Geomorphology 278 (2017) 60–77

Contents lists available at ScienceDirect

Geomorphology

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

Cirques have growth spurts during deglacial and interglacial periods: Evidence from ^{10}Be and ^{26}Al nuclide inventories in the central and eastern Pyrenees

Y. Crest [a,*], M. Delmas [a], R. Braucher [b], Y. Gunnell [c], M. Calvet [a], ASTER Team [b,1]:

[a] Univ Perpignan Via-Domitia, UMR 7194 CNRS Histoire Naturelle de l'Homme Préhistorique, 66860 Perpignan Cedex, France
[b] Aix-Marseille Université, CNRS–IRD–Collège de France, UMR 34 CEREGE, Technopôle de l'Environnement Arbois–Méditerranée, BP80, 13545 Aix-en-Provence, France
[c] Univ Lyon Lumière, Department of Geography, UMR 5600 CNRS Environnement Ville Société, 5 avenue Pierre Mendès-France, F-69676 Bron, France

ARTICLE INFO

Article history:
Received 14 June 2016
Received in revised form 25 October 2016
Accepted 27 October 2016
Available online 29 October 2016

Keywords:
Cirque
Denudation rate
Cosmogenic nuclide dating
Buzzsaw
Pyrenees

ABSTRACT

Cirques are emblematic landforms of alpine landscapes. The statistical distribution of cirque-floor elevations is used to infer glacial equilibrium-line altitude, and the age of their frontal moraines for reconstructing glacial chronologies. Very few studies, however, have sought to measure cirque-floor and supraglacial ridgetop bedrock downwearing rates in order to confront these denudation estimates with theoretical models of Quaternary mountain landscape evolution. Here we use ^{10}Be nuclide samples ($n = 36$) from moraines, bedrock steps, and supraglacial ridgetops among a population of cirques in the east-central Pyrenees in order to quantify denudation in the landscape and detect whether the mountain topography bears any relevance to the glacial buzzsaw hypothesis. Minimum exposure ages (MEAs) obtained for a succession of moraines spanning the Oldest Dryas to the Holocene produced a deglaciation chronology for three different Pyrenean ranges: Maladeta, Bassiès, and Carlit. Based on a series of corrections, calibrations, and chronostratigraphic tuning procedures, MEAs on ice-polished bedrock exposures were further used to model denudation depths at nested timescales during the Würm, the Younger Dryas, and the Holocene. Results show that subglacial cirque-floor denudation was lower during glacial periods (Würm: ~10 mm/ka) than during deglacial and interglacial periods (tens to hundreds of mm/ka). The relative inefficiency of glacial denudation in the cirque zone during the Würm would have resulted from (i) cold-based and/or (ii) low-gradient glaciers situated in the upper reaches of the icefield; and/or from (iii) glacier-load starvation because of arrested clast supply from supraglacial rockslopes situated in the permafrost zone. Denudation peaked during the Younger Dryas and Holocene glacial advances, a time when cirque glaciers became steeper, warmer-based, and when frost cracking weakened supraglacial ridgetops, thus enhancing subglacial erosion by providing debris to the sliding glacier base. Cirques, therefore, grow faster during more temperate periods of cirque glaciation than under full glacial conditions. Another key finding was the very low rates of ridgetop lowering averaged over the Würm and Holocene (10–25 mm/ka). A comparison of the denudation rates obtained from the cirque zone with regional estimates of crustal uplift indicates that the alpine topography is not in a steady state. The low intensity of glacial denudation failed to bring the topography to a buzzsaw equilibrium state.

1. Introduction

The idea that feedback between climate and crustal uplift drove accelerated mountain uplift during the late Cenozoic has been an underlying hypothesis of research in Earth sciences (Molnar and England, 1990; Small and Anderson, 1995; Whipple et al., 1999; Whipple, 2009; Champagnac et al., 2012). Among the various geomorphic agents contributing to denudation, glaciers are recognized as being very efficient at reshaping mountain topography and generating isostatic-driven uplift. This statement is based on a growing body of quantitative data acquired worldwide, using a range of methods of measurement and spanning different spatial and timescales (Champagnac et al., 2014). Low-temperature thermochronology (LTT: e.g., apatite fission-track analysis, apatite helium, and ^{4}He/^{3}He dating) captures long-term denudation rates (10^5 to 10^8 years; Shuster et al., 2005, 2011; Ehlers et al., 2006; Densmore et al., 2007; Berger et al., 2008; Thomson et al., 2010; Valla et al., 2011). In a variety of mountain ranges, results based on these methods have recorded high denudation rates since 6 Ma and accelerated denudation after 2 Ma (review in Herman et al., 2013). This acceleration has been attributed to several climate-changing events during the late Cenozoic, e.g., global cooling and onset of glaciation in

---

[*] Corresponding author at: Université de Perpignan – Via Domitia, UMR 7194 CNRS, 52 avenue Paul Alduy, 66860 Perpignan, France.
E-mail address: yannick.crest@univ-perp.fr (Y. Crest).

