Quaternary Science Reviews 177 (2017) 10–33

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Time constrains for post-LGM landscape response to deglaciation in Val Viola, Central Italian Alps

Riccardo Scotti [a], [*], Francesco Brardinoni [a], Giovanni Battista Crosta [b], Giuseppe Cola [c], Volkmar Mair [d]

[a] Department of Biological, Geological and Environmental Sciences (BiGeA), University of Bologna, Via Zamboni 67, 40126 Bologna, Italy
[b] Department of Earth and Environmental Sciences, University of Milano Bicocca, Piazza della Scienza 4, 20126 Milano, Italy
[c] Glaciological Service of Lombardy (SGL), Via Motta 45, 20871 Vimercate MB, Italy
[d] Office for Geology and Building Materials Testing, Autonomous Province of Bolzano, Via Val d'Ega 48, 39053 Cardano BZ, Italy

## ARTICLE INFO

*Article history:*
Received 12 May 2017
Received in revised form
24 August 2017
Accepted 11 October 2017

*Keywords:*
Lateglacial
Holocene
Glacial geomorphology
Schmidt-hammer exposure-age dating
Deglaciation
Rock glaciers
Rock avalanches

## ABSTRACT

Across the northern European Alps, a long tradition of Quaternary studies has constrained post-LGM (Last Glacial Maximum) landscape history. The same picture remains largely unknown for the southern portion of the orogen. In this work, starting from existing $^{10}$Be exposure dating of three boulders in Val Viola, Central Italian Alps, we present the first detailed, post-LGM reconstruction of landscape (i.e., glacial, periglacial and paraglacial) response south of the Alpine divide. We pursue this task through Schmidt-hammer exposure-age dating (SHD) at 34 sites including moraines, rock glaciers, protalus ramparts, rock avalanche deposits and talus cones. In addition, based on the mapping of preserved moraines and on the numerical SHD ages, we reconstruct the glacier extent of four different stadials, including Egesen I (13.1 ± 1.1 ka), Egesen II (12.3 ± 0.6 ka), Kartell (11.0 ± 1.4 ka) and Kromer (9.7 ± 1.4 ka), whose chronologies agree with available counterparts from north of the Alpine divide. Results show that Equilibrium Line Altitude depressions (ΔELAs) associated to Younger Dryas and Early Holocene stadials are smaller than documented at most available sites in the northern Alps. These findings not only support the hypothesis of a dominant north westerly atmospheric circulation during the Younger Dryas, but also suggest that this pattern could have lasted until the Early Holocene. SHD ages on rock glaciers and protalus ramparts indicate that favourable conditions to periglacial landform development occurred during the Younger Dryas (12.7 ± 1.1 ka), on the valley slopes above the glacier, as well as in newly deglaciated areas, during the Early Holocene (10.7 ± 1.3 and 8.8 ± 1.8 ka). The currently active rock glacier started to develop before 3.7 ± 0.8 ka and can be associated to the Löbben oscillation. Four of the five rock avalanches dated in Val Viola cluster within the Early Holocene, in correspondence of an atmospheric warming phase. By contrast, the timing of the main Val Viola rock avalanche, 7.7 ± 0.3 ka during the Holocene Thermal Optimum, suggests a possible causal linkage to permafrost degradation. Overall, Schmidt-hammer proved to be an effective, inexpensive and versatile tool for improving the spatial resolution of Val Viola post-LGM landscape history, starting from existing numerical age constrains.

## 1. Introduction

In mountain landscapes, glaciation and deglaciation cycles have produced profound modifications on the topography, the organization of currently active geomorphic process domains, and the spatial distribution of surficial materials (e.g., Benn and Evans, 1998; Montgomery, 2002; Brocklehurst and Whipple, 2004; Brardinoni and Hassan, 2006). Understanding and reconstructing the timing and styles of landscape response to deglaciation is critical for understanding the evolution of formerly glaciated settings (e.g., Church and Ryder, 1972; Ballantyne, 2002), as well as for predicting the response potential of currently glacierized ones (e.g., Dadson and Church, 2005; Haeberli et al., 2016). To achieve these goals it is fundamental to map the spatial organization of relict glacial and periglacial landforms, characterize the relevant constituent materials, and constrain the chronology of their formation and development.

