to-date classification for the Alps by Ivy-Ochs et al. (2008), which is also associated to a preliminary chronology based on radiocarbon and cosmogenic-nuclides dating. Nevertheless, as previously stated, we have used also the “present-day” ELA by G.B. Castiglioni (1961), in order to compare his findings with ours.

Having no reference publications to rely on for the local LIA’s ELA, we considered as local “present-day” ELA the range of values reported in Masini (1998), i.e., 2800-2900 m, subtracting some 100 m, being that the average depression value found in literature between the LIA’s and the “present-day” ELA (Kerschner et al., 1999 for the Gschnitz valley; Kerschner et al., 2000; Pelfini, 1994 for Ortles-Cevedale glaciers; Masini, 1998 for Altopiani di Fanes, Sennes e Fosses). The “present-day” ELA values, ranging from 2800 to 2900 m, find a partial validation in the glacieret currently present 2.5 km east of the study area, in the Ciadin de Fanes corrie, close to peak Piza Sud (Fig. 1), its altitude ranging between 2750 and 2920 m (classified by the World Glacier Inventory with the code IT4L00023005). In the recently published “The new Italian glacier inventory” (Smiraglia & Diolaiuti, 2015), the glacieret is described as “*split into many ice bodies, not easily recognizable and almost totally debris-covered*”. The validation is only partial because glacierets are not suitable for calculating equilibrium line altitudes, laying most of the times completely within the ablation zone. Anyhow, the upper limit of 2900 m is likely to be the closest to the local “present-day” equilibrium line. In Baratto et al. (2003) the present day ELA for the Dolomites is reported, without supporting data, at 2850 m.

Recently, an analysis has been carried out on the extension of glaciers from the LIA to the present for the whole Trento Region (Bertoni & Casarotto, 2016). For the Marmolada glacier, the LIA’s frontal moraines have been precisely identified, at an average altitude of 2300 m. The calculation of the LIA’s ELA with the tools by Pellitero et al. (2015; 2016) has given a value of 2757 m for the LIA’s ELA at Marmolada. The value of 2972 m has been eventually found for the current glacier. This result reinforces the choice we have made in this study for a reference ELA of 2800 m: the lower value of 2757 m found using the LIA’s moraines can be explained considering the high inclination of Marmolada mount (30-35° mean) and its uniform orientation to the north, which are two topographic factors that might favour the lowering of the ELA.

4. RESULTS

Results of the Lateglacial reconstruction are presented identifying each moraine arc with a progressive number - reported in red in Fig. 2 - and the name of the closest locality, starting from the valley’s lowermost arc to the uppermost one, describing its main geomorphological characteristics and reconstructing the paleosurface of the glacier. ELA-depression is then calculated and the stadial assigned to each paleo-glacier.

4.1. Paleo-glacier and paleo-ELA reconstruction

(1) Armentarola frontal moraine complex: northwestern sector of the study area, at the junction between torrent Rü Sciarè and torrent Rü de Störes, near locality “Armentarola”, extending, in altitude, from 1614 to 1622 m.

Seven moraine ridges composed by dolomite blocks, partly immersed in a mainly coarse matrix and of mean NE-SW direction, have been identified at locality Armentarola. They form a frontal moraine complex of a glacier likely hosted within the entire Valparola valley, probably with ice contributions from the plateau of Monte de Lagazuoi and from the Alpe di Fanes Piccola. The longitudinal topographic profiles used to reconstruct the glacier surface have been traced following the main depressions of the valley up to the uppermost ridges bordering the valley. To account for the side-drag along the valley sides (shape factor), cross profiles have been traced at several points along the longitudinal profiles, in order to account for the change of the shape factor itself along the longitudinal profile from the frontal moraine until the watershed.

As it can be seen by the modelled surface, the glacier's accumulation area can be identified with the entire valley, extending laterally towards Plan da Lega in the ablation zone, where later on, thick debris-flow cones and alluvial deposits have masked all previous till and glacial landforms. Worth noticing are the two gentle-sloping areas west of Plan de Lot and at Störes, ice free from the modelling result. These areas match quite well with the findings of highly rounded blocks which we attributed to earlier phases of the local glacial history, possibly LGM related, outlined in Fig. 2.

The Armentarola glacier ELA has been calculated at 2000 m, identified by the red line in Fig. 4. Within the Rea's (2009) confidence interval around the BR value of 1.6, the ELA ranges from 2040 (BR=1) to 1980 (BR=2.2), i.e. +40 and -20 m from the $ELA_{BR=1.6}$.

(2) Malghe Valparola frontal moraine: central depression of Valparola, where torrent Rü de Pudres becomes torrent Rü de Col dai Furns, near locality "Malghe Valparola", at 1750 m mean altitude.

A complex of five moraine ridges, composed by dolomite blocks of metric diameters with no significant finer matrix, has been identified from Malghe Valparola to Fontane Nere (Fig. 5), with a mean W-E trend. The altitude of the ridge tops is the same for the three parallel ridges at Malghe Valparola and it is only a few metres higher than the mean valley bottom in the same sector. A SW-NE trend characterizes the ridge on the left side of the torrent Rü de Pudres. Its mean altitude is around 1760 m and its orientation suggests to interpret it as a lateral-frontal moraine built by a glacier coming from the valley stretching from the Borat-Vallone Pudres areas to Malghe Valparola. The similar altitude (among them) of the three lowermost W-E-trending ridges and their relative proximity has led to interpret them as remnants of an ablation till, dissected by successive gully erosion, instead of lateral moraines. The uppermost fifth ridge appears to be another elongated remnant of the same ablation till. This last proxy led to hypothesize the presence of another glacier branch coming from Passo Valparola to Malghe Valparola, here joining with the first one.

