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A critical appraisal of allometric growth among alpine cirques based on multivariate statistics and spatial analysis

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ABSTRACT

When considering the morphometric attributes of a glacial cirque, imbalances between length, width, and amplitude have been deemed relevant tools for discriminating between two possible pathways of cirque growth: downwearing by glaciers or backwearing by freeze–thaw processes. Based on a sample of 1071 cirques in the French Pyrenees, we reframe the concern for climatic variables by also granting systematic consideration to cirque lithology. Insight into the factors that control cirque shape is gained from Principal Component Analysis, where maps of eigenvalues assigned to six classes of bedrock display spatial patterns of cirque form as a function of position along the regional climatic gradient. Among crystalline rocks (granite, gneiss, migmatite), cirque form is predominantly determined by climatic controls. This is highlighted in the contrast between the elevated core of the Pleistocene icefield, where cirque isometry prevails, and the more peripheral areas (external sierras of the Atlantic precipitation zone and high sierras of the drier Mediterranean zone) where the lighter imprint of glaciation on the landscape has failed to erase (through glacial deepening) the allometric signature of pre-Pleistocene topographic features such as shallow valley heads and etch-basins. As a result, wide and shallow cirques occur in these settings. Among schist outcrops, in contrast, cirque form appears randomly distributed, suggesting that bedrock characteristics (e.g., structure) rather than climate are the key controls on cirque growth patterns. Given the importance of geological structure and preglacial topographic inheritance, cirques are complex landforms for which assumptions of allometric growth may be spurious. It follows that form is not always a reliable guide to process.

1. Introduction

The key processes that drive bedrock denudation by glaciers and affect the growth pattern of alpine cirques continue to be a topic of debate in Quaternary geomorphology (Dühnforth et al., 2010; Sanders et al., 2010, 2012, 2013). By definition, all cirques contained glaciers intermittently during the Pleistocene; however, the connection between glacier-related processes and the morphology of the topographic basin remains ambiguous. Nonetheless, the geometry of cirques is often the only dependent variable available for speculating over what their formative processes might be. As a result, morphometric analysis, i.e., statistical geomorphology, has long been the main tool used for inferring trends and interpretations (Peterson and Robinson, 1969; Andrews and Dugdale, 1971; Aniya and Welch, 1981; Evans and Cox, 1995; Haynes, 1998; García-Ruiz et al., 2000; Federici and Spagnolo, 2004; Hughes et al., 2007; Ruiz-Fernández et al., 2009; Mîndrescu et al., 2010; Barr and Spagnolo, 2013) even though these can never directly reveal the real physical controls on cirque formation. The main purpose of statistical analysis is to reduce the dimensions of the parameter set initially defined to a smaller set from which correlations can emerge and lead to plausible interpretations. Much scientific research relies on statistical expedients of this nature and is useful insofar as it helps to (i) identify meaningful trends in large data sets, to (ii) narrow working hypotheses down to a tractable shortlist, and to (iii) plan rational sampling strategies for further field research including, for example, surface exposure dating.

Currently, evolutionary models reviewed in Evans (2008) offer two major alternatives: either headwall recession caused by freeze–thaw action (which suggests that cirques are largely periglacial landforms) or mechanical floor lowering by temperate-based glaciers (which emphasizes instead that cirques are glacial landforms). Studies of headwall recession have highlighted the importance of frost weathering along the *bergschrund* (Johnson, 1904; Gardner, 1987; Sanders et al., 2012), whereas studies of cirque floor features emphasize subglacial processes (Galibert, 1962; White, 1970). A composite model, arguing for a systemic link between frost-driven headwall retreat and subglacial scouring promoted by rotational slipping of glacier ice, contends that debris released from the headwall provide abrasive tools to the glacier base. In that case, cirques lengthen, broaden, deepen, and increase their concavity as they grow (Gordon, 1977). Nevertheless, correlations between

