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Weathering-limited hillslope evolution in carbonate landscapes

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A B S T R A C T

Understanding topographic evolution requires integrating elementary processes acting at the hillslope scale into the long-wavelength framework of landscape dynamics. Recent progress has been made in the quantification of denudation of eroding landscapes and its links with topography. Despite these advances, data is still sparse in carbonate terrain, which covers a significant part of the Earth's surface. In this study, we measured both long-term denudation rates using in situ-produced ^{36}Cl concentrations in bedrock and regolith clasts and surface convexity at 12 sites along ridges of the Luberon carbonate range in Provence, Southeastern France. Starting from ∼30 mm/ka for the lowering of the summit plateau surface, denudation linearly increases with increasing hilltop convexity up to ∼70 mm/ka, as predicted by diffusive mass transport theory. Beyond this point denudation rates appear to be insensitive to the increase in hilltop convexity. We interpret this constant denudation as indicating a transition from a regime where hillslope evolution is primarily controlled by diffusive downslope regolith transport, toward a situation in which denudation is limited by the rate at which physical and chemical weathering processes can produce clasts and lower the hilltop. Such an abrupt transition into a weathering-limited dynamics may prevent hillslope denudation from balancing the rate of base level fall imposed by the river network and could potentially explain the development of high local relief in many Mediterranean carbonate landscapes.

1. Introduction

Our understanding of landscape dynamics relies on the ability to predict rates of denudation from the measurement of topographic properties. The possibility of establishing a causal link between the two has been greatly enhanced over the last two decades, mainly due to several critical methodological breakthroughs. First, the availability of high resolution representations of the topographic surface, through LiDAR or photogrammetric techniques, has allowed the systematic measurement of elevation over length-scales that are relevant for the elementary geomorphic processes at work, in particular across hillslopes (e.g. Roering et al., 1999; Perron et al., 2008). Second, we can now measure in situ-produced cosmogenic nuclides concentrations in various near-surface materials, allowing accurate quantification of the rates of geomorphic processes. The combination of these spatial and temporal constraints has allowed the investigation and validation of several Geomorphic Transport Laws (Dietrich et al., 2003) pertaining to first-order open questions in landscape evolution (e.g. Small et al., 1999; Roering et al., 2007; Hurst et al., 2012; Johnstone and Hilley, 2015; Foster et al., 2015). For example, based on a simple conceptual model for the evolution of soil-mantled hillslopes (Gilbert, 1909; Culling, 1960), field observations of diagnostic relationships between landscape morphology (slope angles, curvature) and rates of evolution (downslope regolith transport, denudation) are direct hints of the occurrence of specific processes (e.g. McKean et al., 1993; Heimsath et al., 1997; Anderson, 2002; Hurst et al., 2012).

Many of the aforementioned studies have focused on the evolution of landscapes developed on quartz-rich lithologies, where the measurement of in situ-produced ^{10}Be concentrations in bedrock or regolith materials provided direct constraints on processes timescales. Recent advances on the calibration of ^{36}Cl production rate from Ca spallation have opened the way for the implementation of similar approaches in carbonate landscapes (Stone et al., 1994; Schimmelpfennig et al., 2009). For example,

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Ryb et al. (2013, 2014b, 2014a) have provided important insights into the spatial distribution of denudation for carbonate dominated landscapes across a strong climatic gradient in Israel. The significant control of the precipitation gradient on the denudation pattern support the idea that dissolution is the major regulator of the evolution of such landscapes and that physical processes play only a secondary role, unless water availability becomes limiting for chemical weathering. However, in many carbonate landscapes hillslopes display convex hilltops that are commonly associated with diffusion-like regolith transport (Gilbert, 1909; Culling, 1960). These observations suggest that physical weathering and regolith transport may play a significant role in the evolution of carbonate hillslopes in addition to total dissolution. Due to their frequent occurrence, especially in peri-Mediterranean regions, it is of major interest to understand the dynamics of carbonates dominated landscapes, in particular to assess to what extent the evolution processes and Geomorphic Transport Laws that have been proposed and validated for soil mantled hillslopes are transferable to these settings.

The purpose of this study is to provide such quantitative insights into the dynamics of these landscapes and hillslopes through the combination of detailed morphological measurements with estimates of denudation based on in situ-produced cosmogenic nuclides inventories. We focused on the carbonate ranges of Provence in South-Eastern France which provide an ideal setting for such investigations. In particular we test if the fundamental relationship between surface curvature and denudation, which is often considered diagnostic of diffusive transport over regolith-mantled hillslopes, holds in this type of environments. We observe a two-stage evolution, with first a linear increase of denudation rates with hilltop curvature, as predicted by linear diffusion transport theory, and then a plateau where denudation is almost constant despite increasing curvature. We interpret this transition as the consequence of a limit in the ability of weathering processes to produce regolith fast enough to match hillslope transport capacity. We postulate that such evolution could lead to the decoupling of hillslopes evolution from the channels incising at their bottom and promote relief growth in carbonate landscapes.

