Lithology controls the regional distribution and morphological diversity of montane
Mediterranean badlands in the upper Llobregat basin (eastern Pyrenees)

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Abstract

Badlands are pervasive in a wide range of environmental conditions across the Mediterranean region, including arid, semiarid, and humid environments. On montane (cold subhumid and humid) Mediterranean landscapes, harsh thermal conditions on north-facing hillslopes favour intense bedrock weathering by freezing and impose serious constraints on plant colonization. The above are the customary arguments to explain the high abundance of montane badlands on north-exposed shady aspects. We studied the distribution and morphological diversity of badlands in the upper Llobregat basin (Catalan Pyrenees, NE Spain), using remote sensing information (high-resolution orthophotos and complementary Landsat 8 imagery), digital elevation data, and regional information on lithology. Badlands extend over about 200 ha in the upper Llobregat basin and occur on two different parent materials, swelling (smectite-rich) continental Garumnian lutites of late Cretaceous age, and nonswelling (illitic) marine Eocene marls. Vegetation, assessed by remote-sensed vegetation greenness, is less developed on north-facing badland slopes. However, badland slope-aspect distribution varies considerably with lithology. While badlands on Eocene marls show preferential distribution on north-facing shady slopes, badland occurrence on Garumnian lutites does not reveal clear slope-aspect anisotropy patterns. Lithology also affects slope gradient, with badlands on Eocene marls showing rougher topography (30-40° average slope angle) than on Garumnian lutites (20-30°). Badland morphological differences induced by lithology are discussed in terms of the greater weathering susceptibility and slope instability of the swelling, smectite-rich Garumnian lutites than of the nonswelling Eocene marls. Elevation, which broadly controls annual precipitation and winter air temperature within the region, shows no clear influence on badland distribution. Overall, our results reveal

lithology as the main factor controlling badland distribution and morphological diversity under the montane Mediterranean conditions of the upper Llobregat basin.

Keywords: badland; lithology; Mediterranean mountains; morphology; smectite; slope angle; slope instability; vegetation; weathering

1. Introduction

The term badland describes highly dissected areas, comprising hillslopes and divides carved in soft rock outcrops (e.g., lutites, marls, shales) and unconsolidated sediments, with little or no vegetation, that are useless for agriculture (Bryan and Yair, 1982; Gallart et al., 2002). Intensive bedrock weathering, creeping, piping, rilling, gullyng, and landsliding, among other factors, usually leads to high erosion rates in badlands, exceeding in some cases $10 \text{ kg m}^2 \text{ yr}^{-1}$ (Schumm, 1956; Regüés et al., 2000a; Descroix and Mathys, 2003; Nadal-Romero et al., 2011; Desir and Marín, 2013; Gallart et al., 2013). Despite representing (in general) minor catchment fractions, badlands can contribute to large proportions of the total sediment transported within the regional drainage networks (i.e., rivers and water reservoirs) and are, therefore, considered *hotspots* of sediment production on a regional scale (Clotet, 1984; López-Tarazón et al., 2012; García-Ruiz et al., 2013).

In the Mediterranean basin, the interactions between seasonally contrasted climate, high rainfall erosivity, rugged topography, high abundance of erodible soils, soft and/or (dispersive) salt-rich sedimentary rock outcrops, and a long history of human influence have led to intense erosion and explain the common occurrence of badlands in these environments (García-Ruiz et al., 2013). Badlands commonly evoke aridity, although in Mediterranean areas they are found in a variety of landscapes, encompassing arid,

semiarid, and montane subhumid and humid environments (Gallart et al., 2002). Badland distribution and dynamics are in general fully explained by bedrock characteristics and the spatiotemporal variations of soil surface conditions in arid environments, where these systems are apparently geomorphologically stabilized under present climate conditions (Howard, 1994; Yair et al., 2013). Interactions between site geomorphology, climate, and biotic factors explain preferential distribution and higher erosion activity of Mediterranean semiarid badlands on sunny, south-facing hillslopes, where vegetation density is strongly limited by scarce soil moisture and, therefore, cannot exert any control on soil erosion (Kirkby et al., 1990; Cantón et al., 2002; Calvo-Cases et al., 2014). Humid and subhumid badlands, usually much younger than arid and semiarid badlands, generally show higher erosion rates caused by deep weathering and relatively high annual precipitation (Gallart et al., 2002; García-Ruiz et al., 2013). Unlike in arid and semiarid badlands, where regolith (i.e., weathering mantle) formation is controlled by the action of wetting-drying cycles, in montane (cold subhumid and humid) Mediterranean landscapes the weathering role of gelivation (i.e., freezing) is much more important (Regüés et al., 1995; Pardini et al., 1996). Characteristically, this is more common on shady, north-exposed slope aspects (Regüés, 1995; Descroix and Olivry, 2002; Nadal-Romero et al., 2007). Vegetation growth and colonization in these montane badland systems is not limited by the availability of water, but it is affected by the harsh thermal conditions, which reduce the vegetative period, particularly on north-facing hillslopes (Guàrdia et al., 2000; Nadal-Romero et al., 2014). Accordingly, slope-aspect distribution of montane Mediterranean badlands may not be as clearly asymmetrical as semiarid systems or may even show (reverse) preferential distribution on shady aspects, as has been argued to occur in Mediterranean mountain sites (Regüés et al., 2000b; Gallart et al., 2002; Nadal-Romero et al., 2006).