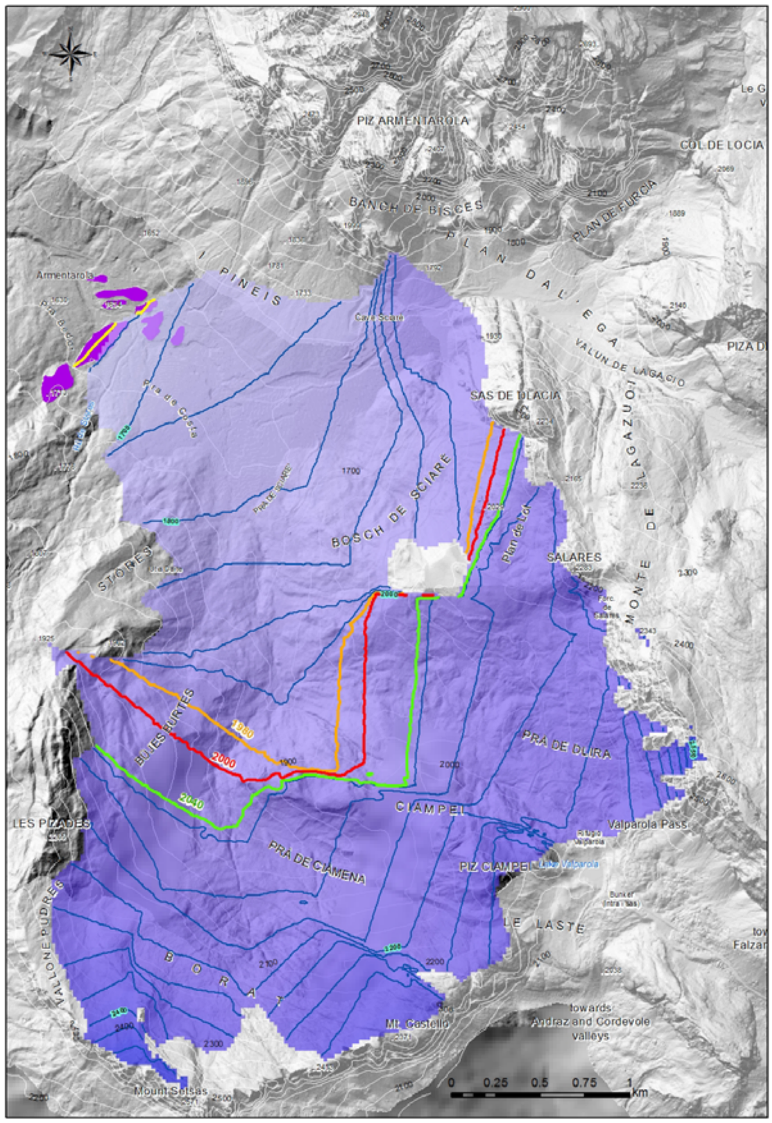


Fig. 4 - Modelled Armentarola paleo-glacier, represented in semi-transparent blue, with its frontal moraines (violet polygons and ridge in yellow) and paleo-ELA (BR = 1.6, red line, BR=1, green line, BR=2.2, orange line). Surface of paleo-glacier reconstructed using the "GLARE" toolbox for ArcGIS by Pellitero et al. (2016). Blue isolines are for the paleo-glacier's surface. White isolines are for the current topography. Paleo-ELA calculation performed using the "ELA calculation" toolbox for ArcGIS by Pellitero et al. (2015).

This is why two longitudinal topographic profiles were used to reconstruct the glacier surface profile: one has been traced following the main depression joining Malghe Valparola with Valparola Pass, the second one, joining the areas of Borat and Vallone Pudres with Malghe Valparola. Other minor longitudinal profiles, joining with the main one in the Borat area, have been traced hypothesizing the presence of an ice mass also within the main concavity of Mount Setsas. To account for the side-drag along the valley sides (shape factor), cross profiles have been traced at several points along the longitudinal profiles, in order to account for the change of the shape factor itself along the longitudinal profile from the frontal moraine until the watershed.

At this moment in time, the Valparola glacier was composed by two main tributary glacial bodies, one confined within the Passo Valparola-Malghe Valparola valley, and one confined within the bowl-shaped area of Vallone Pudres-Borat-Prà de Ciàmena. Regarding the lateral-frontal moraine at Malghe Valparola, worth notic-

