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^{10}Be exposure dating of the timing of Neoglacial glacier advances in the Ecrins-Pelvoux massif, southern French Alps

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ABSTRACT

Alpine glacier variations are known to be reliable proxies of Holocene climate. Here, we present a terrestrial cosmogenic nuclide (TCN)-based glacier chronology relying on 24 new ^{10}Be exposure ages, which constrain maximum Neoglacial positions of four small to mid-sized glaciers (Rateau, Lautaret, Bonnepierre and Etages) in the Ecrins-Pelvoux massif, southern French Alps. Glacier advances, marked by (mainly lateral) moraine ridges that are located slightly outboard of the Little Ice Age (LIA, c. 1250-1860 AD) maximum positions, were dated to 4.25 ± 0.44 ka, 3.66 ± 0.09 ka, 2.09 ± 0.10 ka, c. 1.31 ± 0.17 ka and to 0.92 ± 0.02 ka. The '4.2 ka advance', albeit constrained by rather scattered dates, is to our knowledge exposure-dated here for the first time in the Alps. It is considered as one of the first major Neoglacial advance in the western Alps, in agreement with other regional paleoclimatological proxies. We further review Alpine and Northern Hemisphere mid-to-high latitude evidence for climate change and glacier activity concomitant with the '4.2 ka event'. The '2.1 ka advance' was not extensively dated in the Alps and is thought to represent a prominent advance in early Roman times. Other Neoglacial advances dated here match the timing of previously described Alpine Neoglacial events. Our results also suggest that a Neoglacial maximum occurred at Etages Glacier 0.9 ka ago, i.e. during the Medieval Climate Anomaly (MCA, c. 850-1250 AD). At Rateau Glacier, discordant results are thought to reflect exhumation and snow cover of the shortest moraine boulders. Overall, this study highlights the need to combine several sites to develop robust Neoglacial glacier chronologies in order to take into account the variability in moraine deposition pattern and landform obliteration and conservation.

1. Introduction

The considerable quasi-global glacial wastage that has been taking place for more than a century is currently accelerating in the European Alps (Vincent et al., 2017) in response to a warming trend that is higher than the hemispheric average (Auer et al., 2007). Glacier mass changes measured over the last three decades cannot be explained without accounting for anthropogenic forcing (Marzeion et al., 2014). Conversely, glacier mass losses immediately following the end of the Little Ice Age appear to have been primarily driven by natural forcings (Vincent et al., 2005; Lüthi, 2014; Marzeion et al., 2014; Sigl et al., 2016). The knowledge of the timing and amplitude of Holocene LIA-type glacial events and the underlying natural climate forcings could improve our understanding of the glacier evolution and responsible climate drivers since the LIA. Though, the temporal and spatial patterns of such glacial events remain poorly constrained, making causes highly debated (Wanner et al., 2011; Solomina et al., 2015, 2016). A better spatio-temporal knowledge of Holocene climate characteristics is necessary to decipher forcing factors and improve climate model simulations (Schmidt et al., 2014; McCarroll, 2015).

Small to medium-sized alpine glaciers react sensitively to short-term climate variations (Jóhannesson et al., 1989; Oerlemans, 2005; Six and Vincent, 2014; Roe et al., 2017). This has last been evidenced

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in the Alps by the decadal-scale period of minor climate deterioration in the second half of the 20th century that led to significant glacier advances and moraine deposition in the early 1980s (Patzelt, 1985). The glacial-geologic record (i.e. moraine ridge stratigraphy) is hence often considered as one of the most straightforward climate proxies beyond the instrumental period (e.g. Putnam et al., 2012; Young et al., 2015). However, full use of this archive as paleoclimate proxy is restricted by its discontinuous nature, by the selective preservation of glacial deposits and by possible non-climatic controls on moraine deposition, such as glacier stagnation or advance due to coverage of the glacier tongue by rockfall debris.

The glacial geologic record could differ between nearby sites due to different glacier hypsometry and ice-flow dynamics (Winkler et al., 2010; Barr and Lovell, 2014). For this reason, dating of moraine complexes provides not only insights into the timing of past glacier-friendly periods, but also allows interpreting the glacial record in terms of landform deposition, conservation and obliteration (Gibbons et al., 1984; Kirkbride and Winkler, 2012; Barr and Lovell, 2014). Well-distributed regionally-significant chronologies based on a homogeneous set of glaciers (size, hypsometry) are therefore requisite to obtain a more complete picture of glacier advances in response to local climate changes. This is particularly true with regard to the Neoglacial, a period during which the glacier advances were of nearly the same magnitude throughout the Northern Hemisphere (Solomina et al., 2015), favouring self-censoring of the moraine record. These chronologies will also permit to assess if climate was the main driver of the glacier variations, because non-climatic controls should not affect several glaciers simultaneously.