Lithology exerts major control on the morphology and dynamics of badlands (Schumm, 1956; Howard, 1994; Calvo-Cases and Harvey, 1996; Gallart et al., 2002; Faulkner, 2013). Morphological properties, erosion mechanisms, and sediment yield spatially differ in badland areas showing a variety of contrasting lithology. Paradigmatic examples are *calanchi* and *biancane* badland forms, extensive in the Apennine chain (Italy), which can develop in the same area and geological setting, though on different lithology (Alexander, 1982). *Calanchi* have steep slopes affected by gullyng and landsliding. In contrast, *biancane*, with higher contents of clay and exchangeable sodium percentage on parent materials, have gentler slopes, forming hummocks affected by micropipe formation and rilling (Torri and Bryan, 1997; Battaglia et al., 2002). Clay mineralogy may also affect the dynamics and morphology of badlands. Bedrock weathering and regolith formation by freezing-thawing and wetting-drying cycles is deeper and more intense on parent materials containing swelling clays (e.g., smectite), which may also affect soil erosion rates and badland morphology (Solé et al., 1992; Pardini et al., 1996; Kusanin-Grubin, 2013; Benton et al., 2015).

We study the regional distribution and morphological diversity of badlands in the upper Llobregat basin (Catalan Pyrenees, NE Spain), a montane, Mediterranean humid environment. Previous studies reported widespread occurrence of young badlands in the region, apparently initiated by mass movements (i.e., large slumps and surface slips in forested areas with a high slope gradient) caused by low-frequency (≥ 100 year recurrence) extreme events (Clotet, 1984; Clotet et al., 1988). Badland occurrence in the area is concentrated on two parent materials, smectite-rich Garumnian lutites of continental origin (late Cretaceous age) and (nonswelling) marine Eocene marls, both of which are mainly weathered by gelivation (Cervera et al., 1991; Solé et al., 1992; Guàrdia, 1995; Regüés, 1995; Gallart et al., 2013). We hypothesize that differences in

lithology (smectite-rich Garumnian lutites vs. nonswelling Eocene marls) will affect badland slope anisotropy and morphology. Precipitation amount and winter air temperature, which mediate weathering by freezing, vary within the basin with elevation, which has a significant impact on the distribution of mass movements in the region (Gallart and Clotet, 1988; Baeza and Corominas, 2001). Therefore, we expect that elevation will also have an impact on the spatial distribution of badlands in the upper Llobregat basin.

2. Study area

The upper Llobregat basin (Fig. 1) is a 503-km² mountain region, with an elevation gradient of about 1900 m from the base of the basin at La Baells reservoir (650 masl) to the highest peak, the Comabona (2548 masl). The basin lies at the headwaters of the River Llobregat, in the Catalan Pyrenees (NE Spain). Annual precipitation and mean temperature ranges from 850 mm and 11°C at 700-900 masl to 1100 mm and 8°C at 1700-1900 masl. Similarly, mean winter (December-February) temperature and frost period ranges from 4°C and ~85 days at 700-900 masl to 1°C and over 100 days at 1700-1900 masl. The climate is Mediterranean humid with two wet periods (April-May and August-October) that concentrate about 70% annual precipitation (Ninyerola et al., 2003). Precipitation traits have a seasonal pattern, with short storms of high rainfall intensity occurring in summer, and large precipitation events of moderate or low intensity in autumn and spring (Gallart et al., 2013).

Badlands in the upper Llobregat basin are distributed on two different geological materials: continental Garumnian lutites of late Cretaceous age; and marine, brittle marls of Eocene age (Fig. 1). Garumnian deposits of lutites in the area are allochthonous fine-grained deposits derived from soils that were developed on the

incipient Pyrenean chain (Trempe Formation; Mey et al., 1968). As these deposits were never buried deeper than 1,000 m, clay materials were not significantly affected by burial diagenetic processes (Arostegui et al., 2011). In contrast, Eocene marls in the upper Llobregat basin represent relatively autochthonous, near-shore, and deeper marine deposits (Armancies Fm., with minor contributions from the Vallfogona, Sagnari, Cal Bernat-Coubet and Bracons Fms., Serra-Kiel et al., 2003), which were affected by more intense burial diagenesis (Martínez et al., 1997). Garumnian lutites in the area are silty-clay in texture, containing 25-45% of clays with a high abundance of smectite (40-70% total clay content), cemented by calcium and magnesium carbonates (Solé et al., 1992; Regüés, 1995). Eocene marls are also silty-clay in texture, with 25-40% of nonswelling clay (mainly illite) and, similarly, are cemented by calcium carbonates (Cervera et al., 1991; Guàrdia, 1995).