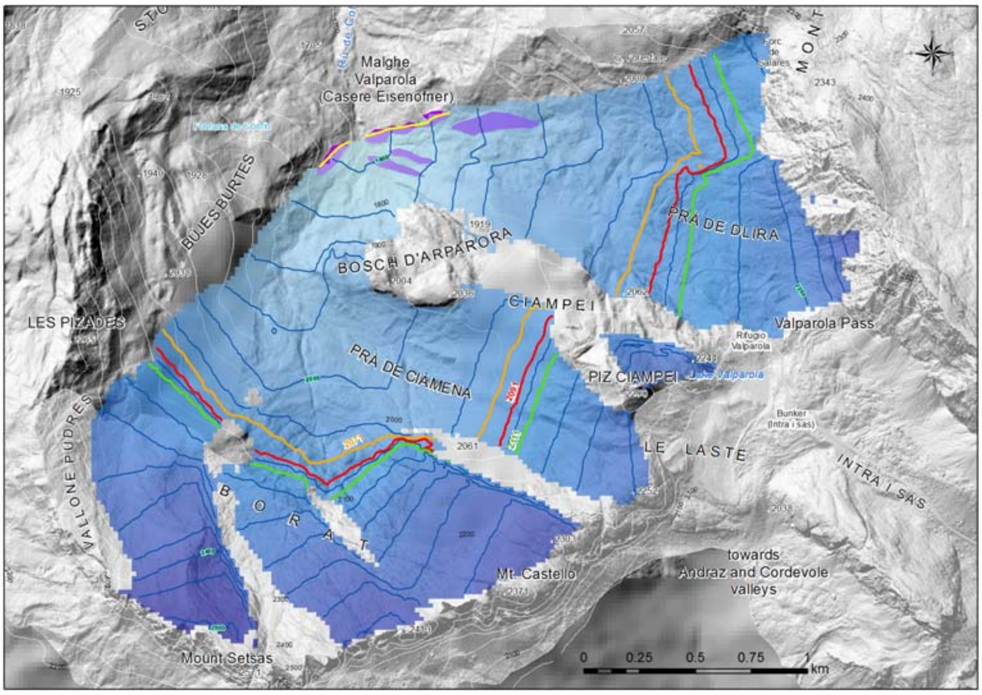


Fig. 5 - Modelled Malghe Valparola paleo-glacier, represented in semi-transparent blue, with its frontal moraines (violet polygons and ridge in yellow) and paleo-ELA (BR = 1.6, red line, BR=1, green line, BR=2.2, orange line). Surface of paleo-glacier reconstructed using the "GLARE" toolbox for ArcGIS by Pellitero et al. (2016). Blue isolines are for the paleo-glacier's surface. White isolines are for the current topography. Paleo-ELA calculation performed using the "ELA calculation" toolbox for ArcGIS by Pellitero et al. (2015).

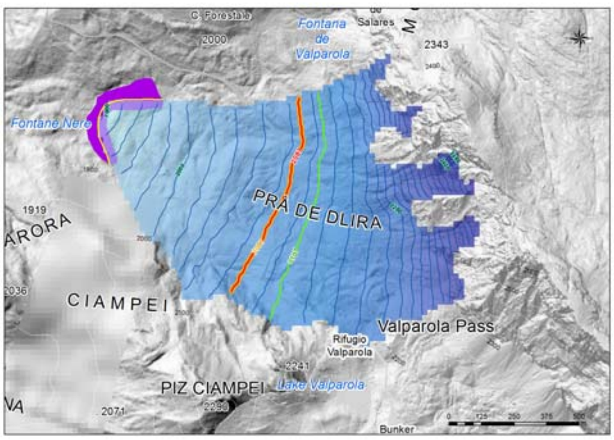


Fig. 6 - Modelled Dlira I paleo-glacier, represented in semi-transparent blue, with its frontal moraines (violet polygons and ridge in yellow) and paleo-ELA (BR = 1.6, red line, BR=1, green line, BR=2.2, orange line). Surface of paleo-glacier reconstructed using the "GLARE" toolbox for ArcGIS by Pellitero et al. (2016). Blue isolines are for the paleo-glacier's surface. White isolines are for the current topography. Paleo-ELA calculation performed using the "ELA calculation" toolbox for ArcGIS by Pellitero et al. (2015).

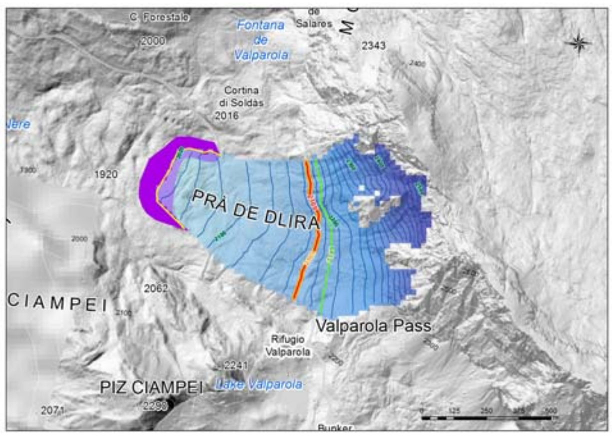


Fig. 7 - Modelled Dlira II paleo-glacier, represented in semi-transparent blue, with its frontal moraines (violet polygons and ridge in yellow) and paleo-ELA (BR = 1.6, red line, BR=1, green line, BR=2.2, orange line). Surface of paleo-glacier reconstructed using the "GLARE" toolbox for ArcGIS by Pellitero et al. (2016). Blue isolines are for the paleo-glacier's surface. White isolines are for the current topography. Paleo-ELA calculation performed using the "ELA calculation" toolbox for ArcGIS by Pellitero et al. (2015).

ing is the fact that it is adjacent to a wide block-slide deposit which probably moved from the Les Pizades slope to the west. This observation leads to infer a relative dating of the landslide which should have occurred before the glacier readvance in the Malghe Valparola area. The presence of the landslide deposit must have narrowed considerably the valley of Rü de Pudres, confining the ice mass within a rather small-extent area. This may have favoured the mechanical stabilization of the landslide deposit for as long as the ice mass was in place. Nowadays, the left slope of the Rü de Pudres valley is continuously subject to shallow earth slides.

The Malghe Valparola's glacier ELA has been calculated at 2091 m, identified by the red line in Fig. 5.

