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Environmental controls on alpine cirque size

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ABSTRACT

Pleistocene alpine cirques are emblematic landforms of mountain scenery, yet their deceptively simple template conceals complex controlling variables. This comparative study presents a new database of 1071 cirques, the largest of its kind, located in the French eastern Pyrenees. It is embedded in a review of previous work on cirque morphometry and thus provides a perspective on a global scale. First-order cirque attributes of length, width, and amplitude were measured; and their power as predictors of climatic and lithological variables and as proxies for the duration of glacier activity was tested using ANOVA, simple and multiple linear regression, and their various post-hoc tests. Conventional variables such as cirque aspect, floor elevation, and exposure with respect to regional precipitation-bearing weather systems are shown to present some consistency in spatial patterns determined by solar radiation, the morning–afternoon effect, and wind-blown snow accumulation in the lee of ridgetops. This confirms in greater detail the previously encountered links between landforms and climate. A special focus on the influence of bedrock lithology, a previously neglected nonclimatic variable, highlights the potential for spurious relations in the use of cirque size as a proxy of past environmental conditions. Cirques are showcased as complex landforms resulting from the combination of many climatic and nonclimatic variables that remain difficult to rank by order of importance. Apart from a few statistically weak trends, several combinations of different factors in different proportions are shown to produce similar morphometric outcomes, suggesting a case of equifinality in landform development.

1. Introduction

In recent decades, investigations on the origins and geomorphological significance of glacial cirques have focused on their growth patterns and on the nature of acting processes. Evolutionary models (reviewed in Evans, 2008) have emphasized processes that are active during glacier presence, thus implying that cirques are landforms strictly generated in cold Quaternary environments. Within the remit of this theory, morphometric analysis has led some scholars to infer from the morphology of glaciated cirques the growth trajectories of entire cirque populations and to discriminate between the dominant cold-climate processes responsible for cirque development. Several models have been proposed, with varying emphasis on backwearing and downwearing (Evans, 2008). Depending on whether focus is on cirque wall recession or on cirque deepening, primary importance has been given either to frost weathering along the bergschrund (Johnson, 1904; Gardner, 1987) or to subglacial processes such as abrasion and quarrying (Dort, 1957; Galibert, 1962; White, 1970). More recent models have subsumed both hypotheses, emphasizing a systemic link between periglacially driven headwall retreat and subglacial scouring promoted by rotational sliding of glacier ice, with debris released by frost action providing abrasive tools to the glacier base (Gordon, 1977). Different combinations and intensities of process depend on past glacial environments (Gordon, 2001), with the idea that cirques are not only produced by cirque glaciers in alpine ice fields but also form beneath the ice sheets. In such cases, periglacial processes must be ruled out, with plucking processes appearing to operate equally on cirque walls and floors;Richardson and Holmund, 1996 (Rudberg, 1984; Hooke, 1991).

Other scholars have taken a broader perspective on the geomorphological nature of cirques, directly inspired by the 'trio of control' of Davis (1899) in which (i) climatic, (ii) lithological or structural, and (iii) time-related factors are examined. Most of the emphasis is, again, on the climatic controls of cirque features and is mainly expressed through cirque floor elevation as a proxy for the equilibrium line altitude (ELA) (Meierding, 1982; Porter, 2001) and on cirque aspect as an expression of the 'morning–afternoon' radiation contrast in mid-latitudes (see Evans, 1977, for modern cirque glaciers; Trenhaile, 1976; Olyphant, 1977; Embleton and Hamann, 1988; García-Ruiz et al., 2000; Mîndrescu et al., 2010, in the case of Pleistocene cirques). Nonclimatic variables such as lithology and structure have been considered of secondary importance (Evans, 1994; Evans and Cox, 1995). Though based on small samples or sporadic observations, lithology or structure have occasionally been recognized as capable of modulating cirque size (Haynes, 1968; Peterson and Robinson, 1969; Evans, 2006; Hughes et al., 2007): but the relative weights of these controlling variables on cirque size and morphology remain poorly documented

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(Evans, 2004). The time factor has been granted comparatively greater consideration, with findings of direct proportionality between cirque size and estimated cirque age being interpreted as a simple function of the cumulative duration of Pleistocene glacier activity (Sugden, 1969; Aniya and Welch, 1981; Haynes, 1998; De Blasio, 2002; Brook et al., 2006).