Long-term (>30 years) monitoring results of geomorphic and hydrological processes in a small research basin with badlands (Vallcebre catchments, ~4 km², 1100-1650 masl) illustrate the temporal dynamics of the upper Llobregat badlands. Regolith weathering takes place in winter from repeated freezing cycles that lead to the development of highly erodible *popcorn* surfaces, particularly after snow melting (Clotet et al., 1988; Solé et al., 1992; Regüés et al., 1995; Pardini et al., 1996). Soil freezing cycles throughout the winter season typically are (>1.5 times) longer on north-facing hillslopes, resulting in more intense (i.e., deeper) weathering potential for shady badland slope aspect (Regüés, 1995; Regüés et al., 2000b). High-intensity convective storms occurring in summer produce rill incision, eroding the regolith. Most of the sediment is deposited a short distance away in low-order channels and is not washed away until long-lasting autumn precipitations cause high runoff flow by saturation mechanisms (Regüés et al., 2000a; Gallart et al., 2013). Similar temporal erosion/sediment dynamics

have been observed in other montane Mediterranean badland areas in the central Pyrenees and southern Alps (Descroix and Mathys, 2003; Nadal-Romero and Regüés, 2010).

3. Methods

3.1. Badland mapping, morphological and supplementary data sources

Badlands within the upper Llobregat basin were manually digitized using recent (2009-2014) high-resolution (25 cm per pixel) digital orthophotos distributed by the Institut Cartogràfic i Geològic de Catalunya (ICGC). Bare or barely covered areas that showed clear signs of active erosion (e.g., carved landforms with the presence of gullies and/or rills) were digitized, generating a GIS badland distribution map for the region. Highly eroded, derelict surface-mining landscapes were excluded from the digitized badland map.

Basic morphometric information for characterizing the digitized badlands was derived from a high-resolution (5 m per pixel) digital elevation model (DEM) with a root mean square error (RMSE) of 50 cm, developed with LiDAR technologies within the Spanish National Plan for Land Observation and distributed by the ICGC. The DEM-derived morphological variables for badland characterization included altitude, elevation gradient (i.e., the difference between the top and base elevations of the badlands), slope gradient, and aspect angle. The aspect angle was cosine-transformed for analysis, taking values ranging from 0.38 to 1.0 for shady (north-exposed) aspect (angles 0-67.5° and 297.5-360°), 0.38 to -0.38 for neutral (east- and west-exposed) aspect (angles 67.5-112.5° and 247.5-297.5°), and -0.38 to -1.0 for sunny (south-exposed) aspect (angles 112.5-247.5°). We also determined the distance of the digitized badlands from the regional drainage network. The regional drainage network was extracted from the DEM

by a D8 flow-routing algorithm with Strahler order >6 (range 1-12) and a minimum 100-m segment length as network initiation conditions, which accurately represented the regional distribution of mountain streams and rivers depicted on local (scale 1:5000) topographic maps. Complementary information on site lithology was taken from the Catalan Digital Geological Map (scale 1:50,000), also distributed by the ICGC. Information on vegetation development for the digitized badlands was gained by calculation of the Modified Soil-Adjusted Vegetation Index (MSAVI), using a recent (September 2015) Landsat 8 image (15- and 30-m resolution for the panchromatic and multispectral bands, respectively), distributed by the U.S. Geological Survey. The MSAVI is a vegetation greenness index that correlates closely with vegetation cover and, unlike other vegetation indices (e.g., NDVI), is not affected by variations in soil background brightness and colour (Qui et al., 1994; Rondeaux et al., 1996). Landsat 8 scaled digital numbers were transformed to (corrected) surface reflectance values by using the ATCOR3 algorithms for rugged terrain (Richter and Schläpfer, 2015). Corrected visible and near-infrared spectral bands were pan-sharpened to 15 m by applying Fast Intensity-Hue-Saturation data fusion, which provides very efficient results in downscaling Landsat 8 multispectral information for the calculation of vegetation indices (Johnson, 2015). The pan-sharpened red and near-infrared surface reflectance bands were applied to determine the MSAVI (15 m per pixel), following the calculations described by Qui et al. (1994).

3.2. Data analysis

3.2.1. Interactions and effects of elevation, lithology, and slope aspect on badland distribution

We explored badland slope-aspect distribution (i.e., badland slope anisotropy over shady, sunny, and neutral aspects) as a function of elevation and lithology, using the

cumulative distribution of badland surface abundance. The distribution of the upper Llobregat badlands was further compared with the general spatial arrangement of Garumnian and Eocene geological deposits of continental lutites and marine marls within the region, to test for structural dependencies of the elevation and aspect distribution of the badlands under study. Specifically, we tested for differences in elevation distribution between the badlands and the geological deposits of their parent materials, using a χ^2 goodness of fit test, taking elevation bins of 100 m for analysis. Similarly, we used a χ^2 goodness of fit test to check for differences in slope aspect (i.e., sunny, neutral, or shady) between the upper Llobregat badlands and the regional geological deposits of Garumnian lutites and Eocene marls.