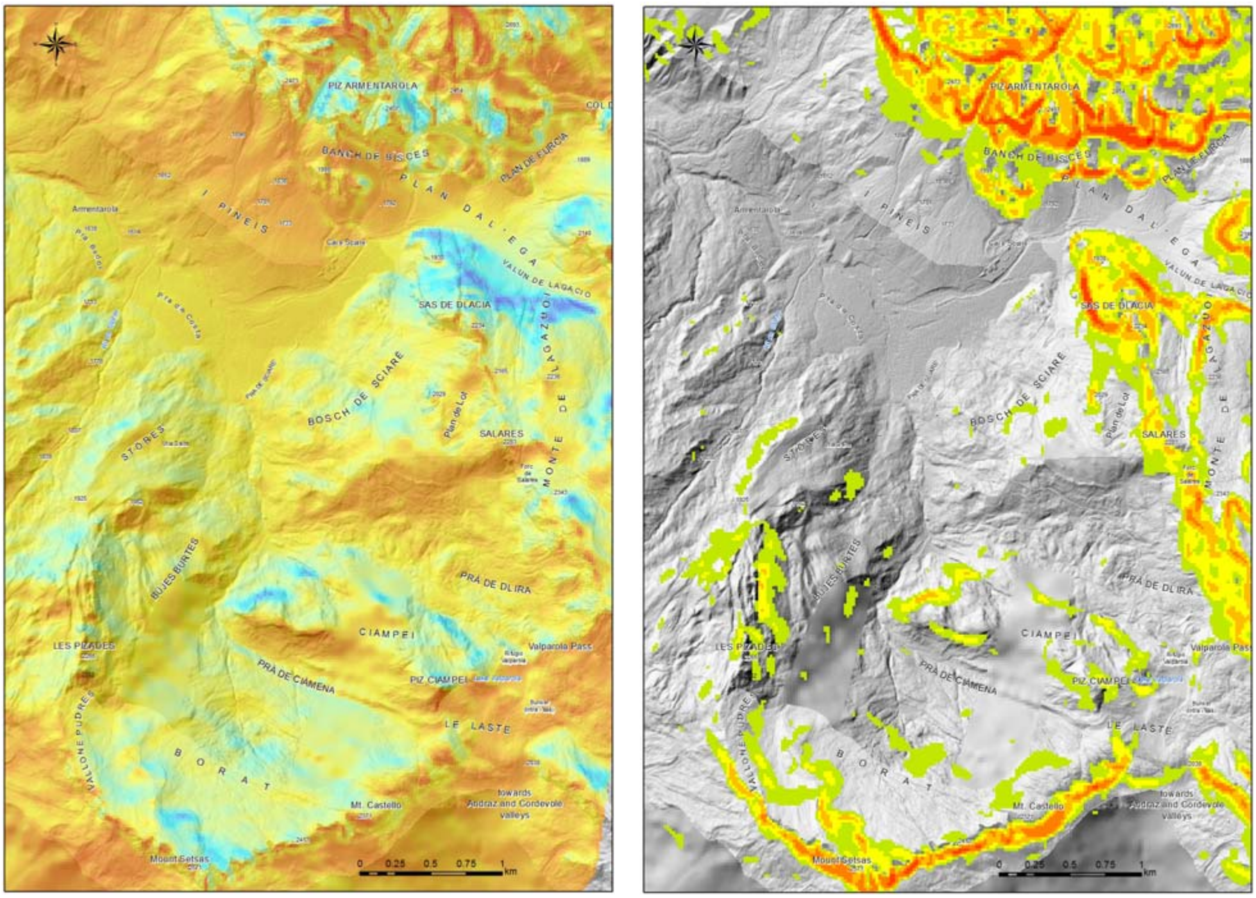


Fig.8 - Left: distribution of yearly global solar radiation (intensities increasing from dark blue to dark brown). Right: distribution of areas with slope angles above 30° (slope angles increasing from green to red).

Within the Rea's (2009) confidence interval around the BR value of 1.6, the ELA ranges from 2111 (BR=1) to 2071 (BR=2.2), i.e. +20 and -20 m from the $ELA_{BR=1.6}$.

(3) – (4) Dlira frontal moraine sequence (I-II) – (I): secondary valley stretching almost W-E from Malghe Valparola to Valparola Pass, a few metres uphill from Fontane Nere springs, at 1873 m mean altitude; (II): secondary valley stretching almost W-E from Malghe Valparola to Valparola Pass, at locality "Pra de Dlira", just a few metres west of the provincial road nr. 24, at 2004 m mean altitude.

A series of two concentric moraine arcs, stretching SW-NE with some 400 m length between Malghe Valparola and Prà de Dlira, is formed by dolomite blocks with metric diameters, highly weathered by karst action and largely masked by trees and underwood. Uphill, two small back-arc plains are formed by finer colluvium (gravel, mostly) transported by running waters and by debris-flows. These arcs may represent a sequence of stadial readvances quite close to each other in time and they lie within a wide ablation-till deposit occupying the entire depression from Valparola Pass to Malghe Valparola.

The longitudinal topographic profiles used to reconstruct the two glacier surface-profiles have been traced following the main longitudinal depressions joining the back-arcs with Valparola Pass and surrounding areas. To account for the side-drag along the valley sides (shape factor), cross profiles have been traced at several points along the longitudinal profiles, in order to account for the change of the shape factor itself along the longitudinal profile from the frontal moraine until the watershed.

At the time the frontal arcs of Dlira I and Dlira II formed, the Valparola ice masses seem to have been definitely separated, with a main glacier tongue stretching from Valparola Pass to the Dlira I-II frontal arcs (Fig. 6 and 7) and a minor ice tongue contained within the Pudres valley (see further on in the text) and possibly, partly in the Borat and adjacent areas eastward. Nevertheless, the lack of glacial landforms do not allow to infer any ice extent for the latter areas. The feeding area of the main tongue is confined to the slopes surrounding the pass, probably with no substantial contributions from the north-facing slopes. The clear sequence of recessing moraine ridges allows to argue that the ice masses had more favourable conditions for their preservation in this part of the valley than on Mount Setsas slope. The latter, in fact, is wide, gently inclined, with not much shade effect from surrounding peaks, and thus more subject to direct solar radiation and ablation (Fig. 8, left). On the other hand, the Valparola Pass - Malghe Valparola valley is narrower, partly shaded by a crest line to the south and richer in sediment production (from rock falls and debris flows) which could form an ice-protecting surficial moraine. Moreover, the head of the Valparola Pass - Malghe Valparola valley appears to be more prone to avalanche events than the Setsas valley, as it can be deduced by the spatial distribution of slopes with inclination higher than 30° (Fig. 8, right).