[1] ASTER Team: G. Aumaître, D.L. Bourlès, K. Keddadouche.

http://dx.doi.org/10.1016/j.geomorph.2016.10.035
0169-555X/© 2016 Elsevier B.V. All rights reserved.

the northern hemisphere, activation of the Gulf Stream after closing of the isthmus of Panama ca. 4 Ma. These changes are recorded at all latitudes but appear sharpest among mid-latitude mountain belts, which during the Pleistocene hosted temperate-based and polythermal glaciers (Herman et al., 2013; Champagnac et al., 2014). Lower denudation values recorded among a variety of high-latitude mountain ranges are ascribed, accordingly, to the presence of cold-based glaciers (e.g., south Patagonia: Thomson et al., 2010; Koppes et al., 2015; northwest Svalbard: Gjermundsen et al., 2015). Sediment fluxes from current proglacial rivers and Holocene outwash sequences in fjords or lakes record denudation indirectly over shorter timescales (10 to 10^4 years) than LTT and provide catchment-averaged glacial denudation rates (Delmas et al., 2009). Case studies based on these methods have tended to provide high denudation rates (Hallet et al., 1996; Koppes and Hallet, 2006; Fernandez et al., 2011), but reviews report a wide spectrum of values spanning four orders of magnitude (from 0.001 to 10 mm/a; Delmas et al., 2009) and show that glacial and fluvial denudation rates can be similar (1 to 10 mm/a) under specific circumstances such as rapid tectonic uplift (Koppes and Montgomery, 2009).

In the same way, many numerical models based on basal ice sliding velocity and discharge show that Pleistocene glaciations have greatly controlled landscape evolution. The impacts of glacial denudation on topography have been argued to increase local relief and topographic steepness, either by overdeepening glacial trunk valleys (MacGregor et al., 2000; Valla et al., 2011) or by increasing preglacial topographic roughness (Sternai et al., 2015). The overall result is one of enhanced energy in the geomorphic system. Glacial erosion in tectonically active mountain ranges is also known to generate a characteristic hypsometric signature (deemed typical of the so-called glacial buzzsaw) displaying (i) a large proportion of land area occurring at the level of some Quaternary equilibrium-line altitude (e.g., the Quaternary average ELA, or QA-ELA, of Mitchell and Humphries, 2014); (ii) a limited elevation band immediately above this QA-ELA; and (iii) a tendency to produce a network of narrow ridges and peaks (Brozović et al., 1997; Brocklehurst and Whipple, 2002, 2004; Mitchell and Montgomery, 2006; Foster et al., 2008).

Given that the QA-ELA concept is expedient but problematic in a number of ways (see Evans et al., 2015; Mitchell and Humphries, 2015; Robl et al., 2015a), for the purpose of this study we settle instead for the regionally established notion of an average Pleistocene ELA, which was defined for the central and eastern Pyrenees using standard methods of ELA delimitation reported in Delmas et al. (2015). Within the buzzsaw narrative, altitude limits on ridgetops have been attributed to cirque floors acting as local base levels that control slope processes on cirque headwalls and generate sharpened arêtes by receding the headwall intersection (Schmidt and Montgomery, 1995; Egholm et al., 2009; Anders et al., 2010). Coalescing cirques are expected to promote the development of uniform lowering of ridgetops. This is advocated as one possible way of explaining crest and summit accordance in alpine settings (the 'Gipfelflur' problem of Penck, 1919), which nonetheless is also observed in unglaciated mountain ranges where regular patterns of fluvial dissection can appear to constrain ridgetops to a narrow elevation band.