3.2.2. Regional patterns of badland morphological diversity

We explored badland morphological patterns across the upper Llobregat region applying Principal Component Analysis (PCA). We used badland size, elevation gradient, average slope gradient, general slope aspect (determined as the badland average for the cosine of slope aspect), distance to the regional drainage network and MSAVI as internal PCA variables. All variables were standardized by their mean and standard deviation prior to running the PCA ordination. We tested for the effects of badland elevation on the morphology and diversity patterns established within the PCA by studying the Pearson's R correlation against the two main PCA factors. Similarly, we studied the impact of lithology on the PCA ordination (i.e., badland distribution along the PCA factors) by means of Student's t tests.

In order to group the study badlands in a series of homogeneous types for discussion of the region's badland morphological diversity, we conducted a k -means cluster analysis using the PCA variables (badland size, elevation gradient, average slope gradient,

general slope aspect, distance to the regional drainage network, and MSAVI) plus badland elevation and lithology, which was introduced into the analysis as a dummy variable. We applied a MANOVA test to determine the agreement of the *k*-means badland classification with the PCA ordination. In addition, we used Kruskal-Wallis ANOVA tests to characterize the established badland types in terms of altitude, size, elevation and slope gradient, aspect, basal connection with the regional drainage network, and vegetation development (i.e., MSAVI level). We applied non-parametric tests for badland-type characterization because data transformation did not satisfy homoscedasticity and/or normality assumptions in most cases.

4. Results

4.1. Distribution and slope anisotropy of badlands: effects of lithology and elevation

Badlands in the upper Llobregat basin extend over 202 ha (0.4% of the basin). They are mostly concentrated in the River Saldes subbasin (on continental Garumnian lutites) and at the confluence of the Bastareny and Llobregat rivers (on marine Eocene marls; Fig. 1). Badlands in the region are spatially distributed across a variety of elevations (chiefly between 700 and 1700 masl) and are slightly more abundant on Garumnian lutites (58% of total badland extension) than on Eocene marls (42% total; Figs. 1 and 2A).

The shady (north-exposed) aspect is particularly frequent (relative abundance >50%) at low elevations and decreases above 1300 masl (Fig. 2A). Badland elevation distribution is influenced by differences in lithology. Marly badlands are concentrated mostly below 1300 masl and show a very high abundance of shady slope aspect (about 60% of total badland surface, Figs. 2A and B). Unlike these, badlands on Garumnian lutites show a more uniform slope-aspect distribution (39%, 27%, and 34% for shady, neutral, and

sunny aspects, respectively; Fig. 2A) and are mainly distributed between 900 and 1700 masl, as illustrated by their cumulative distribution (Fig. 2B).

Elevation and slope-aspect distribution of badlands on Garumnian lutites do not significantly differ from the regional distribution of Garumnian geological deposits of lutites (elevation: $\chi^2 = 19.8$, d.f. = 14, $p = 0.14$; slope aspect: $\chi^2 = 1.25$, d.f. = 2, $p = 0.54$), which are also concentrated (89% of total) between 900 and 1700 masl and show a nearly uniform distribution of north- and south-exposed slope aspects (Figs. 2C and D). Similarly, elevation distribution of badlands on Eocene marls hardly differs from the elevation distribution of marly geological deposits in the upper Llobregat basin ($\chi^2 = 22.6$, d.f. = 14, $p = 0.07$) that are concentrated (90% of total) between 700 and 1300 masl (Figs. 2C and E). However, slope-aspect distribution for the geological deposits of Eocene marls shows a great abundance (51% of total extension) of sunny, south-exposed slope aspects (Fig. 2E), which significantly differs ($\chi^2 = 34.4$, d.f. = 2, $p < 0.01$) from the (extensively north-exposed) slope-aspect distribution of marly badlands for the region.

4.2. Regional patterns of badland morphological diversity

The first two PCA factors explain 60% of total data variance (Fig. 3A) and show an ordination pattern organized across two general gradients (Fig. 3B): (i) badland magnitude (i.e., size and elevation gradient) is opposed to badland disconnection from (or distance to) the regional network of mountain streams, while (ii) badland vegetation greenness (MSAVI) is opposed to slope gradient and (north-exposed) shady slope aspect (i.e., high values of cosine of aspect angle). Lithology shows significant differences in the first ($t = 2.32$, d.f. = 458, $p < 0.05$) and second ($t = -4.10$, d.f. = 458, $p < 0.01$) PCA factors. Although both badland lithologies are distributed across the full

badland magnitude gradient, badlands on marine Eocene marls show a distinct association with the most extreme topographic levels (i.e., highest slope gradient and cosine of aspect angle scores) of the PCA ordination slope topography gradient (Fig. 3A). Elevation shows significant (although weak) correlations with PCA factors 1 and 2 (-0.38 and -0.33, respectively; $p < 0.01$), increasing toward the negative side of the factors, where lutitic badlands are preferentially clustered (Fig. 3B).