The Dlira I-II's glacier ELAs have been calculated at 2087 and 2169 m respectively, identified by the dashed lines in Fig. 6 and Fig. 7. Within the Rea's (2009) confidence interval around the BR value of 1.6, the ELA ranges, respectively, from 2107 (BR=1) to 2087 (BR=2.2) and from 2189 (BR=1) to 2169 (BR=2.2), i.e. +20 and -0 m from the $ELA_{BR=1.6}$ in both cases.

(5) Pudres frontal moraine: at the outlet of the secondary valley named "Vallone Pudres", in the south-western sector, west of Mount Setsas, at 2154 m mean altitude.

A well preserved frontal moraine arc has been identified at the outlet of the suspended valley of Vallone Pudres, on the western side of Mount Setsas. The arc, whose lenght is some 100 m, is composed by dolomite blocks with metre and sub-metre diameters within a gravel-to-sandy matrix, almost completely covered by grass and musk.

The longitudinal topographic profile used to reconstruct the Pudres glacier surface-profile has been traced following the main depression joining the valley's headwall and the moraine arc. To account for the side-drag along the valley sides (shape factor), cross profiles have been traced at several points along the longitudinal profiles, in order to account for the change of the shape factor itself along the longitudinal profile from the frontal moraine until the watershed.

Based on geomorphological evidence, the narrow Vallone Pudres valley is likely to have hosted the last readvance for the whole Valparola. Here, the valley altitude, from 2000 m to 2500 m, its narrow shape, northward orientation and the shade effect of the surrounding mountain peaks created favourable conditions for the permanence of ice while, at the same time, the rest of Valparola was almost entirely ice-free. Contribution from avalanching is relatively high too, especially from the western slope (Fig. 8, right).

The Pudres's glacier ELA has been calculated at 2327 m, identified by the red line in Fig. 9. Within the Rea's (2009) confidence interval around the BR value of 1.6, the ELA ranges from 2327 (BR=1) to 2307

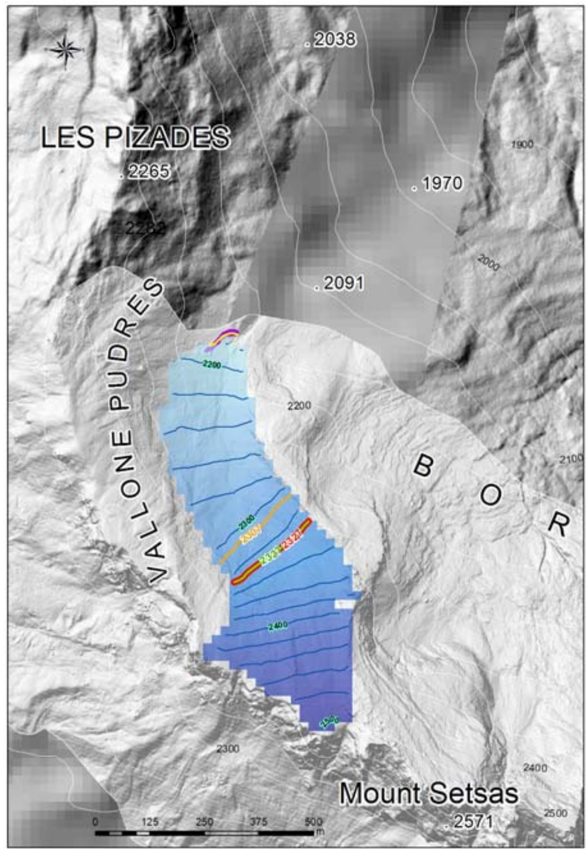


Fig. 9 - Modelled Pudres paleo-glacier, represented in semi-transparent blue, with its frontal moraines (violet polygons and ridge in yellow) and paleo-ELA (BR = 1.6, red line, BR=1, green line, BR=2.2, orange line). Surface of paleo-glacier reconstructed using the "GLARE" toolbox for ArcGIS by Pellitero et al. (2016). Blue isolines are for the paleo-glacier's surface. White isolines are for the current topography. Paleo-ELA calculation performed using the "ELA calculation" toolbox for ArcGIS by Pellitero et al. (2015).

(BR=2.2), i.e. +0 and -20 m from the $ELA_{BR=1.6}$.

The paleo-ELAs calculated for all Valparola's glaciers are summarized in Tab. 2.

4.2. Stadial attribution and comparisons with previous authors

Analysing the comparison table for ELA's depressions (Tab. 3), the difference between the paleo-ELA calculated for the Armentarola glacier and the hypothe-

Glacier name	Elevation of frontal moraine (m)	ELA with AABR method (BR=1.6)
Armentarola	1633	2000
Malghe Valparola	1738	2091
Dlira I	1884	2087
Dlira II	1998	2169
Pudres	2155	2327

Tab. 2 - ELA calculations for the Valparola paleo-glaciers, performed using the toolbox for ArcGIS by Pellitero et al. (2015). AABR: Area x Altitude Balance Ratio method (used in this study).

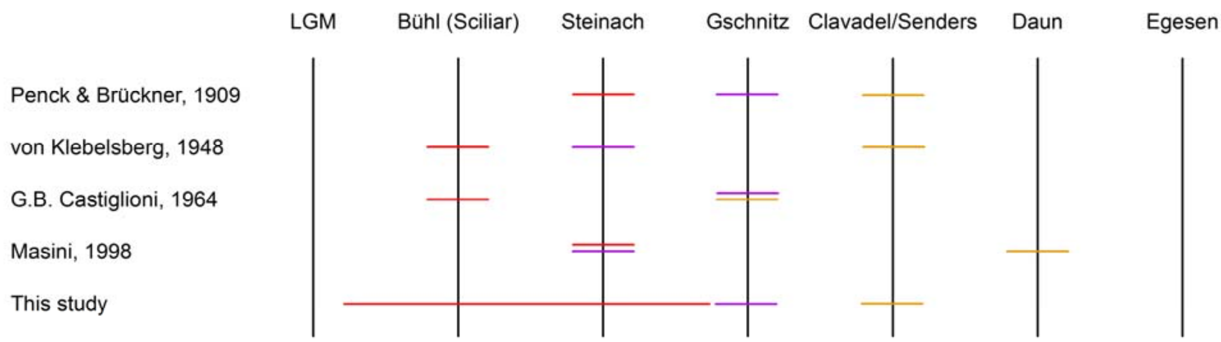


Fig. 10 - Comparison of the stadial attributions to Valparola's paleo-glaciers given by this study with those given using former authors' classifications. Red lines: Armentarola paleo-glacier; purple lines: Malghe Valparola paleo-glacier, Dlira-I and Dlira-II paleo-glaciers; ochre lines: Pudres palo-glacier.