The alpine cirque zone is the main focus of this study, with implications for the buzzsaw hypothesis and in a context where denudation rates responsible for alpine cirque development have remained poorly documented (see Barr and Spagnolo, 2015, Table 1 therein). Moreover, most publications on the quantification of cirque growth provide mean denudation values, without any distinction between the downwearing and backwearing components, because data are based either on cirque landform change (Andrews and LeMasurier, 1973; Olyphant, 1981; Brook et al., 2006) or on sediment volume output by cirque glaciers (Reheis, 1975; Anderson, 1978; Mills, 1979; Larsen and Mangerud, 1981; Hicks et al., 1990; Bogen, 1996). In the latter case, clast roundedness analysis has been used to discriminate between debris generated by subglacial processes and those generated by supraglacial hillslope processes operating on cirque headwalls (including rockfall, frost cracking, snow avalanches, etc.). Data thus obtained report headward denudation rates that are consistently lower than downwearing values, with 5 to 40% of the total sediment volume originating from headwalls against 95 to 60% from the subglacial bedrock (Reheis, 1975; Anderson, 1978; Larsen and Mangerud, 1981; Hicks et al., 1990). In contrast, a sediment budget involving a detailed inventory of sediment sources, transport pathways (supra-, sub- and englacial iceload, river suspended load and bedload, etc.), and storage sites in a glaciated alpine cirque of British Columbia (Canada) yielded greater headwall denudation rates (0.2–5.2 mm/a) than vertical subglacial cirque deepening rates (0.9–1.2 mm/a; Sanders et al., 2013). Those results were based on a quantification of debris accumulations produced and stored in the sediment system and relied on a large array of field measurements and remote sensing data. Overall, published data on cirque denudation rates compiled in Barr and Spagnolo (2015) span either very short (a few years to a few 10^3 years) or very long timescales (at least the entire Pleistocene in the case of estimates of landform change among cirques). With the exception of Sanders et al. (2013), none provide data on cirque growth patterns during the interval of an entire Pleistocene glacial/interglacial cycle, and none are based on in situ measurements likely to offer a distinction between back- and downwearing. Theoretical models have hypothesized, for example, that cirques grow mainly during interglacial periods, i.e., at times when glaciers are restricted to the cirque zone rather than during periods of extensive (i.e., icefield or icesheet) glaciation (Cook and Swift, 2012; Barr and Spagnolo, 2015).

Here we explore and test these ideas based on field measurements. We investigate the variability of glacial denudation rates at nested timescales within the alpine cirque zone of a mid-latitude intracontinental orogen, the Pyrenees, based on 36 measurements of cosmogenic ^{10}Be produced in situ obtained from three different Pyrenean ranges and measured among three kinds of rock surface: (i) boulders embedded in successive generations of frontal or lateral moraines, which are used as tools for establishing the chronology of cirque glaciation; (ii) polished bedrock steps, which are used to quantify glacial downwearing rates on cirque floors at nested timescales (entire Würmian glaciation cycle, Younger Dryas and Holocene readvances); and (iii) bedrock exposures on adjacent supraglacial ridgetops, which allow comparisons with glacial denudation on the cirque floors. The study focuses on three crystalline massifs located in the most elevated part of the mountain belt (Fig. 1), each having undergone somewhat contrasting impacts from the Pleistocene icefields. The Maladeta range (Pico de Aneto: 3404 m) is the most elevated massif of the Pyrenees and still bears a few small residual glaciers and a number of Holocene moraines. The Bassiès and Carlit ranges, which occur ~60 and ~100 km to the east of the Maladeta, respectively, are currently entirely deglaciated and bear no obvious vestiges of Holocene glacial landforms. The contrast in glacial histories and hypsometric attributes (Figs. 2, 3, and 4) between the three massifs provides additional value to the purpose of comparing these ranges. The aim is (i) to quantify in each case the rates of cirque-floor and ridgetop downwearing over the time scales of the Würm (regional icefield with large outlet glaciers), the Younger Dryas, and the Neoglacial (regrowth of cirque glaciers in the mid-Holocene after partial or complete deglaciation during the early Holocene; Matthews, 2013), respectively; (ii) to discuss inferences about the effects of glaciation on alpine topography in the Pyrenees; and (iii) to compare the results with other mid-latitude mountain ranges.

2. Geological and geomorphological settings

2.1. Long-term landscape evolution

The Pyrenees formed as a result of collision between Europe and the Iberian microplate during and after the late Cretaceous. The Axial Zone forms the inner and most elevated core of the mountain belt and consists of a Paleozoic basement—mainly granite, orthogneiss, and metasedimentary rocks. To its north and south, the Axial Zone is flanked by a succession of fold and thrust belts dominated by Mesozoic and