Our *k*-means badland type classification gives three groups of badlands on continental Garumnian lutites (types L1, L2, and L3; Fig. 3C) and two additional groups on marine Eocene marls (types M1 and M2; Fig. 3C), which overall show significant differences in PCA ordination ($F_{8, 908} = 220.6$, $p < 0.01$; Figs. 3A and C). Badlands on Garumnian lutites (types L1, L2, and L3) show higher elevation (25th-75th percentiles: 1000-1700 masl) and smaller mean slope gradient (15-35°) than badlands on Eocene marls (types M1 and M2: 800-1100 masl, 30-45°; Figs. 4B and E). The three lutitic badland types show significant differences in badland magnitude (i.e., size and elevation gradient; Figs. 4C and D), accounting for a group of large badlands (L1: size 0.3-2.0 ha, elevation gradient 30-90 m) and two groups of small badlands (L2 and L3: size <0.4 ha, elev. gradient <40 m). Similarly, marly badland types encompass two groups with important differences in size (0.3-1.8 ha for M1 and <0.5 ha for M2; Fig. 4C) and elevation gradient (30-100 m and <50 m for M1 and M2, respectively; Fig. 4D). Overall, large badland types L1 and M1 affect a broader extension of the upper Llobregat basin and are better connected with mountain streams (i.e., they have smaller distance from the regional drainage network) than small badland types L2, L3, and M2 (Figs. 4A and F).

Badland types show a variety of general slope aspects (Fig. 4G). Large badlands on Garumnian lutites (type L1) have no preferential slope aspect, whereas the two groups of small lutitic badland types L2 and L3 have sunny and shady slope aspects,

respectively. Large badlands on Eocene marls (type M1) show north-exposed, shady aspects, whereas small marly badlands (type M2) have no preferential slope aspect. Vegetation greenness (MSAVI) for the variety of badland types shows a clear association with their general slope aspect: north-exposed, shady badland types L3 and M1 with the lowest MSAVI scores; and the south-exposed, sunny badland type L2 with the highest MSAVI values (Fig. 4H).

5. Discussion

Badlands in Mediterranean environments can develop on a broad variety of parent materials (e.g., lutites, marls, shales, unconsolidated sediments) and climate conditions (e.g., from arid to humid), typically appearing as highly dissected, bare or barely covered landforms strongly affected by a diversity of surface and subsurface processes, such as regolith weathering, landsliding, gullying, rilling, and pipe erosion (Bryan and Yair, 1982; Gallart et al., 2002, 2013; García-Ruiz et al., 2013; Calvo-Cases et al., 2014). Although badland gross morphology displays common characteristics between sites, badland processes may vary greatly in their forms, activities, and efficiencies, which ultimately affect badland distribution, detailed morphology, sediment yield, and long-term landform evolution (Torri and Bryan, 1997; Faulkner, 2008; Nadal-Romero et al., 2011; Yair et al., 2013). For example, interactions between regolith weathering, climate, and vegetation spread greatly influence slope asymmetry and activity of badlands across semiarid and humid Mediterranean environments (Gallart et al., 2002). Water-scarcity limitations for the development of vegetation cover on sunny hillslopes explain south-aspect badland slope anisotropy in semiarid environments (Kirkby et al., 1990; Cantón et al., 2002; Calvo-Cases et al., 2014). Differently, Gallart et al. (2002) hypothesized that the combined effects of intense regolith weathering by freezing and

harsh thermal limitations for the establishment of Mediterranean vegetation on shady slope aspects may explain the higher occurrence of badlands on north-facing hillslopes in montane (cold subhumid and humid) environments.