sized local LIA's ELA (last column) at 2800 m, allows us to place that readvance phase between the LGM and the Gschnitz stadial, if we consider the classification by Ivy-Ochs et al. (2008). The ELAs for Malghe Valparola, Dlira-I and Dlira-II glaciers place those glacier readvances within the Gschnitz stadial, if the values of 700 m and 650 m are taken as the maximum and minimum values for the Gschnitz-stadial's ELA-depression range. The ELA depression for the Malghe Valparola and Dlira-I glaciers is close to the upper value, while that of the Dlira-II glacier is close to the minimum one. According to Kerschner & Ivy-Ochs (2008), the ELA depression for the Gschnitz stadial could have been even greater for the southern alpine chains near the Adriatic Sea, reaching 1000 m; values of 900-1000 m have also been estimated for the northwards trending valleys of the Carnian Alps (Kerschner & Ivy-Ochs, 2008). Taking 1000 m as the upper value for the Gschnitz's ELA-depression range would place also the Armentarola glacier within the Gschnitz stadial. The same ELA-depression found with this study, following Penck & Brückner's (1909) classification, would place the Armentarola readvance between the Bühl and the Gschnitz stadials and the ones of Malghe Valparola, Dlira-I and Dlira-II in the Gschnitz. According to von Klebelsberg's (1948) classification, the Armentarola readvance could have taken place during the Sciliar, while the Malghe Valparola, Dlira-I and Dlira-II readvances could have been within the Steinach stadial. G.B. Castiglioni (1961) classification would place the Armentarola glacier readvance within the Sciliar, while the ones of Malghe Valparola, Dlira-I and Dlira-II within the Gschnitz stadial. The classification used by Masini (1998) would place all the glacier readvances, except the Pudres one, between the Bühl and the Gschnitz stadials.

Regarding the Pudres glacier readvance, the ELA-depression found with this study places it, following the Ivy-Ochs et al. (2008) classification, within the Clavadel/Sanders stadial, while Penck & Brückner's and von Klebelsberg's classifications would place it between the Gschnitz and the Daun stadials. G.B. Castiglioni (1961) would place it within the Gschnitz, while Masini (1998) within the Daun.

Comparison of the stadial attributions to Valparola's paleo-glaciers given by this study with those given using former authors' classifications (Fig. 10), despite the great differences between the adopted approaches, shows the clustering of attributions around common stadials. For the Armentarola glacier we can see a pre-Gschnitz time; the Malghe Valparola and Dlira I-II glaciers cluster quite well around the Gschnitz stadial, while the Pudres glacier is clearly post-Gschnitz, clustering well around the Clavadel/Senders stadial.

If we wanted to test the improvement given by the method here applied with respect to the Castiglioni's method, we would need to adopt the Author's parameters: reference ELA altitude - derived from Marinelli (1910) and equal to 2950 m (first column in Tab. 3) - and stadial classification. Before that, differences should be pointed out in the interpretation of some glacial landforms between this study and Castiglioni's. The Author interpreted as a series of frontal moraines of the Gschnitz stadial what we have identified as a rock glacier (Fig. 2), near the Valparola Pass, thus not allowing any comparison. The frontal arc at Plan de Lot, assigned by G.B. Castiglioni (1964) to the Sciliar stadial, is here interpreted as a displaced rock mass due to gravity, while the frontal moraine, cut by the torrent Rü Sciarè in G.B. Castiglioni (1964), has not been recognized in our study as such a landform.

The ELA-depression calculated with the method selected for this study, but using Castiglioni's reference ELA and stadial classification, would place the Armentarola glacier between the LGM and the Sciliar stadial, confirming Castiglioni's result. The Malghe Valparola glacier would be placed within the Sciliar stadial, again confirming the Author's assignment. The Dlira-II glacier (Dlira-I was not identified by the Author) would be placed between the Sciliar and the Gschnitz, while Castiglioni assigned it to the Gschnitz one. Finally, the Pudres glacier would be placed within the Gschnitz stadial and this is again confirmed also by Castiglioni.

4.3. Valparola evolution since the end of the LGM throughout the Lateglacial

Considering the mean height of 2000 m of the till found on the two stable and gently sloping structural surfaces, as described in section 2 and Fig. 2, the LGM ice may have almost completely covered the Valparola topography, leaving out, as *nunatak*, just the crest of Les Pizades, to the west. The evidence of a till totally composed by local lithologies confirms the theory by

"Reference" ELA

$ELA_{\text{Marinelli-1910}}$	*$ELA_{\text{Local LIA}}$*
2950	***2800***

ARMENTAROLA — **Paleo_ELA 2000**

ΔELAs, with respect to "reference" ELAs

950	**800**

Stadials, based on the ΔELA

Bühl	Gschnitz-Bühl	$\Delta ELA_{\text{Penck \& Brückner, 1909}}$
(Bühl)Sciliar-LGM	(Bühl)Sciliar	$\Delta ELA_{\text{von Klebelsberg, 1948}}$
(Bühl)Sciliar-LGM	(Bühl)Sciliar	$\Delta ELA_{\text{G.B. Castiglioni, 1964}}$
Bühl-LGM	Gschnitz-Bühl	$\Delta ELA_{\text{Masini, 1998}}$
Gschnitz-LGM	**Gschnitz-LGM**	$\Delta ELA_{\text{Ivy-Ochs et al., 2008}}$

