Badlands in the Tabernas Basin, Betic Chain   17

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Abstract

The complex badland landscape at Tabernas results from a combination of relief amplitude generated by tectonic uplift since the Pliocene and reactivated several times during the Pleistocene, the properties of the Tortonian sedimentary rocks and a predominantly arid climate. The landscape is dominated by deep incision of the main river systems, which continues in part of the headwater tributaries, and characterized by contrasting slope morphologies and a variety of microecosystems. The Tabernas badlands exhibit a diversity of landforms resulting from the combination of multi-age soil surface components that allow a variety of processes to operate at different rates. These are dominated by rilling and shallow mass movements on south-facing hillslopes. On old surfaces and north-facing hillslopes, where biological components are present, overland flow with variable infiltration capacity and low erosion rates prevail. Incision in the gully bottoms occurs in the most active areas.

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17.1   Introduction

Tabernas badlands, in Almería, constitute one of the most extensive badland landscapes in semi-arid south-east Spain and one of the driest areas in Europe (Fig. 17.1). The badland area occupies most of the centre of a tectonic basin filled during the Upper Miocene by marine marls, shales and turbidites, with occasional interbedded calcareous sandstones. The basin is bounded by faults that delimit three important Betic mountain ranges; Sierra de los Filabres, Sierra de Gádor and Sierra Alhamilla (Fig. 17.1). The basin is elongated in an E-W direction, from the Canjáyar Corridor in the west to the Sorbas basin at the east (see Harvey et al. 2014 in this volume).

The dissection of the Upper Miocene sedimentary rocks, mainly since the Pliocene period, has created a singular erosional landscape dominated by badlands, but with a wide variety of landforms resulting from the sequence of dissection and stability phases controlled by environmental changes and pulses of uplift and tectonic deformation in the
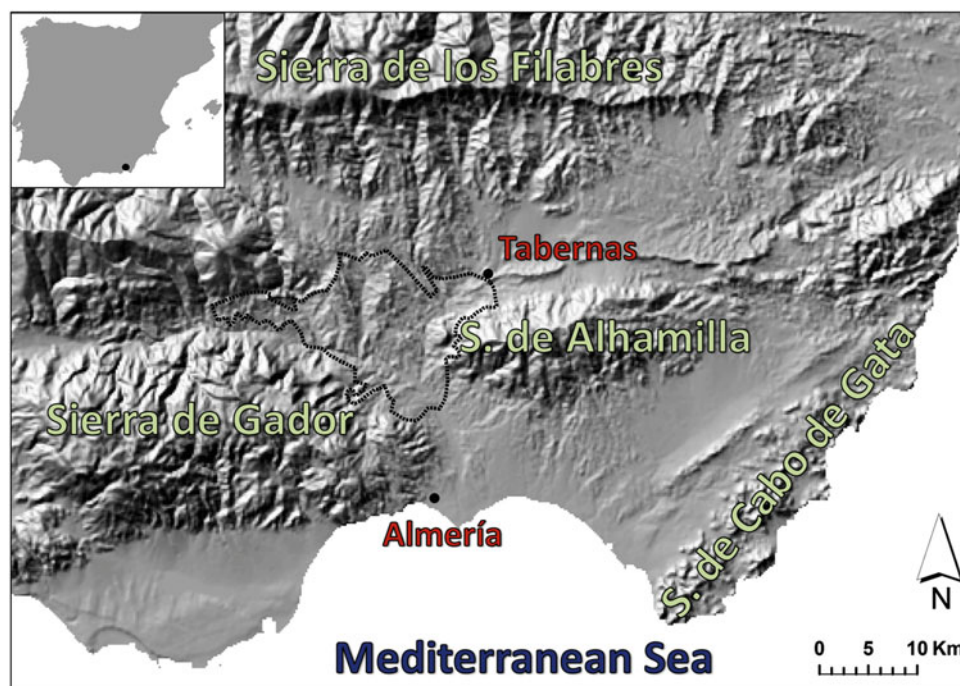
basin. The role of land-use changes, that is relevant in many other badlands areas around the Mediterranean, seems to be less important here although they can be considered effective in some parts of the basin.

17.2 Geological and Geographical Setting

The Tabernas basin is a tectonic depression that was created ca. 10 Ma ago by the folding and faulting phases that have occurred since the Burdigalian–Serravallian stages of the Miocene, affecting the Alpujárride–Nevado–Filabride basement. After a continental erosion–sedimentation sequence during the first 2–3 Ma of this period, the environment became marine during the Tortonian and Messinian, resulting in the sedimentation of a sequence of more than 700 m of deep water (up to 800 m of sea depth) turbidites and gypsiferous calcareous mudstones, alternating with layers of coarser sediments and submarine fan deposits. The sedimentary sequence includes the Chozas, Turre and Yesares formations, characteristic of the region as a whole. Later, in the Pliocene, marine conditions were restricted to the west and south-west of the basin, depositing marine fan deltas and mudstones (Abrioja formation), followed by a thick cover of Plio-Pleistocene continental alluvial fan deposits (Gador formation) (see Mather et al. 2001).

Since the Pliocene, uplift of the basin switched the conditions from net deposition to net erosion (Harvey 2001). The main drainage network developed during the Pliocene and dissected the easily erodible sediments of the Tortonian basin fill. The drainage exited the basin to the south, through the Rioja corridor, which was filled with large volumes of fan-delta deposits (Postma 1984), and was later dissected during the Pleistocene, as the Andarax river system prograded towards the coast at Almería (Harvey et al. 2012, 2014 in this volume).

Some of the faults bounding and within the basin remain active today (Mather 2009), and tectonic activity during the Quaternary has affected the landscape evolution. During the Pleistocene, the central part of the basin, in the lower section of the Rambla de Tabernas, has been affected by uplift that obstructed the drainage creating two shallow water lakes. The upper lake was placed near Tabernas town (see Harvey et al. 2003, 2014 in this volume) and the lower lake upstream of the confluence with the Andarax River (Fig. 17.2). During the latest Pleistocene and through the Holocene, dissection has been dominant, resulting in the erosional modern landscape.