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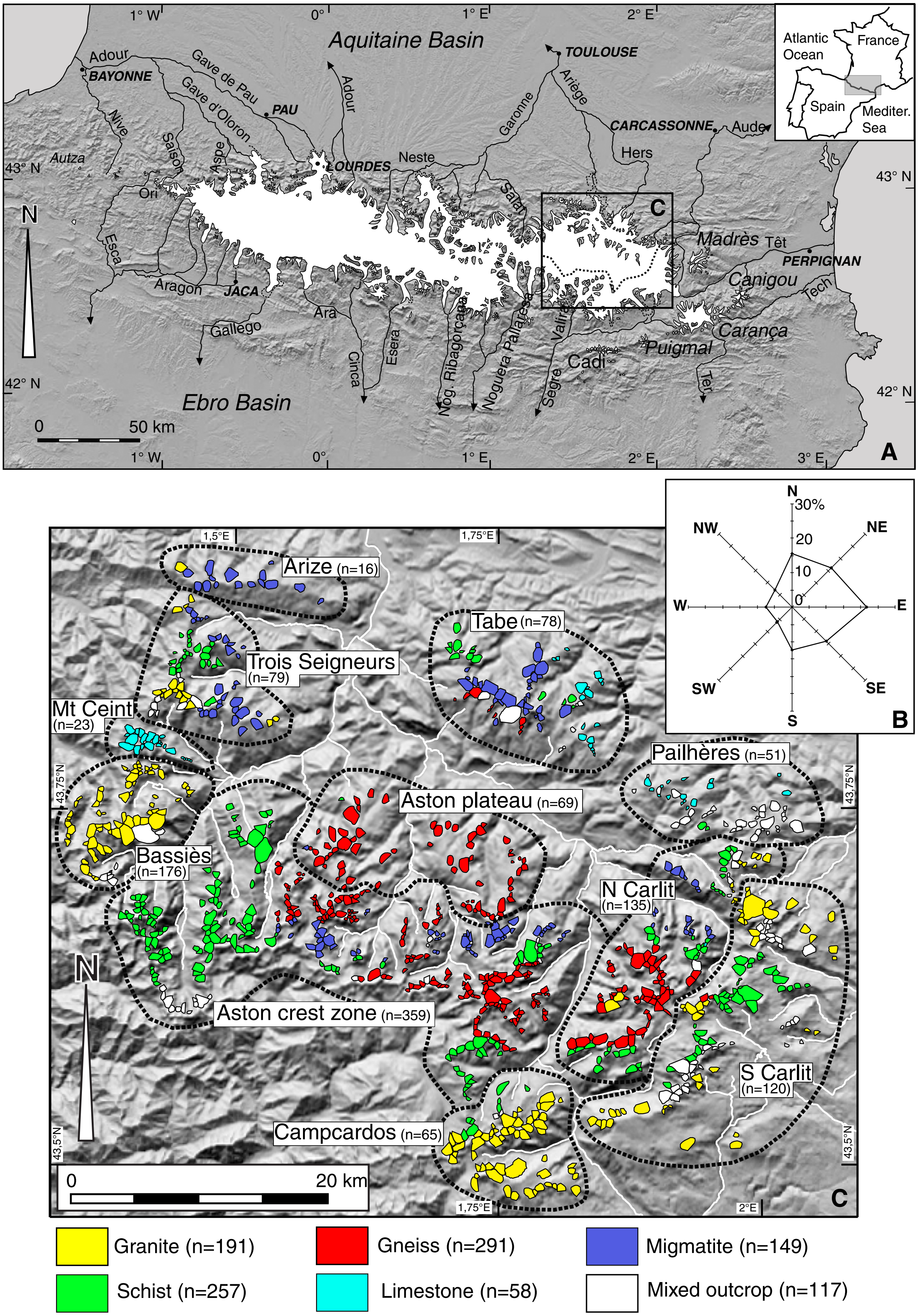

1° W
0°
1° E
2° E
Aquitaine Basin
TOULOUSE
Adour
BAYONNE
Gave de Pau
PAU
Gave d'Oloron
Adour
Garonne
Ariège
CARCASSONNE
Aude
Hers
Nive
Saison
Aspe
LOURDES
Neste
Autza
43° N
Ori
Salat
C
N
Esca
Madrès
Têt
PERPIGNAN
Aragon
JACA
Canigou
Tech
Ara
Gallego
Cinca
Esera
Nog. Ribagorçana
Noguera Pallaresa
Valira
Segre
Cadi
Puigmal
Carança
Ter
42° N
Ebro Basin
0
50 km
3° E
A
Atlantic Ocean
France
Spain
Mediter. Sea
N
30%
20
10
0
NW
NE
W
E
SW
SE
S
B
1,5°E
1,75°E
Arize (n=16)
Tabe (n=78)
Trois Seigneurs (n=79)
Mt Ceint (n=23)
Pailhères (n=51)
43,75°N
Aston plateau (n=69)
Bassiès (n=176)
N Carlit (n=135)
N
Aston crest zone (n=359)
S Carlit (n=120)
Campcardos (n=65)
43,5°N
0
20 km
1,75°E
2°E
C
Granite (n=191)
Gneiss (n=291)
Migmatite (n=149)
Schist (n=257)
Limestone (n=58)
Mixed outcrop (n=117)