Our regional results for the upper Llobregat basin show lower vegetation greenness levels in north-exposed badlands (Figs. 4G and H), which agrees with other local and regional observations in Mediterranean montane badlands, where vegetation on north-facing hillslopes generally showed less development and poorer species diversity than south-facing badland slopes (Guàrdia, 1995; Guàrdia et al., 2000; Regüés et al., 2000b; Nadal-Romero et al., 2014). Regüés et al. (2000b) studied the interactions between bedrock weathering energy and vegetation in montane badlands of the upper Llobregat basin (Vallcebre catchments) and explained the effect of hillslope aspect on species richness and vegetation cover as a response to the shorter plant growth period and higher geomorphological activity (i.e., deeper regolith weathering and erosion) of north-facing badland hillslopes, which strongly constrain vegetation spreading on shady aspect. The regional distribution of badland slope aspects in the upper Llobregat basin appears, however, to be strongly affected by bedrock lithology. Distribution of badlands on marine Eocene marls are more frequent on shady hillslopes (60% of total badland surface; Figs. 2A and B), even though there are more south-facing hillslopes for the regional Eocene geological deposits of marine marls (about 51%; Fig. 2E). Conversely, badlands on Garumnian lutites do not show a clear pattern of slope anisotropy (i.e., shady and sunny hillslopes show nearly uniform abundances; Figs. 2A and B), and their distribution can be fully explained by the general structural organization of the geological deposits of continental Garumnian lutites in the region (Fig. 2D). Therefore, vegetation-spread limitations and higher weathering potential provided by more intense (i.e., longer duration and deeper) freezing on north-facing (shady) hillslopes appears to

have a smaller impact on the regional distribution of badlands developed on the Garumnian lutitic materials of the upper Llobregat basin.

Regolith weathering has different effects on badlands differing in lithology, particularly in clay mineralogy (Kasanin-Grubin and Bryan, 2007). This may explain, at least in part, the differences found in slope-aspect anisotropy between badlands developed on the (swelling, smectite-rich) continental Garumnian lutites and the (nonswelling, illitic) marine Eocene marls of the upper Llobregat basin. Swelling of clay minerals in smectite-rich materials by the effects of wetting-drying and/or freezing-thawing cycles leads to the formation of highly erodible, *popcorn* surfaces (Solé et al., 1992; Regüés et al., 1995; Pardini et al., 1996; Kasanin-Grubin, 2013). Although gelivation shows more intense regolith weathering activity on north-facing hillslopes owing to prolonged frost periods, these characteristic *popcorn* badland surfaces can be formed on the smectite-rich lutites of the upper Llobregat basin on a variety of hillslope aspects (Regüés, 1995), which may contribute to the lack of apparent slope anisotropy of badlands developed on Garumnian materials in the region. Conversely, smectite-poor materials generally show high resistance to regolith weathering by freezing and wetting-drying cycles (Brown and Payne, 1990; Kasanin-Grubin, 2013). Lower regolith weathering vulnerability by freezing of the nonswelling (illitic) marine Eocene marls of the upper Llobregat basin may explain the regional slope anisotropy of marly badlands, which generally have a north-exposed, shady aspect, where gelivation activity is more intense. Accordingly, detailed geomorphological analysis of montane Mediterranean badlands developed on similar (nonswelling and mostly illitic) Eocene marls of marine origin (Araguás catchment, central Pyrenees, Spain) indicated that active regolith weathering with development of *popcorn* badland surfaces only takes place on shady, north-facing hillslopes with prolonged frost periods (Nadal-Romero and Regüés, 2010). Similar

studies in montane Mediterranean badlands developed on (nonsmectite) black marls of marine origin (*terres noires*, Jurassic age, southern Alps, France) indicated a more intense freezing weathering action on shady slope aspects, resulting in (two to four times) higher erosion rates than on south-facing hillslopes (Descroix and Olivry, 2002; Descroix and Mathys, 2003). These hillslope-aspect variations in weathering activity and erosion rates for montane badlands developed on nonswelling parent materials suggest that soil erosion in these systems is strongly limited by the activity of bedrock weathering, reinforcing the emergence of slope-aspect anisotropy. Contrarily, field observations of sediment dynamics on smectite-rich Garumnian badlands in the upper Llobregat basin (Valcebre catchments) indicated that their regolith mantle is hardly ever exhausted because of very intense and deep weathering by freezing (Regüés, 1995), which implies that soil erosion rates for the Garumnian badlands may be more limited by the energy of rainfall than the yearly production of regolith.

Differences in lithology have further implications for detailed badland morphology in the upper Llobregat basin. Our analysis of badland morphological diversity indicates that badlands developed on smectite-rich continental Garumnian lutites have a mean slope gradient considerably lower than badlands developed on nonswelling (illitic) marine Eocene marls (20-30° and 30-40° for lutitic and marly badlands, respectively; Fig. 4E). Similarly, badland morphology studies in the vicinity of the Henry Mountains (Utah, USA) and the White River region (South Dakota, USA) found that badlands developed on the swelling, smectite-rich materials of the Morrison and Chadron Fms. have rounder forms with a lower average slope gradient than badlands developed on the smectite-poor materials of the Mancos and Brule Fms., which was attributed to higher regolith weathering vulnerability and geotechnical instability of smectite-rich materials (Schumm, 1956; Howard, 1994; Benton et al., 2015). Regional geotechnical analyses of

unweathered geological materials for the upper Llobregat basin yielded shear strength levels at 100 kPa normal stress of 20-60 kPa (cohesion $c' = 0$ kPa, friction angle $\varphi' = 10-30^\circ$) for continental Garumnian lutites and 90-110 kPa ($c' = 5-10$ kPa, $\varphi' = 40-45^\circ$) for marine Eocene marls, revealing greater instability for the smectite-rich Garumnian lutites (Alonso and Ripoll, 1988; Pérez-Carreras, 2011). Likewise, landslide-type explorations in the upper Llobregat basin found major variations in these geological materials. They generally showed planar slides favoured by geological discontinuities (e.g., stratification, joints) on (illitic) Eocene marly materials, and large rotational slides, debris flows, and solifluction on more unstable (smectitic) Garumnian lutites (Gallart and Clotet, 1988; Baeza and Corominas, 2001).