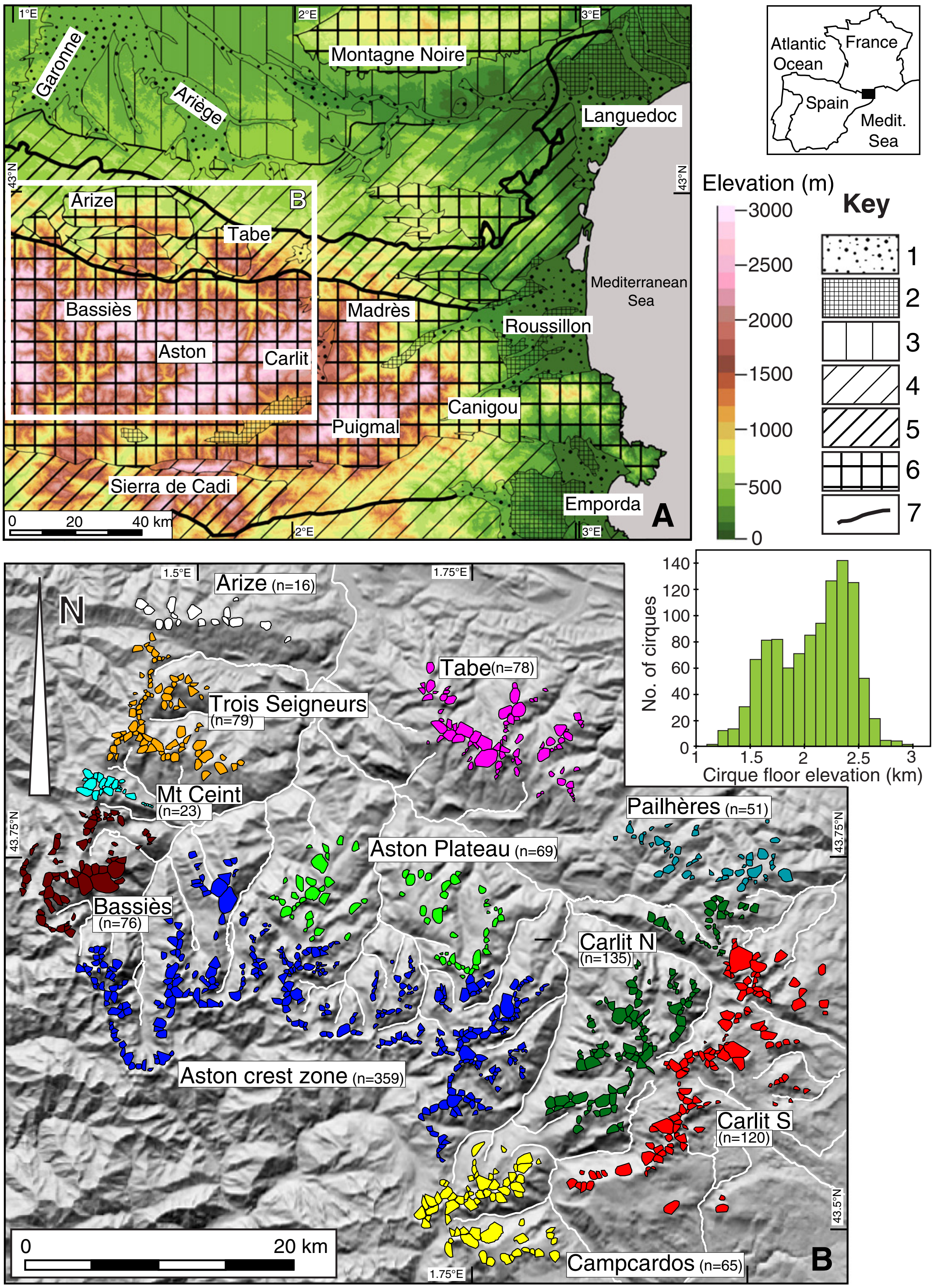

Fig. 1. Location map. (A) Main morphostructural units of the eastern Pyrenees. 1: Quaternary deposits. 2: Neogene pull-apart basin fill sequences. 3: Paleocene and Neogene clastic sequences of the Aquitaine retro-foreland basin. 4: Cretaceous to Oligocene fold and thrust belts forming external sierras. 5: Thrust and folded Triassic to Cretaceous rocks (North-Pyrenean Zone). 6: Paleozoic rocks of the Axial Zone, with satellite massifs (granitic thrust sheets) incorporated into the North-Pyrenean tectonic wedge. 7: Main compressional structures. (B) Location of the 1071 first-order cirques, also providing classes of membership to named massifs, each with an identity defined by its position with respect to Atlantic and Mediterranean climatic features. The Arize, Trois Seigneurs, and Tabe massifs benefit from steady and abundant snow supply owing to their front-line position with respect to Atlantic weather systems. Snowfall is also relatively abundant in Pailhères, north Carlit, and Aston, i.e., where the N–S Ariège valley funnels precipitation into the range from the west. By contrast, Bassiès and Mont Ceint are comparatively sheltered by the Arize and Trois Seigneurs massifs. This sheltered position is well recorded by the palaeogeography of Würmian stades in the Vicdessos glacial trough, which contrast with the glacial record of the Ariège valley (Delmas et al., 2012). Finally, shelter from oceanic precipitation is most acute in the Campcardos and south Carlit, with evidence for this today and from the Pleistocene record (Delmas et al., 2008). In order to satisfy a rule of relatively uniform cirque elevation within each climatic membership class, the cirques in the Aston massif were provided as two separate categories.