The climate of the area is related to its low latitude, but is also very much influenced by local factors related to the position of the basin, surrounded by high mountain ranges and especially by the fact that the circulation of the air masses coming from the west is shaded by the highest elevations (over 3000 m a.s.l.) of the Iberian Peninsula in the Sierra Nevada, a factor also to be considered in relation to past climates. The climate is classified as semi-arid thermo-Mediterranean, with a mean annual precipitation of 235 mm (Lázaro et al. 2001). The average number of days of rainfall per year is 37, although this is very variable (Solé-Benet et al. 1997). The rainfall intensity can be high during rainstorms (maximum recorded 5- and 10-minute
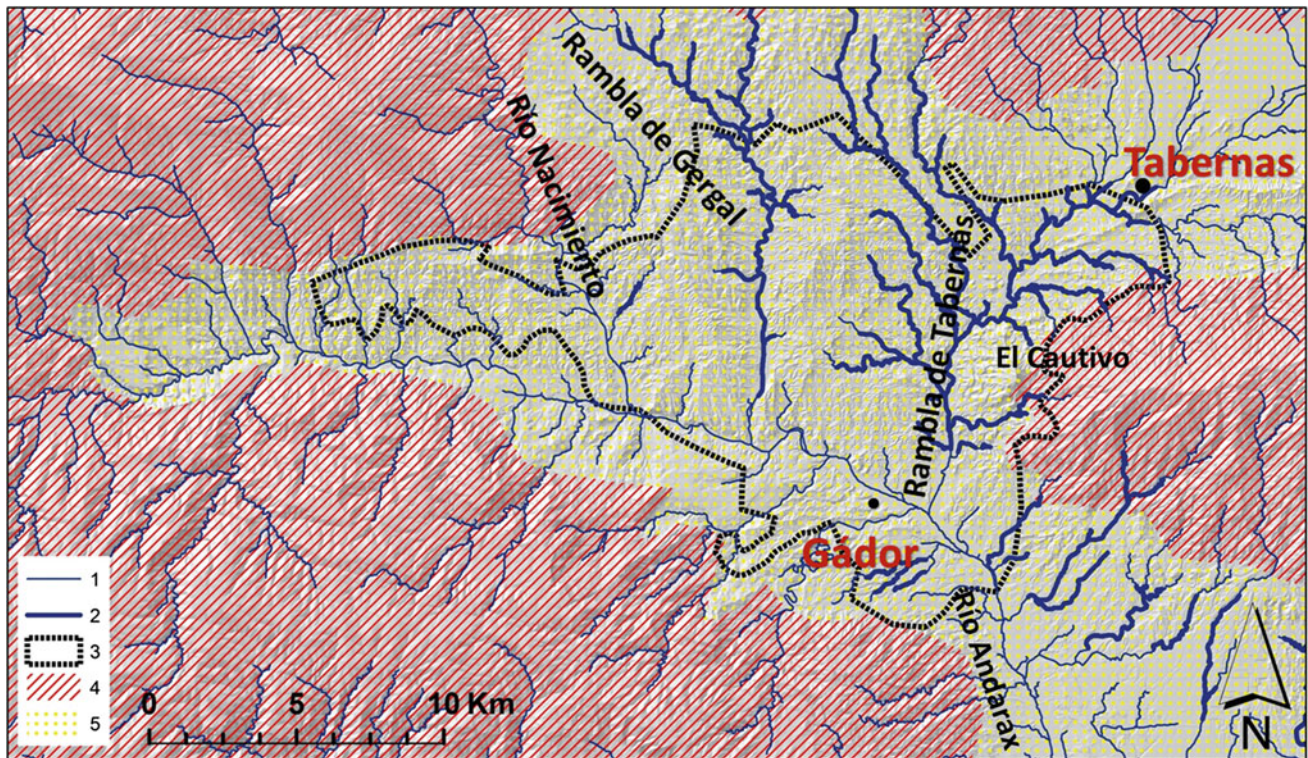
Fig. 17.2 Simplified geological–geomorphic sketch of the Tabernas Basin. *1* Main river channels. *2* Deep canyons. *3* Limit of the badlands area. *4* Surrounding reliefs on non-badlands-prone rocks. *5* Tortonian mudstones

intensities at El Cautivo experimental station are 85.2 and 41.6 mm h^{-1}, respectively). Mean annual temperature is 17.9 °C, with a minimum monthly average in January of 4.1 °C, and a maximum of 34.7 °C in August. Mean annual potential evapotranspiration reaches 1,500 mm, indicating a considerable annual water deficit (Cantón et al. 2003); between 6 and 9 months per year can be considered as dry at El Cautivo. The climatological conditions and the sparsely vegetated landscape justify the local name of "Desierto de Tabernas" despite its Mediterranean climate (Lázaro et al. 2001).

Natural vegetation is dominated by species adapted to severe drought, and although the Mediterranean element accounts for the main part of the flora, the Iberian–North African element often accounts for the majority of individuals and of the biomass. Richness of species and endemic plant rates are high. Vegetation is patchy, and both physiognomy and life-form spectrum are more similar to those of North Africa than Europe (Lázaro et al. 2001). Chamaephytes, terophytes and cryptogams are the main life-form types. Sparse dwarf shrubs or tussock grasses physiognomically dominate the landscape, whereas annual plants account for more than 50 % of the total flora, particularly in wet years. Biological soil crusts can cover a high proportion of the ground surface (more than 50 % in El Cautivo, the best studied part of the area). Trees are absent

and medium and large shrubs are very sparse (Lázaro et al. 2008).

17.3 Geomorphology

The Andarax River with its three main tributaries crossing the badland area (Río Nacimiento, Rambla de Gergal and Rambla de Tabernas) has a large catchment area (ca. 2,000 km^2), with its headwaters in the Sierra Nevada, Sierra de Gádor and Sierra de los Filabres (Fig. 17.1). Here, annual rainfall is much higher and storms are more frequent, giving a high energy to the system.

In most of the central and eastern part of the Andarax catchment, drained mainly by the Rambla de Tabernas, lithology, climate, relief and rapid incision have combined to create a typical but also distinctive badlands landscape (Fig. 17.3a).

As in many other areas with badlands, the landscape comprises a series of entrenched valleys with high drainage density and short and steep hillslopes, usually dissected by rills and gullies. This is the characteristic landscape of most of the tributaries of the main rivers, where incision is more recent. In the areas where the incision is older, the drainage is characterized by wide braided channels flanked by a flood plain or lower terrace, largely disconnected from the

Fig. 17.3 General view of the lower Rambla de Tabernas valley (**a**) and two perspectives of El Cautivo area (**b**) and (**c**) where surfaces from different stages can be identified as hanging pediments, valley floors and talus flatirons. Note the contrast in the vegetation cover between the old surfaces and the more degraded hillslopes affected by incision

hillslopes. Changes in local base level have been critical for the development of these badlands. In the western part of the basin (Andarax and Nacimiento catchments), pure badlands are restricted to specific sites and most of the rest of the hillslopes are more regular, covered by sparse vegetation and only locally affected by gullying. In the central part of the basin (mid- and lower Rambla de Tabernas catchment), the coupling (sensu Harvey 2002) between hillslopes, tributaries and main channels is complete. In contrast, the north-facing hillslopes, the remains of old pediments and old hanging hillslope parts, have more stable surfaces still disconnected from the local base level.