MALGHE VALPAROLA — **Paleo_ELA 2091**

ΔELAs, with respect to "reference" ELAs

859	**709**

Stadials, based on the ΔELA

Gschnitz-Bühl	Gschnitz	$\Delta ELA_{\text{Penck \& Brückner, 1909}}$
(Bühl)Sciliar	Steinach	$\Delta ELA_{\text{von Klebelsberg, 1948}}$
(Bühl)Sciliar	Gschnitz	$\Delta ELA_{\text{Castiglioni, 1964}}$
Gschnitz-Bühl	Gschnitz-Bühl	$\Delta ELA_{\text{Masini, 1998}}$
Gschnitz-LGM	**Gschnitz**	$\Delta ELA_{\text{Ivy-Ochs et al., 2008}}$

DLIRA-I — **Paleo_ELA 2087**

ΔELAs, with respect to "reference" ELAs

863	**713**

Stadials, based on the ΔELA

Bühl	Gschnitz	$\Delta ELA_{\text{Penck \& Brückner, 1909}}$
(Bühl)Sciliar	Steinach	$\Delta ELA_{\text{von Klebelsberg, 1948}}$
(Bühl)Sciliar	Gschnitz	$\Delta ELA_{\text{Castiglioni, 1964}}$
Gschnitz-Bühl	Gschnitz-Bühl	$\Delta ELA_{\text{Masini, 1998}}$
Gschnitz-LGM	**Gschnitz**	$\Delta ELA_{\text{Ivy-Ochs et al., 2008}}$

DLIRA-II — **Paleo_ELA 2169**

ΔELAs, with respect to "reference" ELAs

781	**631**

Stadials, based on the ΔELA

Gschnitz-Bühl	Gschnitz	$\Delta ELA_{\text{Penck \& Brückner, 1909}}$
Steinach-(Bühl)Sciliar	Steinach	$\Delta ELA_{\text{von Klebelsberg, 1948}}$
Gschnitz-(Bühl)Sciliar	Gschnitz	$\Delta ELA_{\text{Castiglioni, 1964}}$
Gschnitz-Bühl	Gschnitz-Bühl	$\Delta ELA_{\text{Masini, 1998}}$
Gschnitz-LGM	**Gschnitz**	$\Delta ELA_{\text{Ivy-Ochs et al., 2008}}$

PUDRES — **Paleo_ELA 2327**

ΔELAs, with respect to "reference" ELAs

623	**473**

Stadials, based on the ΔELA

Gschnitz	Daun-Gschnitz	$\Delta ELA_{\text{Penck \& Brückner, 1909}}$
Steinach	Daun-Gschnitz	$\Delta ELA_{\text{von Klebelsberg, 1948}}$
Gschnitz	Gschnitz	$\Delta ELA_{\text{Castiglioni, 1964}}$
Gschnitz-Bühl	Daun	$\Delta ELA_{\text{Masini, 1998}}$
Clavadel/Senders-Gschnitz	**Clavadel/Senders**	$\Delta ELA_{\text{Ivy-Ochs et al., 2008}}$

Mutschlechner (1933) according to which the most surficial portion of the LGM ice, in this sector of the valley, was depleted in crystalline erratics.

If we accept the hypothesis that Valparola represented the southernmost reach of the Val Badia glacier, a left branch of the main glacier residing within the Pusteria valley, during the LGM (Mutschlechner, 1933), we can argue that with the climatic amelioration that followed the last expansion phase of the LGM, the ice flow switched direction, starting its northward dynamics which characterized the local valley glacier from the Lateglacial onset until the Clavadel/Senders stadial, covering a time period that could span, roughly, from 19 ka to 15.5/16 ka (Klasen et al., 2007; Ivy-Ochs et al., 2008). In this period, one glacier stagnation phase can be recognized, marked by the complex of seven frontal moraines classified between the LGM and the Gschnitz stadial at Armentarola. The first clear readvance phase occurred during the Gschnitz stadial, when the local valley glacier was almost completely confined to the upper sectors of the valley, with the lower Gschnitz moraine at Malghe Valparola and the upper Gschnitz one at Dlira-II.

After the Gschnitz readvance phase, the whole accumulation area of Valparola may have rapidly become almost ice-free, leaving just one ice body within the well shaded, narrow and deep hanging valley of Vallone Pudres. There, during the Clavadel/Senders stadial, the Pudres glacier had a small readvance marked by a frontal moraine a little above the slope change between the hanging valley and the Rü de Pudres valley.

The Egesen and Kartell stadials are absent in Valparola. The identification of rock glaciers, extending down slope until some 2000 m, leads to hypothesize that during the Egesen stadial (and maybe throughout the whole Younger Dryas), periglacial conditions characterized the valley. Other authors have identified rock glaciers developing during the Egesen stadial, indicating a lowering of the permafrost to 2000-1900 m. (Kerschner, 1978; Sailer & Kerschner, 1999; Frauenfelder et al., 2001). Nowadays, active rock glaciers reach the lowest altitude at 2500 m, in the near Valun de Ciampestrin NW-facing valley (Holzner, 2011), some 3 km NE from the eastern limit of Valparola. Therefore, the local depression of the permafrost lower limit between the Younger Dryas and now is around 500 m, 200 m, even lower than the value found in literature (Ivy-Ochs et al., 2009).

At the onset of the Holocene, the permafrost reached higher elevations than during the preceding colder stage (Ivy-Ochs et al., 2009), thus leading to hypothesize that the Valparola's rock glaciers were at that time already inactive.