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[*] Corresponding author.
*E-mail address:* riccardo.scotti@unibo.it (R. Scotti).

https://doi.org/10.1016/j.quascirev.2017.10.011

**Abbreviations**

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|---|---|
| AAR | Accumulation Area Ratio |
| AABR | Area Altitude Balance Ratio |
| Bø/Al | Bølling/Allerød |
| EH | Early Holocene |
| ELA | Equilibrium Line Altitude |
| ΔELA | ELA depression compared to the Little Ice Age |
| DSM | Digital Surface Model |
| LGM | Last Glacial Maximum |
| LH | Late Holocene |
| LIA | Little Ice Age |
| MAAT | Mean Annual Air Temperature |
| MH | Middle Holocene |
| OD | Oldest Dryas |
| GI-1b | Gerzensee oscillation |
| PBO | Pre Boreal Oscillation |
| SHD | Schmidt-hammer exposure-age dating |
| YD | Younger Dryas |

Today, cosmogenic nuclide (CRN) dating represents the most reliable and widely used technique in Quaternary studies to obtain exposure ages of post-LGM (Last Glacial Maximum) landforms (e.g., Ivy-Ochs et al., 2006b, 2007; Wirsig et al., 2016a; Palacios et al., 2017). However, the relatively high analytical costs and the onerous procedures involved with sample preparation, limit the number of landforms that are typically dated in CRN-based alpine case studies i.e., from 1 to 11, with an average of 3 (Table A1; e.g., Ivy-Ochs et al., 2006a; Böhlert et al., 2011; Chenet et al., 2016). In this context, we think that complementary dating techniques have not been fully exploited, especially in the European Alps, to expand the number of dated sites and improve the spatial resolution of post-LGM reconstructions.

Schmidt-hammer exposure-age dating (SHD), through the application of numerical age calibration curves, forms an inexpensive and effective complement to augment the number of dated sites (Shakesby et al., 2006, 2011). This technique has been widely used to date moraines, bedrock surfaces, pronival ramparts, rock glaciers, rock avalanche deposits and fluvial terraces in Norway (e.g., McCarroll and Nesje, 1993; Nesje et al., 1994; Matthews and Owen, 2010; Matthews and Winkler, 2011; Matthews et al., 2011, 2013, 2014), New Zealand (e.g., Winkler, 2005, 2009; Stahl et al., 2013) and Poland/Slovakia (e.g., Kłapyta, 2013; Zasadni and Kłapyta, 2016). By contrast, SHD has been rarely used in the European Alps, with only few studies focused on rock glaciers in Switzerland (e.g., Frauenfelder et al., 2005; Scapozza and Ramelli, 2011; Böhlert et al., 2011; Scapozza, 2015b; Scapozza et al., 2011, 2014b) and Austria (e.g., Kellerer-Pirklbauer, 2008; Rode and Kellerer-Pirklbauer, 2012).

The ability to date a wide range of landforms allows to gain additional insights on how different landscape components and geomorphic processes have interacted and responded to past climatic fluctuations. Moraines directly testify to past glacier advances driven by climate deterioration. They are reference paleoclimatic proxies that can be used to reconstruct post-LGM glacier fluctuations (e.g., Penck and Brückner, 1901–1909; Maisch, 1982; Ivy-Ochs et al., 2006b). Rock glaciers represent additional morphologic benchmarks for better constraining paleo-climatic reconstructions solely based on glacier-derived chronologies (e.g., Frauenfelder et al., 2005; Ivy-Ochs et al., 2009b; Krainer et al., 2015). Being associated with the creeping of permafrost-rich debris in glacier-free areas, the spatial distribution of rock glaciers, and their degree of activity, are tightly related to climate-driven ground thermal conditions (Hoelzle et al., 2001; Haeberli et al., 2006). Last but not least, information on mass wasting events can add further chronological constraints for reconstructing post-LGM landscape evolution (e.g., Bichler et al., 2016). In particular, rock avalanches are discrete events producing distinct deposits that are particularly suitable for exposure age dating (e.g., Ivy-Ochs et al., 2009a; Chenet et al., 2016).