These contrasting landscapes have been created primarily by the spatially differential response to tectonic activity that has favoured incision in some parts of the basin, while at certain times, it has impeded this process in other parts. The landscape not only shows a variety of landforms, but also landforms of different ages within the basin.

17.3.1 General Landforms

The slope map shown in Fig. 17.4 contains six slope classes that illustrate the morphology of the basin. Harvey (1987) described the erosional parts as composed of canyon landscapes, deeply dissected soft rock areas and scarplands. Half of the area consists of hillslopes <30°, and 20 % of the surface includes steeper areas, both recently dissected valley walls and scarps associated with the caprocks in the higher parts of the relief. The remaining 30 % corresponds to flat and gentle sloping areas such as valley bottoms, terraces and pediments.

The valleys of the main rivers have wide braided channels similar to those described by Thornes (1976) in the neighbouring area of the Alpujarras. They are characterized by high transport capacity during flood events and active bank erosion maintaining very steep sidewalls, as in the Rambla de Tabernas and some parts of the Rambla de
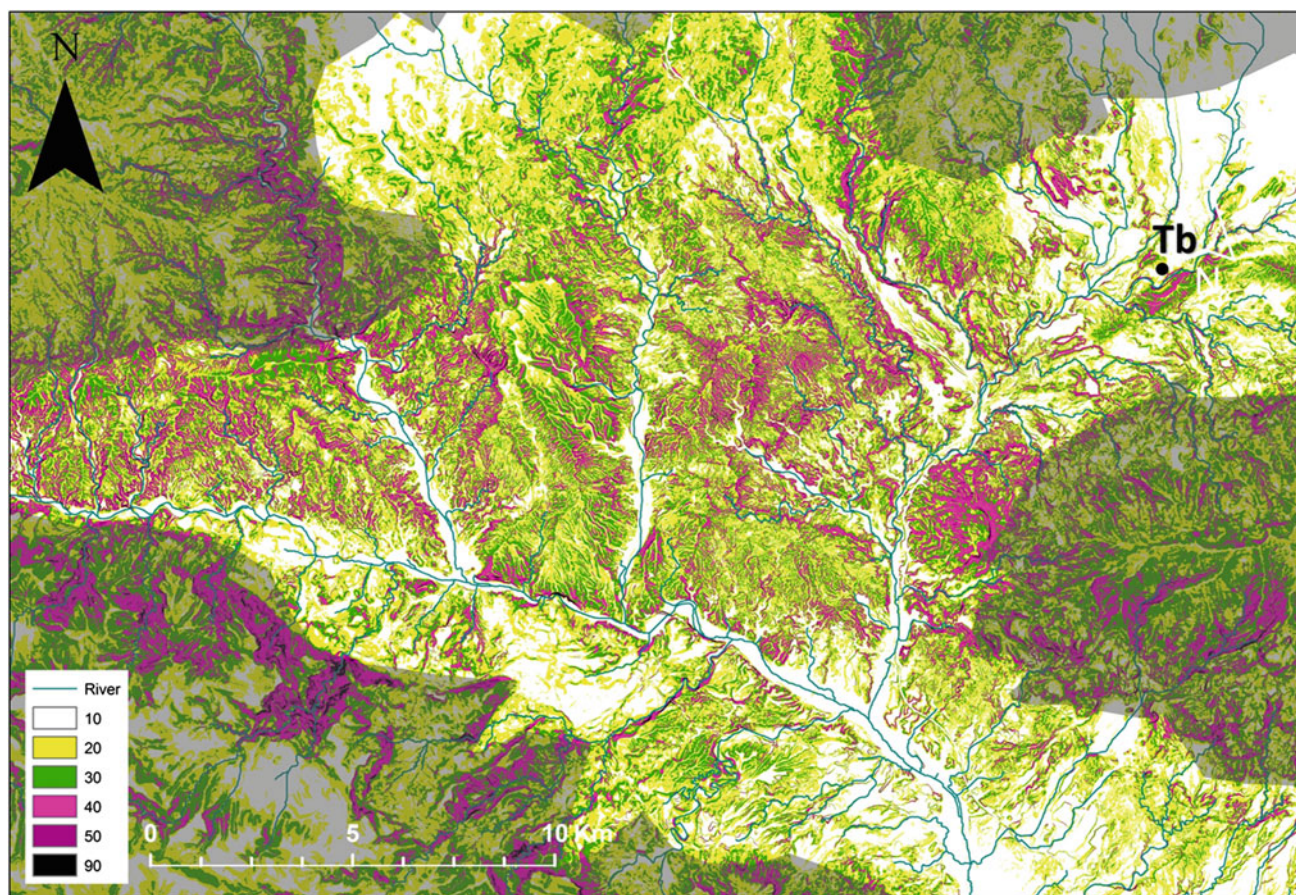
Fig. 17.4 Slope map of the badlands area and surrounding reliefs. Legend shows the upper limits of the slope intervals in degrees

Gergal. Both ramblas have excavated deep canyons in most of their mid-catchment (Fig. 17.2 and 17.3a). The rapid incision of these channels is related to the uplift episodes during the Pleistocene and especially with several interruptions of the drainage that produced at least two palustrine areas in the catchment of the Rambla de Tabernas (Harvey and Mather, 1996; Harvey et al. 2003). The easily erodible palustrine sequence around 20 m thick (Harvey 2001) has been dissected during the last ca. 15 ka (Alexander et al. 2008).

Some parts of the landscape have less steep landforms inherited from pedimentation periods during the Pleistocene, hanging above the present-day base level. These features are more frequent in the Rambla de Tabernas area due to its more recent evolution. Also remains of the two main sets of fluvial terraces (Harvey 1987) contribute to the lower gradient areas on the map (Fig. 17.4). These terraces correlate in part with the undissected alluvial fans that characterize the eastern part of the basin (Harvey and Mather 1996; Harvey et al. 2003).

The older terraces exhibit calcrete development (Nash and Smith 1998) (Fig. 17.5a), including pedogenic calcretes at the mesa surfaces and groundwater calcretes at the

contact between the terrace gravels and the underlying Tortonian mudstones. Locally, like at Las Salinas site (Fig. 17.5b), $CaCO_3$ precipitation occurs as travertine curtains (Mather et al. 1997; Mather and Stokes 1999).