Differences in weathering susceptibility and geotechnical stability between parent materials may also explain the higher sediment yield of badlands developed on Garumnian lutites in the region. Soil erosion monitoring at two small (75-90 m²) badland plots during 1989-1991 within the upper Llobregat basin recorded annual average erosion rates of 86 and 36 kg m⁻² for Garumnian lutites and Eocene marls, respectively (Guàrdia, 1995). These sediment yield levels probably represent the upper boundary of representative erosion rates for the region, owing to the small size of the plots and short monitoring period. Combined short-term (1990-1993) monitoring and further 15-year extended modelling estimation of erosion rates in a 1240 m² subbasin of badlands developed on Garumnian lutites of the upper Llobregat region (El Carot macroplot, Vallcebre catchments) pointed to an annual average rate of nearly 9 kg m⁻² (Gallart et al., 2013). Similarly, volumetric sediment surveys of a natural sediment trap (i.e., a landslide dam), delimiting a nearby 3 ha basin extensively affected by lutitic badlands in the Vallcebre area, provided a 40-year estimation of 6-17 kg m⁻² annual average erosion or an equivalent 9 mm yr⁻¹ mean denudation rate (Clotet et al., 1988). A

first-order estimation of the contribution of the two types of badlands to the overall sediment budget of the upper Llobregat basin yields nearly 22,000 Mg yr⁻¹, which represents about 10% of the sediments deposited in La Baells reservoir between the dam construction in 1967 and 2002 (218,000 Mg yr⁻¹ bathymetric, average deposition estimate by CEDEX, 2002), and illustrates the sediment *hotspot* nature of these minority (i.e., <1% of total basin extension), highly erosive landscapes.

Overall, our research indicates that lithology broadly controls the regional distribution and morphological diversity of badlands in the upper Llobregat basin, which is consistent with a variety of observations carried out in other environments (Alexander, 1982; Howard, 1994; Calvo-Cases and Harvey, 1996; Torri and Bryan, 1997; Faulkner, 2013; Kananin-Grubin, 2013; Benton et al., 2015). Elevation mediates average annual precipitation (particularly in the form of snow) and winter air temperature within the upper Llobregat basin. The spatial abundance of landslides for the region correlates positively with altitude owing to the increased precipitation (Gallart and Clotet, 1988; Baeza and Corominas, 2001). However, our analysis does not depict any direct effect of elevation on the regional patterns of badland distribution and morphology. The shady, north-exposed badland aspect is more frequent at low elevation (Fig. 2A). Similarly, elevation shows a significant association with the regional organization of badland morphological patterns (Fig. 3B). Nevertheless, those apparent effects respond entirely to the structural distribution of Garumnian and Eocene geological deposits of continental lutites and marine marls within the upper Llobregat basin. In fact, geological deposits of marine Eocene marls in the region are generally distributed at lower elevations than continental Garumnian lutite deposits (Figs. 2D and E). Consequently, the distinctive features of marly badlands (i.e., shady aspect, high slope gradient) are more frequent at lower elevations, while those of lutitic badlands (i.e., lower slope

gradient, lack of badland slope-aspect anisotropy) are more abundant at higher elevations.

Clotet et al. (1988) suggested a natural origin for the relatively young badlands of the upper Llobregat basin. They attributed the origin to the effects of low-frequency, extreme rainfall events, which are the main trigger for large mass movements (i.e., large hillslope slumps and slips) in forested areas over Garumnian lutitic and Eocene marly bedrocks in the region (Gallart and Clotet, 1988). These mass movements may initiate badland development under particular environmental conditions, such as high slope gradient and shady aspect. Faulkner (2008) explained the initial stages of mesoscale badland development as an internal integration process of isolated, large gullies into spatially continuous badland landscapes with greater basal connection with the regional drainage network. Our badland-type classification indicates that large (i.e., horizontally and vertically extensive) badlands in the upper Llobregat basin (types L1 and M2) generally connect better with the regional network of mountain streams than small badlands do (types L2, L3, and M2; Figs. 4C and F). This suggests a more developed landform evolution stage for large badland types. Exploration of the dominant slope aspect of badland types (Fig. 4G) allows further refinement of the hypothesis of Clotet et al. (1988) regarding the critical environmental conditions that facilitate the evolution of areas affected by large mass movements into spatially well-integrated badlands, based on the above-discussed implications of hillslope aspect and lithology for the activity of weathering processes and hillslope stability. Small badlands developed on the (nonswelling, illitic) Eocene marls (type M2) show no marked hillslope aspect preference, whereas extensive marly badlands in the region (type M1) only occur on shady, north-hillslope aspects, which suggests that only north-facing, mass-wasted areas have regolith weathering potential for the development of large-size badlands. On the

