The Barranco de Tirajana basin, Gran Canaria (Spain). A major erosive landform caused by large landslides

Alejandro Lomoschitz a,*, Joaquín Meco b,1, Jordi Corominas c,2

Departamento de Ingeniería Civil, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Islas Canarias, Spain
Departamento de Biología, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Islas Canarias, Spain
Departamento de Ingeniería del Terreno, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain

Received 20 April 2000; received in revised form 31 March 2001; accepted 3 April 2001

Abstract

The Barranco de Tirajana (BdT), located on the island of Gran Canaria (Spain), has some specific features that differentiate it from the ravines of other volcanic islands in the Atlantic Ocean. The origin of this unusually wide upper basin (35 km²) has been under discussion over the last century although its erosional origin is nowadays widely accepted. The purpose of this paper is to describe the landslide deposits that appear at the bottom of the basin and to assess their role in the geomorphological evolution of the basin. We suggest that the BdT basin is a major erosional landform initiated by important ravine incision and widened by a large number of landslides.

There are 28 large landslides within the BdT basin. The main movements were of rock-slide and debris-slide types, affecting 70% and 25% of the total area, respectively. In addition, modes of displacement were predominantly translational (rock-, debris-, and earth-slides) consisting of 89% of the total, compared to rotations and flows that constitute only 11%.

Three main periods of landslide activity have been established in the development of the BdT basin, using geomorphological criteria. Period I includes ancient movements that could have started at about 0.6 Ma or even 2.7 Ma ago and are considered as abandoned landslides. Period II corresponds to old landslides considered as dormant, which occurred within the Middle–Upper Pleistocene. Finally, period III includes recent Upper Pleistocene landslides and Holocene landslides that are still active. We suggest that interglacials in the Canary Islands and NW Africa included humid and wet episodes that could account for the occurrence of periods of landslide activity in the BdT basin. © 2002 Elsevier Science B.V.

Keywords: Landslides; Volcanic islands; Climate change; Quaternary; Gran Canaria

1. Introduction

The Barranco de Tirajana (BdT) is one of the main ravines of Gran Canaria (Canary Islands, Spain). It starts in the central-southern part of the island, at a height of about 1600 m, and flows into the ocean on the SE coast (Fig. 1).
The BdT has some features in common with other ravines on Gran Canaria and other volcanic islands in the Atlantic (e.g. Gomera, La Palma and Madeira). These have a radial pattern, with both very deep and narrow valleys, and steep stream gradients.

However, some characteristics of the BdT are specific: (a) it has an unusually wide upper basin with an extent of 35 km² and a depth of 900 m; (b) the bottom of the upper basin is full of landslides, some of them of huge dimensions (more than 1 km long and 0.5 km³ in volume); (c) its axial channel is narrow and deeply incised (350 m), and it crosses a wide range of bedrock formations; (d) its end flows through a thick mass of sediments, which prograded into the ocean forming the Juan Grande alluvial fan, the largest form on Gran Canaria; and (e) current climate in the BdT is temperate subtropical, with 375 mm of mean annual rainfall, and temperatures in winter of 15–20°C and in summer of 20–32°C.

These specific characteristics allow us to raise some important questions about the BdT: (1) How was its deep and wide upper basin formed? Is it a volcanic
caldera or an erosional depression? (2) What are the features of the landslides? How did they move and what was the sequence of movements? (3) When did the main development of the BdT basin occur? Can we know the principal phases of its geomorphologic evolution? And (4) can some relationships be established between the periods of landslide activity and the regional paleoclimatic context?

2. The study area

The Barranco de Tirajana (BdT) is a ravine (“barrenco” in Spanish) located in the SE sector of Gran Canaria. Nowadays, it can be divided in three main sectors: a wide upper basin, about 5 km wide and 12 km long; an incised channel 7 km long; and the mouth that feeds the alluvial fan of Juan Grande, which extends 6.5 km towards the ocean. The overall morphology of the ravine is similar to a mountain torrent but, in this case, the alluvial fan reaches the sea and its onshore zone is 25 km² in extent (Fig. 1).

Bedrock outcrops in the cliffs and in some points of the bottom of the upper basin (Fig. 1) and along the steep walls of the incised channel. As a whole, the BdT cuts through materials of the three magmatic cycles of Gran Canaria (Table 1).