17.3.2 The Role of Biological Activity

Geomorphological processes affect, and are affected by, biotic components such as shrubs, annual plants or biological soil crusts (BSC) (Fig. 17.5d), and these interactions act across different spatial and temporal scales. According to Lázaro et al. (2000), the rich variety of microhabitats existing in Tabernas badlands is a consequence of the landform diversity, which in turn is related to the complex geomorphology of the system. The microhabitats show different topographical, erosional and edaphic features, explaining the spatial patterns exhibited by the main physiognomic types of vegetation. The cover of BSCs, annual and perennial vegetation is largely controlled by the landform type, and consequently, landform distribution is a proxy for the vegetation map (Alexander et al. 1994). Cantón et al. (2004) demonstrated the significant correlation

Fig. 17.5 Dissected hillslopes on the Tortonian mudstones capped by calcrete (**a**). Travertine curtain at Las Salinas site (**b**). Rock fall on the walls of the Rambla de Tabernas main channel (**c**). North-facing hillslope covered by a continuous biological soil crust (BSC) in an advanced development stage (**d**)

between the landforms resulting from a non-hierarchical classification of the terrain attributes, and the ground-cover pattern. This association shows the influence of geomorphology in determining the type and characteristics of the biotic components.

Two levels of spatial segregation can be observed in the area: (1) between eroded and vegetated areas. The former mainly correspond to steep south- or south-west-facing hillslopes, almost completely devoid of vegetation and practically without soil development, which account for one-third of the total area. The latter are mainly associated with pediments and less steep north- or north-east-facing hillslopes; (2) inside the vegetated areas, spatial segregation often exists among the communities dominated by different life forms: grasses, dwarf shrubs, annual herbs and BSCs. This segregation is associated with landforms and, in addition, to the nested topographical levels (see Alexander et al. 1994, 2008 and below for a description of these nested levels). The older the level, the longer the time elapsed since the stabilization of the surface and consequently the more developed the vegetation succession and soils, particularly leaching of the topsoil.

The community dominated by perennial grasses, mainly *Macrochloa tenacissima* (=*Stipa tennacissima*, alpha grass), which is a late-successional stage, is located mainly on the oldest remains of hillslopes and pediments, in the higher topographical positions, often disconnected from the current drainage network. Typical semi-arid dwarf shrubs (often endemic or Ibero-North African species, e.g. *Helianthemum almeriense, Euzomodendron bourgeanum, Hammada articulata, Anabasis articulata* and others) and annual plants (e.g. *Stipa capensis, Plantago ovata, Bromus rubens, Linum strictum, Asteriscus aquaticus, Brachypodium distachyon* and many others) occur mainly in the intermediate nested levels (on the older surfaces they have been progressively replaced by grassland). Shrubs and annuals often occupy the same habitats although they are not stratified, but form a non-random mosaic, the shrubs being slightly more water demanding than the annuals, which require more stable areas (Cantón et al. 2004). BSCs are distributed on the

driest sites, on recent surfaces and in the upper half of the stabilized slopes of the medium levels (Lázaro et al. 2000; Cantón et al. 2004). On the oldest levels, they also appear, but are less frequent, as they have already been replaced in the great part of these sites. BSCs show an important cover on more than two-thirds of the total area and in one-third constitute the main or even the only cover. BSCs are composed of three main communities, dominated, respectively, by Cyanobacteria and diverse small colonizing lichen species; *Diploschistes diacapsis* and *Squamarina lentigera*, and *Lepraria isidiata* and *Squamarina cartilaginea*. This abundance of BSC is characteristic of these badlands and is due to the high proportion of the rainy days with only small total rainfall amounts and the frequency of the dew. This favours poikilohydric organisms constituting the BSC in comparison with vascular plants, as the main part of the low-magnitude rainfall events is intercepted by the canopies and does not reach the roots (Lázaro 2004).

The features and activity of biotic components also control geomorphological processes at a detailed scale. These controls, which have implications at the landform scale, operate through several clusters of mechanisms:

1. By stabilizing the soil surface, decreasing erosion and allowing soil development (Alexander et al. 1994). In addition to the known stabilizing role of the vascular vegetation, BSCs have been suggested to be the first colonizers and often constitute the initial stabilization mechanism (Lázaro et al. 2008). The role of BSCs in reducing soil erosion at Tabernas badlands has been widely demonstrated (Alexander and Calvo 1990; Calvo-Cases et al. 1991a; Solé-Benet et al. 1997; Cantón et al. 2001b; Lázaro et al. 2008; Chamizo et al. 2012).

2. By modifying infiltration, run-off paths and amount, as well as the amount and spatial distribution of sediment deposition (Puigdefabregas et al. 1999). This effect of vegetation is dynamic and species-specific, and particularly significant in tussock grasses because they are able to intercept an important percentage of run-off and sediment flow; about 50 % for *Macrochloa tenacissima*, the dominant grass at Tabernas, according to Puigdefábregas and Sánchez (1996). Very local biotic components affect feedback processes at landform scale such as the asymmetry present in many of the small catchments within these badlands. This asymmetry is always linked to the vegetation pattern: north- to east-facing hillslopes are vegetated, larger, more stable and less steep. The opposite slopes are affected by erosion; they are shorter, steeper and bare.

3. By introducing feedbacks in the surface processes and in the plant-soil relationships tending towards vegetation development (Eviner and Chapin 2003; Ehrenfeld et al. 2005). Many of the soil–plant interactions are based on the effects of vegetation on the hydric fluxes (Pugnaire et al. 1996a; Horton and Hart 1998), gas fluxes (Raich and Tufekcioglu 2000), energy fluxes (i.e. temperature modifications; Hillel 1998), or on the soil enrichment by organic matter (Mora and Lázaro 2013). The most labile fractions of organic matter, coming from the root exudates and from the litter, favour the activity and diversity of the soil microbial communities (Kourtev et al. 2003; Ravit et al. 2003), which play a key role in the formation of soil aggregates (Jastrow et al. 1998; Rillig et al. 2002) and in the nutrient availability for plants (Northup et al. 1998; Hinsinger 2001). The sum of these processes gives rise to "islands of fertility" under the main vegetation patches, in which the facilitation relationships among plants dominate (Pugnaire et al. 1996b).

In the Tabernas badlands, the vegetation development, during which the mechanisms detailed above operate, can be synthesized as follows:

1. The eroded and unstable sites are colonized only by a few vascular species (mainly the shrub *Salsola genistoides* and the annual *Moricandia foetida*), creating the typical appearance of these badlands, particularly in wet years, during which *Moricandia* grows abundantly and flowers in a short period. However, none of them is able to have significant stabilization or pedogenesis effects on these sites (Lázaro 1995; Gallart et al. 2002), and no vegetation succession exists.