There is still a dramatic lack of direct constraints on Holocene glacier variability in the westernmost Alps. Investigations on the French side of the Alps have mainly focused on the Mont Blanc massif (see Le Roy et al., 2015 and references therein). The Ecrins-Pelvoux massif (hereafter EPM) is the south-westernmost currently glaciated area in the European Alps – with the exception of isolated and soon-disappeared glacierets located in the Belledonne massif to the west and in the Ubaye and Maritime Alps massifs to the south (Fig. 1a). To deal with the problem of representativeness and selective preservation of moraine deposits we sampled the outermost Holocene ridges at four different glacier forefields located throughout the EPM (Fig. 1b). The aim of this study was to obtain a local-scale overview of the timing of Holocene/Neoglacial maxima. We present ^{10}Be exposure ages constraining glacier advances that were almost as extended as the late-LIA stages, marked by the so-called ‘AD 1850 moraines’. Given the location of the dated moraine segments, at most a few tens of meters outboard of the LIA extent, we consider in the following text that glacier size during these advances was virtually the same as during the ensuing LIA maxima.

2. Study area and previous work

The EPM (centred on 44°55′N 6°17′E) belongs to the external crystalline massifs of the western Alps. It consists of blocks of European basement, which was intruded by granites and metamorphosed during the Hercynian orogeny, then exhumed along crustal-scale faults since Oligocene–Early Miocene times. Remnants of inverted Jurassic sedimentary basins are interspersed between these blocks (Dumont et al., 2008). Hence, bedrock lithologies of the glaciated catchments are mostly quartz-rich granites and gneisses (Barbier et al., 1976; Barféty and Pêcher, 1984).

The massif presents a high alpine topography with several summits reaching c. 4000 m a.s.l (Fig. 1b). and valley bottoms around 1000–1500 m a.s.l. Imprint of Quaternary glaciations on present-day landscape is strong as shown by the U-shaped valley profiles, valley rock steps and overdeepenings, lateral hanging valleys, and widespread glacial trimlines (Montjuvent, 1974; Delunel et al., 2010b; Valla et al., 2010). Last Glacial Maximum (LGM) ice cover has been reconstructed from mapping and interpolation of glacial features (van der Beek and Bourbon, 2008). Geomorphic evidence also permitted to reconstruct the LIA glacier extent, which amounted to c. 171 km^2 (Fig. 1b; Edouard, 1978; Gardent et al., 2014). Present day glacierization is characterized by highly fractionated small cirque and slope ice bodies ($n = 282$; mean surface: 0.24 ± 0.6 km^2), which covered 68.6 km^2 in 2009 (Fig. 1b; Gardent et al., 2014). Few valley glaciers are still present today, and most of them are debris-covered. The two largest glaciers are the debris-free Girose Glacier (5.1 km^2, that forms an ice surface of 8.1 km^2 with the contiguous Mont-de-Lans Glacier) and Glacier Blanc (4.8 km^2) (2009 data; Fig. 1b).

The deglacial chronology from the LGM maximum was improved recently in the EPM with TCN ages constraining ice thinning and tongue retreat (Delunel et al., 2010b). The Younger Dryas stadial has led to readvances, which were mapped in several catchments (Edouard, 1978; Francou, 1981; Coûteaux, 1983a, 1983b; Colas, 2000; Di Costanzo and Hofmann, 2016) and numerically-dated only at one location (Chenet et al., 2016). It appears that glacier tongues were restricted to the highest cirques at the beginning of the Holocene (e.g. Coûteaux, 1983a). State-of-the-art knowledge on the deglaciation was summarized by Cossart et al. (2011) for the eastern part of the EPM. However, no studies have focused on the dating of Holocene/Neoglacial stadials in the EPM up to now. Only LIA and post-LIA advances were dated by palynology (Tessier et al., 1986) and lichenometry (Cossart et al., 2006; Le Roy and Deline, 2009; Le Roy, 2012). In addition, it should be noted that subfossil woods were found at two glacier forefields in the EPM: at Chardon Glacier (Fig. 1b; Vivian, 1979; Le Roy, unpublished data) where one of the samples yielded a radiocarbon age of 1035–1410 cal. AD (med. prob.: 1245 cal. AD; Vivian, 1979), and at Etages Glacier (this work). However, in these studies, the circumstances of sampling are either not accurately known or indicate detrital woods of unknown original location. A firm link with glacier variations has therefore not yet been established at these sites. In any case, these wood remains indicate periods when the treeline was at higher elevation – as the sites of recovery are nowadays devoid of woody vegetation – and mostly composed of *Pinus cembra*, a species which is rare today in the study area (Coûteaux, 1984).

Pioneering glaciological studies in the EPM date back to the late 19th century with the first punctual glacier length measurements (Bonaparte, 1891, 1892; Kilian, 1900) and were intensified in the 20th century (Jacob and Flusin, 1905; Allix et al., 1927; Letréguilly and Reynaud, 1989; Reynaud, 1998; Reynaud and Vincent, 2000; Bonet et al., 2016). Mass balance is surveyed at Glacier Blanc since AD 2000 with the glaciological method, and was reconstructed for earlier dates based on remote sensing data (Thibert et al., 2005; Rabatel et al., 2008, 2016). Based on remote sensing of the end-of-summer snowline, average ELA was determined to be 3100 ± 80 m for 11 of the main EPM glaciers during the AD 1984–2010 period, with the lowest values occurring during the year 1984 (2995 ± 60 m) and the highest during the year 2003 (3330 ± 75 m) (Rabatel et al., 2013). This can be compared to the average value of 2990 ± 110 m computed over the same time interval for 14 glaciers in the Mont Blanc massif, located 120 km north (Rabatel et al., 2013, Fig. 1a). Additionally, Cossart (2011) derived an ELA rise of c. 250 m