contrary, badlands developed on the highly unstable (swelling, smectite-rich) Garumnian lutites show a variety of slope aspects (i.e., shady, neutral, and sunny aspects), regardless of badland size. This suggests that the hillslope aspect does not constrain the development of large lutitic badlands in the upper Llobregat basin.

6. Conclusions

It has been generally argued that montane (cold subhumid and humid) Mediterranean badlands display a clear pattern of slope-aspect anisotropy caused by the thermal difficulties for vegetation spread and more intense bedrock weathering by freezing on north-facing, shady hillslopes. Our results refine this general assertion and highlight the effect of lithology on the distribution and morphology of montane badlands. Regional differences in badland lithology, particularly in clay mineralogy, have a profound impact on slope-aspect anisotropy and general badland morphology under the montane Mediterranean conditions of the upper Llobregat basin (Catalan Pyrenees, NE Spain). Badlands in the upper Llobregat basin develop on two general parent materials, swelling (smectite-rich) Garumnian lutites of continental origin (late Cretaceous age), and nonswelling (mostly illitic) Eocene marls of marine origin. Badlands developed on Eocene marls generally have shady, north-facing hillslopes and rough topography (i.e., very high slope gradient), while badlands on Garumnian lutites show no distinctive pattern of slope-aspect anisotropy and generally have gentler slopes. These differences can be explained by the higher regolith weathering susceptibility by freezing and slope instability of the (late Cretaceous) swelling, smectite-rich Garumnian materials than of the nonswelling Eocene marls. Elevation, which mediates precipitation amount and winter air temperature for the basin, has little impact on the regional distribution and morphology of the upper Llobregat badlands. Overall, our study indicates that lithology

controls the regional distribution and morphological diversity of montane Mediterranean badlands in the upper Llobregat basin.

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Figure captions

Fig. 1. Study site: the upper Llobregat basin. Badland distribution was digitized using recent (2012-2014) high-resolution (25 cm per pixel) digital orthophotos distributed by the Institut Cartogràfic i Geològic de Catalunya (ICGC). Lithology type is taken from the Catalan Digital Geological Map (scale 1:50,000), also distributed by the ICGC.

Fig. 2. Distribution of badlands and geological deposits of their parent materials (continental Garumnian lutites and marine Eocene marls) in the upper Llobregat basin: (A) general elevation, lithology, and slope-aspect surface distribution (ha) of badlands (sunny, neutral, and shady slope aspects are indicated in colour levels); (B) badland surface cumulative distribution as a function of elevation and slope aspect (colour levels) on Garumnian lutites (solid lines) and Eocene marls (dashed lines); (C) regional distribution of geological deposits of Garumnian lutites and Eocene marls in the upper Llobregat basin; (D) elevation (patterns) and slope aspect (colour levels) regional distribution of Garumnian deposits of lutites; (E) elevation (patterns) and slope aspect (colour levels) regional distribution of Eocene deposits of marls. Map (C) is taken from the Catalan Digital Geological Map (scale 1:50,000), distributed by the Institut Cartogràfic i Geològic de Catalunya.

Fig. 3. Principal Component Analysis (PCA) ordination of badlands and *k*-means clustering of badland types: (A) PCA projection of cases (badlands) showing the ordination distribution of lithologies (colour levels) and *k*-means badland clusters (symbols for badland types L1, L2, L3, M1, and M2); (B) PCA projection of variables (elevation is shown as external variable, in grey); (C) examples of badland type (i.e., *k*-means clusters). Abbreviations of variables in (B): E_Gradien, elevation gradient; CosAspect, general slope aspect (i.e., badland average of the cosine aspect angle);

RDrainage_D, badland distance to the regional drainage network; MSAVI, vegetation greenness (modified soil-adjusted vegetation index levels). Aerial pictures in (C) were provided by the Institut Cartogràfic i Geològic de Catalunya.

Fig. 4. Badland type (i.e., *k*-means clusters) differences in (A) badland surface abundance, (B) badland average elevation, (C) badland size, (D) badland elevation gradient, (E) badland average slope gradient, (F) badland distance to the regional drainage network, (G) badland general aspect (i.e., badland average of the cosine aspect angle), and (H) vegetation greenness (MSAVI). The letters indicate differences at $p < 0.05$ (tested using Kruskal-Wallis ANOVA). Kruskal-Wallis statistics are shown within each graph.

Figure 1.

Figure 2.

Figure 3.

Figure 4.