2. Constructive colonization able to feedback towards stabilization and soil and vegetation development requires a certain degree of previous stabilization caused by abiotic factors (disconnection from the drainage network, obstruction of the channel by sediment deposits, etc.), together with reduced land use (as currently in the Tabernas badlands). Constructive colonization often begins with BSC, which are able to resist splash erosion but unable to resist either trampling, or some erosional processes frequent in the area, such as mass movement, rill/gully development and collapse produced by previous piping (Lázaro et al. 2000). BSCs enrich bare soils with organic matter (Miralles et al. 2012a), initiate biogeochemical cycling of elements (Miralles et al. 2012b), modify local water balance and strongly decrease erosion (Chamizo et al. 2012; Solé-Benet et al. 1997), and thus provide additional stability and enable the ground to be colonized by vascular plants. Vegetation and erosion compete for soil fertility and depth as proposed by Thornes (1990) and beyond a certain threshold; vegetation (and soil) receives a positive feedback. Below that threshold, abiotic stabilization is necessary; otherwise, erosion receives positive feedback and colonization fails. In the Tabernas badlands, vegetation and soil development are usually successful on pediments and in the north- to east-facing slopes of the old and medium nested levels, whereas in the rest of landforms, they often fail.
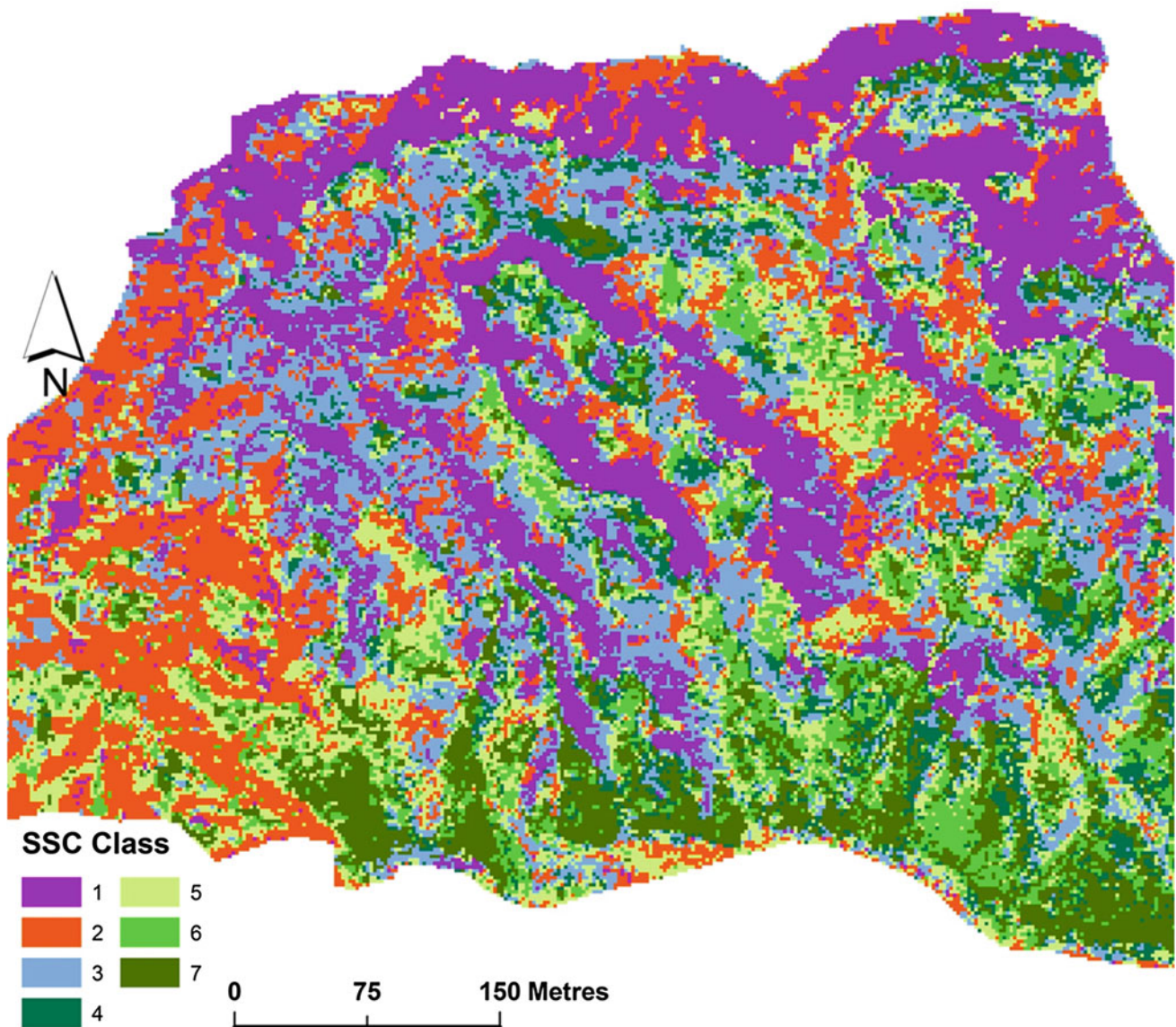
Fig. 17.6 Soil surface components (SSC) map of El Cautivo area by ATM classification (Modified from Calvo-Cases et al. 2009). *1* Actual bare badland hillslopes; (*2*) Rock fragment cover; *3* BSC of lichens; *4* Low-density bushes and BSC; *5* Annual plants cover; *6* Bushes; *7* *Macrochloa tenacissima*. See location in Fig. 17.2

17.3.3 Present-day Geomorphic Processes

One of the best studied parts of the Tabernas badlands is the El Cautivo catchment, located in the eastern part of the area. The catchment is operated as an experimental station for process monitoring by the EEZA-CSIC institute (http://www.eeza.csic.es/eeza/g_geo.aspx).

At El Cautivo, the landscape comprises three main components: (1) bare hillslopes representing 40 % of the surface; (2) remains of Pleistocene and early Holocene pediments that occupy 10 % of the landscape and constitute stable areas with a well-developed plant cover; (3) the remaining 50 % is composed of hillslopes with a BSC cover (33 %) and/or vascular plants (Fig. 17.6).

The Tortonian series, with alternating mudstones and thin calcareous sandstone layers, are easily weathered by wetting and drying sequences (Cantón et al. 2001a), in which the role of the frequent small rainfall events (more than 84 % of the total) is essential. These do not yield run-off, but weather the regolith providing easy-to-transport sediments. Cantón et al. (2001b) showed that annual erosion rates, in most years, are lower than weathering and regolith

production rates. The climate is arid enough to restrict the development of plant cover on the south-facing slopes, but provides enough rainfall to occasionally allow run-off generation with sufficient energy to remove most of the previously weathered material and keep the surface clear of regolith.