In the European Alps, post-LGM glacier reconstructions have mainly focused on the northern part of the orogen (e.g., Heuberger, 1966; Gross et al., 1977; Maisch, 1981, 1987; Ivy-Ochs et al., 2009b; Cossart et al., 2012). South of the continental divide, Quaternary studies have mainly dealt with the LGM morainic amphitheatres (e.g., Bini, 1997; Monegato et al., 2007; Ravazzi et al., 2012, 2014; Rossato et al., 2013; Monegato et al., 2015; Scapozza et al., 2014a). Along the inner valleys, previous glaciological studies have mainly addressed Middle to Late Holocene time scales (e.g., Orombelli and Porter, 1982; Orombelli and Mason, 1997; Gabrielli et al., 2016), while numerical dating of Lateglacial moraines is available at three locations only (Federici et al., 2008; Hormes et al., 2008; Favilli et al., 2009).

In order to link post-LGM glacier extent to concurrent climatic fluctuations, it is critical to complement the numerical dating of Lateglacial and Holocene moraines with the modelling of paleoglacier reconstruction. This linkage allows evaluating the fluctuations of a widely applied climatic proxy, such as the Equilibrium Line Altitude (ELA), in time and space (e.g., Kerschner and Ivy-Ochs, 2008), as exemplified by several investigations conducted in the Northern European Alps (e.g., Kerschner and Ivy-Ochs, 2008; Cossart et al., 2012; Moran et al., 2016a,b). For example, the ELA depression (ΔELA), relative to the Little Ice Age reference, has been used to infer precipitation pattern in the Younger Dryas across the Swiss and Austrian Alps (Kerschner et al., 2000; Kerschner and Ivy-Ochs, 2008). To date, the general lack of data from the southern portion of the European Alps, except for a peripheral site in the Maritime Italian Alps (Federici et al., 2008, 2016), has prevented from extending this analysis at the orogen scale (i.e., Kerschner et al., 2000).

To partially address the foregoing research gaps, in this study, we present new data from Val Viola, Central Italian Alps. The main objective is to reconstruct the post-LGM landscape history associated with glacial, periglacial, and mass wasting processes in a site located south of the main Alpine divide. To this end, starting from existing $^{10}$Be dates (i.e., Hormes et al., 2008), we apply SHD on moraines, rock glaciers, protalus ramparts, talus cones and rock avalanche deposits. To improve the assessment of possible climate-response linkages since LGM, we integrate these data with the modelling of paleo-glacier extent across the relevant stadials, exploiting the spatial distribution of the dated moraines.

## 2. Post-LGM background

A number of studies have documented moraine complexes associated to the Egesen stadial, in which two or three sub-stadials (Egesen I, II and III) were recognized (Maisch, 1981; Kerschner et al., 2000; Ivy-Ochs et al., 2006b; Favilli et al., 2009). The outer moraine complexes are usually smooth and rich in fine sediments (Egesen I), the inner ones (Egesen II or Bocktentälli) are rougher and boulder-richer (Maisch, 1981, 1987; Ivy-Ochs et al., 2009b). Egesen moraines have been traditionally linked to the Younger Dryas (YD) (Patzelt, 1972; Maisch, 1981; Kerschner, 1978; Kerschner et al., 2000), a cold and relatively dry period that lasted for about 1.0 ka (Rasmussen et al., 2006, 2008; von Grafenstein et al., 2013). At this stage, glaciers occupied the upper portion of the main alpine