5. DISCUSSION AND CONCLUSIONS

The present study has shown how the reconstruction of the local paleo-glaciers and of their paleo-ELAs, performed taking advantage of the most up-to-date methodologies, has provided results that, in terms of stadial classification, match reasonably well with those obtained by G.B. Castiglioni (1964), if his reference ELA is used. This proves how the method adopted by G.B. Castiglioni (1964) to reconstruct the ELA of paleo-glaciers - adapting the methodology proposed by Kurowsky (1891) - is able to give results that are comparable to those achievable with much more sophisticated methods, at least in this study area. From this observation it could be deduced that the search for very detailed reconstructions of paleo-surfaces and of refined ELA-calculations, at least for small valley glaciers, my account for just a small percentage to the improvement of the Lateglacial reconstructions. Nevertheless, this conclusion cannot be generalized after a first test in a small area like Valparola, and needs further validation, comparing the results over the whole territory covered by G.B. Castiglioni (1964). The good integration of the tools by Pellitero et al. (2015; 2016) within a GIS platform has proved to drastically reduce the time of calculation for paleo-ELA assessments over large-scale areas, therefore favouring the refinement of G.B. Castiglioni's study for the whole Dolomites. A refinement that could also take advantage, within this study, of a more detailed topography and of recent advances in geomorphological interpretation.

Having selected, for our study, a reference ELA which is 150 m lower than the one used by G.B. Castiglioni (1964), has inevitably placed the paleo-glaciers of Valparola within relatively younger Lateglacial phases. Therefore, it seems that more crucial than the reconstruction method of paleo-glaciers is the selection of the proper reference ELA which, in our case, was only assumed, since no studies are known to us able to define the LIA's ELA for the area. The LIA's ELA is currently taken as the better reference for ELA-depression calculations (Gross et al., 1977, confirmed in Ivy-Ochs et al., 2008). Nevertheless, the assumption we have made of a 100 m-lowering of the LIA's ELA from the current ELA is widely accepted and, anyhow, it should not introduce great variations in ELA-depression calculations (and consequently in stadial attribution) with respect to a more accurately defined local-LIA's ELA. In fact, even by using different stadial classifications, with different ELA depression ranges and reference ELAs, we have shown that differences seem not that great, clustering results around common stadials. Anyhow, we have reconstructed the LIA's ELA from the nearby Marmolada glacier thanks to results from a recent study (Bertoni & Casarotto, 2016), in order to cross validate our assumption, despite the peculiar topographic characteristics of

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Tab. 3 - Stadial attributions of Valparola paleo-glaciers, based on different "present day ELAs" (table's header) and according to stadial classifications proposed by different Authors (last column to the right). The paleo-ELA obtained by this study is in blue. The stadial attribution obtained by this study is in bold in the second column. The stadial attribution obtained using the methodology adopted for this study and Castiglioni's data is the one in bold in the first column.

the Marmolada mount. The resulting 2757 m value fits reasonably well with the 2800 m value taken by us as reference for the ELA-depression calculation, although we think that just one value cannot be sufficient for reconstructing the real LIA's ELA for the area. Therefore efforts should be put in identifying more areas where even approximate calculations of the LIA's ELA can be performed, trying to achieve a sufficient number of values to interpolate.

With respect to the Balance Ratio value used, we have tested how its change from 1 to 2.2 (i.e., the lower and upper confidence limits of the 1.6 value assigned by Rea (2009) to the European Alps) allows for just a +40/-20 m maximum difference in the altitude of the equilibrium line of the paleo-glaciers, again not introducing substantial differences in the calculation of the depression line.

Contribution to the local accumulation zones by snow avalanching has been proved to be of not much relevance, with an Avalanche Ratio (Hughes, 2008) around 0.21. Solar radiation, on the other hand, seems to have played a major role in the mass balance of glaciers during the Lateglacial, with well exposed areas prevailing on sheltered ones, thus favouring preferential ablation. Both observations could explain the limited size of the local paleo-glaciers. The same GIS integration of the tools by Pellitero et al. (2015; 2016) can favour the statistical analysis of paleo-glaciers' ELAs in morphologically different areas (in terms of size of accumulation basins, altitude range, solar exposure, avalanche susceptibility and debris cover).

In our opinion, would the analysis be extended to the whole Dolomites, we propose to maintain the "classic" Lateglacial stadial classification, in its most recent formulation (Ivy-Ochs et al., 2008), above all to limit the number of local stadials which would make comparisons between different areas more complex; secondly, because stadials have a clear relationship with climatic phases at global scale (the Gschnitz with Heinrich event 1 and the Egesen with the Younger Dryas). Instead, the real effort should be put in the identification of the local LIA's ELA, where geomorphological evidence is available or where good estimation can be made of its depression from the current ELA.

Eventually, the stadials identified would need to be dated. Cosmogenic-nuclide exposure dating of moraine rocks has still high costs if statistically sound results are to be achieved and, specifically for dolomite rocks, the method has still uncertainties (Alfimov & Ivy-Ochs, 2009). Moreover, the confidence intervals in cosmogenic-nuclide exposure dating are often comparable to the length of Lateglacial stadials (from ±740 to ±1030 years in Moran et al., 2016), creating doubts on which stadial the dated material belongs to. Nevertheless, dating methods will quite likely improve their effectiveness while at the same time possibly lower their costs, allowing to constrain the relative dating results achieved so far.

AKNOWLEDGEMNTS

The paper is part of the PRIN 2010-11 MIUR Project on the "Dynamics of morphoclimatic systems as a response of global changes and induced geomorphological risks" (co-ordinator: C. Baroni; research unit responsible: M. Soldati). The research benefited from a visit in recently deglaciated areas of the Tierra del Fuego (Patagonia) and discussions with Dr. Jorge Rabassa and his collaborators on the field.

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Ms. received: May 18, 2016
Final text received: April 18, 2017