Mudstone Weathering

The main rock forming the badlands is a marl or more precisely a gypsum–calcareous mudstone, essentially formed by very homogeneous silts: the D_{60} of its mineral grains ranges between 25 and 20 μm, D_{10} between 2 μm and 3.7 μm, and the uniformity coefficient (D_{60}/D_{10}) is 6.5 (Solé-Benet et al. 2009). The main minerals are quartz, muscovite, paragonite, calcite (up to 30 %) and gypsum (up to 30 %), and minor amounts of clay (5 %) of which small amounts are smectites (Solé-Benet et al. 1997). According to Cantón et al. (2001a), a combination of three factors seems to be responsible for mudstone weathering: repeated wetting–drying cycles, the presence of geologically induced cracks and fissures, and dissolution–crystallization of relatively soluble minerals like gypsum. In the laboratory, a few wetting–drying cycles applied to the fresh mudstone are sufficient to enhance a network of cracks and fissures favouring mineral dissolution. In the field, surface weathering rates from 0.7 mm year^{-1} (average after three years of natural rainfall without removing the produced regolith) to 4.7 mm year^{-1} (average when removing the regolith after the main rainfall events, like natural bed scouring) were measured on weathering plots set in 1995 over fresh rock, after removing the original regolith cover (Cantón et al. 2001a). Weathering rates were found to be proportional to the number of rainfall events during the sampling periods, confirming the results of laboratory experiments; the number of wetting–drying cycles has the greatest influence on weathering. These findings confirm: (a) the long-term observations about available material and erosion on bare, regolith-covered slopes: the thickness of weathered, prone to erosion material, is proportional to the number of low-magnitude rains before an erosive high-intensity or high-magnitude event, which occurs on average once or twice a year; (b) a long-term erosion of 3.72 mm in 16 years (equivalent to 3 t ha^{-1} year^{-1}) was measured by erosion pins, laser scanner and profiles in a 100 m^2 sloping area on bare regolith under south-west exposure (Solé-Benet et al. 2012), though a single event caused a surface lowering of 86 mm in a rill.

These weathering rates might be considered as the probable range of incision under present semi-arid conditions. Moreover, the quite homogeneous particle-size distribution of this mudstone indicates susceptibility for piping processes, as observed, in the area.

Rainfall-runoff Processes

The main processes identified by the resulting forms are rainfall-runoff related, rill erosion being the most evident (see Calvo-Cases and Harvey 1996), especially following moderate rainstorms. In contrast, after periods of low rainfall intensity, the regolith becomes thicker (Cantón et al. 2001a) and the rills may be partially destroyed by surface weathering. When subsequent intense rainfall does occur, shallow mudflows can be identified in the concavities usually occupied by the rill network. On south-facing slopes, the rill networks form part of a hierarchy of rills, gullies and small catchments.

Available data on erosion rates, provided by rainfall simulation experiments, measurements in plots and catchments with different sizes, show figures that are lower than could be expected for badland areas. In fact, most of the data analysed in Calvo-Cases et al. (1991a) comparing badland areas in south-east Spain show the Tabernas data in a lower range, for similar soil surface components (SSC), than many other badland areas. Figure 17.6 shows the soil surface components (SSC) at El Cautivo, which are associated with soils of different degrees of evolution (Alexander et al. 1994), controlled by aspect and the distribution of surfaces with different ages.

Experimental data obtained by Calvo-Cases et al. (1991b), Solé-Benet et al. (1997) and Cantón (2001b) indicate that the BSC composed of lichens and the mineral soil crust (MSC) characteristic of the bare areas are the soil surface components with higher runoff coefficients. Erodibility is low when BSC and MSC remain, but increases significantly when they are destroyed (Chamizo et al. 2012). Soils with well-developed vegetation cover have higher infiltration capacity and lower erosion rates.

During ten years of monitoring at El Cautivo, average ground lowering ranges from 2.15 to 0.08 mm year^{-1} for a bare microcatchment (ca. 200 m^2) and 0.35 mm year^{-1} for a small catchment (2 ha) (Solé-Benet et al. 2003). The differential hydrological response is controlled by the distribution of different SSC in the catchment (Cantón et al. 2002).

In comparison with other badland areas in south-east Spain, the lower erosion values of the Tabernas badlands are related partly to the drier climatological conditions with less erosive rainfall Lázaro et al. 2001), and the rock properties yield less erodible soil. The preservation of a complex mosaic of SSC associated with soils with different degree of development is one of the main factors that explain the variability of the response.

Piping

In comparison with other badland areas, the dispersiveness of the Tabernas badlands bedrock is relatively low (Faulkner et al. 2000 and Faulkner 2013; Cantón et al. 2003) and

Fig. 17.7 Gully dissection in a north-facing hillslope and pediment covered by some vascular plants and a well-developed BSC made of lichens; white spots (**a**). Gullies developed in the lower terrace of the Rambla de Tabernas (**b**) and along tracks (**c**). Some human activities damaging the BSC and vegetation cover on the hillslopes of the natural park (**d**)

piping processes are very restricted. The only evidence of forms related to piping appears in collapses of the lower part of hanging pediments where the water flows through macropores produced by roots and salt solution cracks (Solé-Benet et al. 2009), developing galleries in the contact zone between Quaternary soils and regolith and the underlying mudstones. A higher concentration of sodium was found by Alexander et al. (1994) at certain depths (c. 60 cm) as a consequence of the leaching of bases.

Gullies

Some relatively shallow arroyo-like gullies with flat floors and vertical walls dissect the flat terrace surfaces (Calvo-Cases et al. 1991b). They are decoupled from the main rivers by agricultural practices. Since such activities have

ceased, episodes of rapid gully development have occurred (Fig. 17.7b). On some north-facing hillslopes with thick regolith cover, longitudinal gullies (Fig. 17.7a), some decimetres wide and initially as deep as the regolith, appear associated with tracks (Fig. 17.7c) and other areas where the BSC has been degraded by human activities (Fig 17.7d).