In this paper, we first present the geological and geomorphological settings of the carbonate ranges of Western Provence, and in particular the Luberon massif where our investigation is focused. After presenting the methodology used to determine denudation rates from cosmogenic nuclides (^{36}Cl) measurements and hilltop curvature from the production of high resolution Digital Elevation Models, we introduce a simple 1D hillslope evolution model that allows combining the data obtained by both previous methods. At last, after reporting the main data and results we discuss the significance of the observed transition for the mechanisms of landscape evolution in carbonate domains.

2. Setting

The sedimentary sequence of Western Provence is dominated by a thick Mesozoic platform carbonate series that was deformed during Cenozoic orogenesis. This led to the development of narrow ranges with significant relief, which provide an ideal setting to investigate the evolution of carbonate landscapes (Fig. 1A). We targeted an area of the Western Luberon mountain (Petit Luberon, Fig. 1B), a 600 m tall, E-trending and 20 km-long range. It consists mostly of lower Cretaceous carbonates, with Urgonian facies reef limestones outcropping along the crest and northern flank of the range. The Luberon mountain was first uplifted during the Late Cretaceous and Early Eocene Pyrenean tectonic regime. Another major tectonic episode occurred between 10 and 6 Ma prior to the Messinian Salinity Crisis, and led to rejuvenation of the relief and incision (Molliex et al., 2011; Clauzon et al., 2011). Denudation rates on weathering surfaces across south-eastern France range from 20 to 60 mm/ka (Siame et al., 2004; Sadier et al., 2012; Molliex et al., 2013). The lower bound corresponds to tectonically stable areas, whereas higher values are associated with actively uplifting surfaces.

We selected a specific area of the northern flank of the range, where several regularly spaced north-south ridges are connected with a summit surface (Fig. 1C). Their well-developed convex profiles suggest that slope-dependent transport is likely contributing to hillslope evolution (Fig. 2A–B). The low curvature summit surface is being progressively dismantled by regressive erosion along the main valleys draining the southern and northern flanks. This transient evolution is also reflected in the morphology of the ridges, which show significant increases in convexity with distance from the summit (Fig. 1C). Hillslopes become steeper away from the main crest and ultimately develop steep cliff faces associated with narrow gorges in the lower part of the range (Figs. 1 and 8).

The climate consists of a combination of Mediterranean and continental characteristics. Available records in Bonnieux (Altitude 250 m asl, Fig. 1B) over the 1981–2010 period indicate mean annual precipitation is 750 mm/yr, mean minimum annual temperature is 8 °C (1 °C between December and February) and frost is present for 50 days per year. Our sites are located much higher on the crest of the range, between 600 and 700 m asl, and are directly exposed to the dominant wind (North–South blowing *Mistral*), suggesting that the conditions they experience are likely to be significantly colder. The ridges host sparse Mediterranean vegetation characterized by small shrubs and shallow grass. The surface is covered by thin but dense regolith ($<$10 cm in most places) consisting of limestone clasts in the 1–10 cm size range and discontinuous shallow sandy to silty soil pockets (10 to 20 cm deep in most places) (Fig. 2). The dimension of these clasts make them transportable by biotic and frost wedging processes. Bedrock outcrops are widespread along these ridges and display a dense network of incipient dissolution features that contribute to clast production. This joint occurrence of meter-scale bedrock patches and thin discontinuous regolith is observed both on hilltops and hillslope flanks, with no clear downslope thinning or thickening trend for the regolith layer.

Bedrock and regolith observed along the crests have undergone both chemical weathering and physical disaggregation. Dissolution features are widespread on both bedrock outcrops and regolith clasts (Fig. 2E–F). Carbonate dissolution contributes to the progressive rounding of rock fragments and to the development and widening of a network of discontinuities in the rock mass (lapiaz) which in many cases produces transportable clasts. There is also widespread evidence of active fracture development (Fig. 2C), which appears to be related to thermal stresses and frost cracking but is also probably assisted by bioturbation and the development of the root network. We note that the production of clasts is also greatly facilitated by pre-existing tightly spaced fracture planes that are prevalent at most bedrock outcrops (Fig. 2D).

3. Methods

3.1. Sampling strategy

We focus on a single area within which relationships between denudation and morphology can be isolated under constant climate and lithology. Our sites are located on top of the ridges, where no regolith flux from above is contributing to the hillslope evolution. We use in situ-produced ^{36}Cl concentrations measured in both bedrock and regolith fragments (1–10 cm size range) to quantify denudation rates at 12 sites. ^{36}Cl accumulates in near surface carbonates mainly due to nuclear reactions induced by cosmic