Mass Movements

Together with the shallow mudslides and mudflows (described above) that occasionally occur on badland hillslopes, areas where fast incision has created scarps show frequent earth falls consisting of mudstone block accumulations on the gully channel floors, released by the development of unloading cracks. These deposits are easily removed by floods. On the main canyon walls, similar
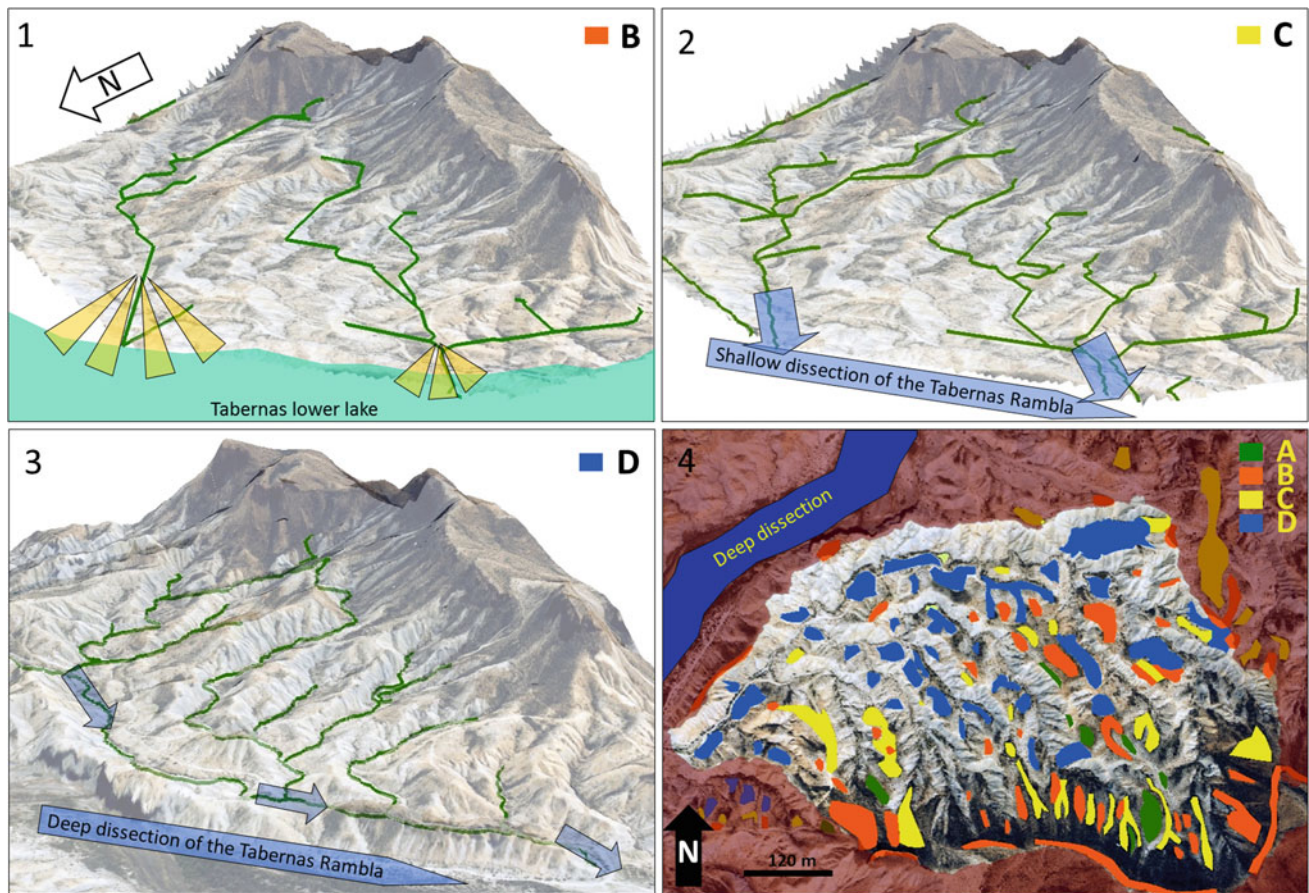
Fig. 17.8 Topographical reconstruction of El Cautivo catchment at three times: from 14 ka ago *1* to the present *3*, and map of the remains of landforms of the different ages *4* (modified from Alexander et al. 2008)

mechanisms produce rock falls of bigger blocks (Fig. 17.5c). Far from the main channels, on the upper part of the relief, rock falls derived from sandstones and Quaternary cemented gravel caprocks underlain by mudstones are also frequent (Fig. 17.5a).

17.4 Evolution

El Cautivo (Fig. 17.3b and c) as part of the lower Rambla de Tabernas catchment has been affected by the above-mentioned differential tectonic uplift and lake formation sequences. The landscape records stabilization and dissection sequences that occurred during the Pleistocene and perhaps over the last few thousand years of the Holocene. Alexander et al. (1994) identified five stages of aggradation separated by incision sequences.

The earlier stages (A, B and C in Fig. 17.8) represent successive badland and pediment stages carved in the marls. They involve long-term hillslope evolution through the retreat of the northern side of a sandstone scarp that forms a caprock over the Tortonian marls (Fig. 17.3c).

Stage A is represented by some talus flatirons (sensu Gutiérrez-Elorza and Sesé-Martínez 2001) remaining in the upper part of the relief, characterized by regular concave hillslopes armoured by a detrital cover and with a distinctive vegetation cover dominated by *Macrochloa tenacissima* tussocks.

Stage B appears in the upper parts of graded hillslopes below the scarp, between the remnants of stage A. It is also recorded by debris cones and fan deposits, small remnants of pediments in the divides and some valley sections hanging over the contemporary relief. Most of these stage B remnants are also associated with a distinctive regolith-soil and vegetation cover similar to stage A sites. The more widespread presence of these remnants allowed Alexander et al. (2008) to create a reconstruction of the stage B topography (Fig. 17.8-1) and to correlate these forms with tributary catchments draining to the north and north-west towards the lower Tabernas Lake. The terminal age of these forms can be considered as contemporary with the top of the lake sediments (OSL date of 14 ± 1 ka BP, Alexander et al. 2008), although they developed during the previous ca. 150 Ka when the lakes were present, U/Th date of
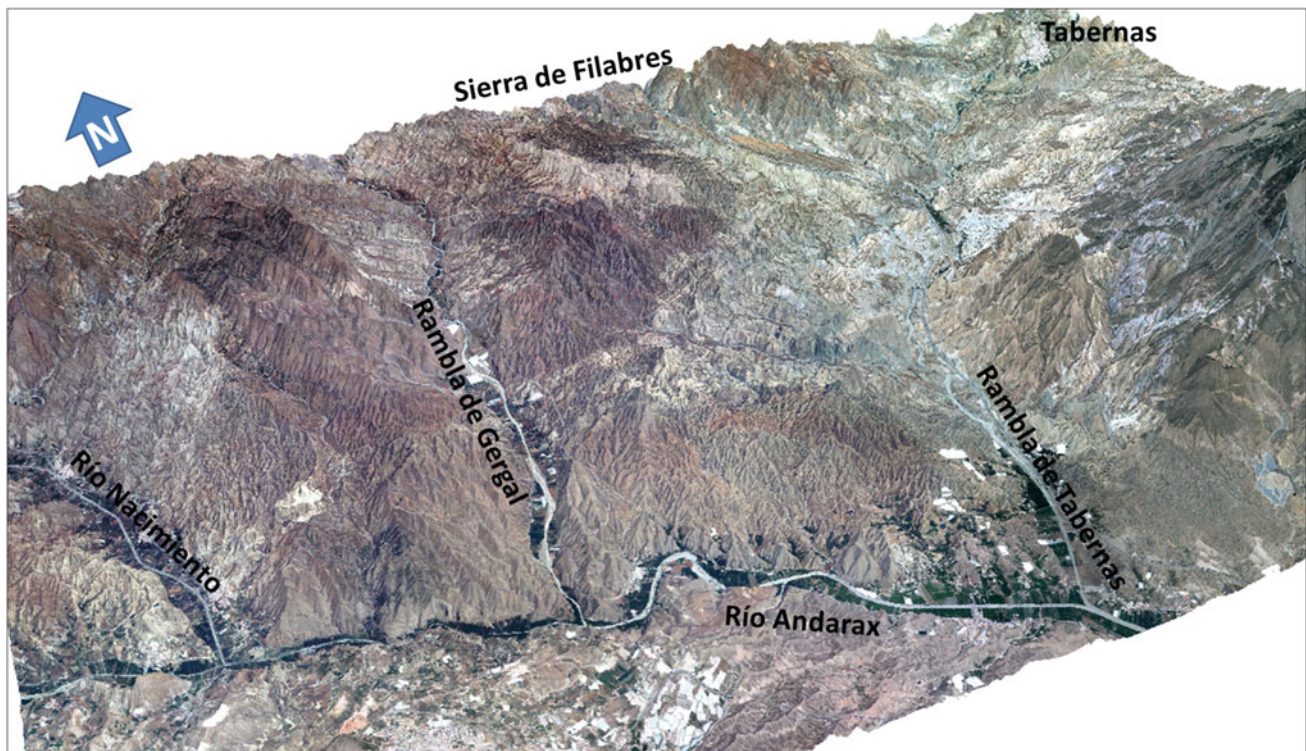
Fig. 17.9 Three-dimensional view of a recent ortophoto with a 5-m resolution DEM (www.cnig.es) covering most of the badlands of the Tabernas Basin

150 ± 50 ka from the lower part of the sediments of the Tabernas upper lake (Delgado-Castilla et al. 1993).

After a limited incision (ca. 3 m) along the main channels, a new period of pediment formation and hillslope stabilization occurred (stage C). The reconstructed topography does not show significant changes in the drainage network from stage B (Fig. 17.8-2). The incision appears to have been driven by a small base-level drop as the palaeo-Rambla de Tabernas began to cut down through the soft lake sediments.

After this stage C, a major change occurred in the El Cautivo catchment (Fig. 17.8-3). All the drainage directed to the north-western side was captured (following the arrows in Fig. 17.8-3) by the western tributary to the Rambla de Tabernas, inducing deep incision of the entire drainage network. The local base level dropped about 30 m due to the entrenchment of the modern Rambla de Tabernas in Tortonian marls, creating the modern canyons. In El Cautivo catchment, the main channel incision (ca. 50 m) and the consequent badlands landscape development during this stage (C–D), that supposed a total volume of denudation of c. 1.4 hm³ of rock within El Cautivo catchment (Alexander et al. 2008), possibly linking to the dry–warm period around 5–4 ka BP (Nogueras et al. 2000). Small pediments of stages D and E occur within the incised

drainage network that were formed sometime during the late Holocene, prior to the present-day active incision.

The detailed study of the landform evolution of the lower Rambla de Tabernas catchment suggests an average ground lowering of 0.16 mm year^{-1} in a period of 14 ka although most of the erosion work was done between stages C and D, as a consequence of the incision of the Rambla de Tabernas. The Quaternary stages of stabilization and incision of the hillslope-pediments-channel systems identified in El Cautivo and other parts of the lower part of the Rambla de Tabernas (stages A, B, C, D) relate to changes in the main drainage axis induced by tectonics, which seem to be primarily confined to the Rambla de Tabernas drainage and seem to apply less to the western part of the basin, drained by the Andarax River main valley, and the lower catchments of the Río Nacimiento and Rambla de Gergal, although Garcia et al. (2003) have suggested some Quaternary fault activity there. The western areas appear as darker tones on the aerial photographs (Fig. 17.9), reflecting a greater vegetation cover and less active hillslope erosion. The geology is also different; this is the main outcrop area of the Plio-Pleistocene Gador conglomerates. Furthermore, late Quaternary tectonically induced incision has perhaps been less active there. In contrast, the Rambla de Tabernas area presents lighter colours on the aerial photograph (Fig. 17.9). The late

Pleistocene reactivation following the post-lake incision of the Rambla de Tabernas has led to the formation of the well-coupled canyon and badland landscapes. Within that area, at a more local scale, coupling is weaker in parts of the north-facing hillslopes, where local microclimatic and dynamic factors decouple the hillslopes from the channels. Also decoupled are places like the upper part of the hillslopes of El Cautivo and many other tributaries, where the wave of aggression has had insufficient time to arrive. Similarly, the upper catchment of the Rambla de Tabernas, upstream of the incision headcuts, preserves a totally different landscape of coalescent alluvial fans where base-level-induced dissection is only just beginning (Harvey 2006).

The development of the Tabernas badlands can be explained, according to Faulkner (2008), by the interaction between a succession of stages of decoupling in the system driven by climatic and/or intrinsic controls under local base-level stability, and a succession of stages in which the reactivation of incision in the main fluvial systems propagates upstream creating a wave of aggression (see Brunsden 2001) increasing the coupling and connectivity.

17.5 Conclusions

The whole Tabernas basin has three morphologically different areas: (1) The eastern part, upstream of Tabernas town, has not been dissected and retains a low-gradient morphology dominated by alluvial fans. (2) The western part has the morphology of an old badlands area, today graded to the main base level with more regular and vegetated hillslopes. (3) The most active badlands appear in the central part, and especially in the lower Rambla de Tabernas catchment, as the consequence of the recent (c. 14 Ka) dissection of the lower Tabernas Lake. Also the upper catchments of the Rambla de Gergal and some parts of the upper Río Nacimiento, both inside the basin sedimentation area, have active badlands.

Tectonic chronology seems to be the main factor differentiating these parts as there has been enough relief created to allow the dissection in some areas while others remain unaffected. Landforms show complex multi-stage development and contain a variety of microecosystems. This variety is enhanced by the control of aspect and the special erosive conditions introduced by climate and bedrock that allow a singular diversity and extension of biological soil crusts and especially of lichens species.

Although erosion rates are high in bare hillslopes oriented to the south, for the area as a whole, they are low in relation to badlands elsewhere in south-east Spain. The low overall rates are due to the scarcity of rainfall events that generate runoff and transport sediments, as well as to the mosaic of soil surface components that results from differences in lithology, landform ages and microclimate, and more than 50 % coverage of the catchments by plants or biological soil crusts. The role of the crusts has been found to be critical in maintaining the stability of the hillslopes when a lack of disturbance allows positive feedbacks that are conducive to runoff rate reduction as vegetation colonizes.

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