3. Origin of the Barranco de Tirajana basin

The upper basin of the BdT is a major form within the volcanic island of Gran Canaria (Fig. 2). Three different groups of hypotheses about its origin have been proposed so far: (a) volcanic genesis: whereby the basin been formed from a collapsed caldera (Buch, 1825; Benítez Padilla, 1945); (b) tectonic genesis: movement of blocks affecting the whole island (Bourcart and Jeremine, 1937) or its central part (Hausen, 1960) that produced a graben; and (c) an erosional genesis: whereby geomorphic processes alone seem to have taken place (Fúster et al., 1968; Araña and Carracedo, 1980) with landsliding being the most evident process observable within the upper basin (Balcells et al., 1990; Lomoschitz and Corominas, 1992).

3.1. Volcanic and tectonic hypotheses

The hypothesis of a collapse caldera has been rejected for several reasons, namely: (a) the upper basin of the BdT is not a closed depression; (b) no volcanic activity in relation to the BdT has been observed either in the basin or in its surroundings; (c) no important volume of pyroclastic deposits or lava flows have been found that could justify the emptying of a magmatic chamber and subsequent collapse of the ground surface; (d) bedrock outcropping at the bottom of the basin is always older than bedrock in the cliff-wall exposures; and (e) materials filling the basin are of an exogenic emplacement.

On the other hand, no signs of tectonic displacements have been observed in the BdT. Bedrock formations are broadly concordant, and they are not affected by either faults or folds. Therefore, there is a lack of evidence to support these hypotheses.

Table 1

<table>
<thead>
<tr>
<th>Magmatic cycle</th>
<th>Period</th>
<th>Time (Ma)</th>
<th>Geological formations and rock types</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>Pleistocene–Upper Pliocene</td>
<td>&lt;0.15</td>
<td>Basanite lava flows. Pyroclastic cones and maars.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.15–0.3</td>
<td>Basanite–Nefelinite lava flows. Pyroclastic cones.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6–2.7</td>
<td>Basanite–Nefelinite lava flows. Pyroclastic cones.</td>
</tr>
<tr>
<td>II</td>
<td>Lower Pliocene</td>
<td>2.9–3.8</td>
<td>Phonolitic domes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.9–4.6</td>
<td>Roque Nublo volcanic breccia.</td>
</tr>
<tr>
<td>I</td>
<td>Miocene</td>
<td>9.6–13</td>
<td>Basaltic–basaltic to trachitic–phonolitic lavas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13–14.1</td>
<td>Phonolitic Fm. Phonolitic ignimbrite and lavas,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.1–14.5</td>
<td>interbedded levels of tuff and pumices.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Trachytic–Rhyolitic Fm. Tuffs, ignimbrites and lavas.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Basaltic Fm. Olivine–piroxene basaltic lavas.</td>
</tr>
</tbody>
</table>
3.2. Erosive hypothesis

Benítez Padilla (1945) was the first to identify the deposits placed on the bottom of the Tirajana basin as landslides. Fuster et al. (1968) noticed the great development of landslide deposits in the basin. They supposed these deposits were formed by the sliding of large rock masses which turned into rock avalanches. They mapped the overall boundaries of the deposits at 1:100,000 scale. The 1:25,000 geological map of Gran Canaria (Balcells et al., 1990) indicates only the outer boundary of the materials filling the basin while suggesting that they were gravitational landslide deposits. Furthermore, on the map, these materials have been differentiated from the Roque Nublo avalanche deposits located in the SW sector of Gran Canaria. The latter must have been triggered by volcanic activity within volcanic Cycle II (Pérez Torrado, 2000).

The occurrence of landsliding was later confirmed by Lomoschitz and Corominas (1992) by using a variety of criteria such as geomorphological (head scarps, tilted surfaces, closed depressions, lack of drainage network, landslide dammed deposits, tilted trees and cracking), lithological–structural (stratigraphic sequences, back-tilted layers) and texture of deposits. Lomoschitz (1995) prepared a geomorphological map (1:10,000 scale), which included significant modifications to both the number and the boundaries of the landslides mapped by Balcells et al. (1990).

Nowadays, the erosional hypothesis (ravine incision, landsliding and subsequent erosion of the slide masses) of the BdT basin is widely accepted. In this way, the term “depression” was proposed by Lomoschitz and Corominas (1997a), rather than “caldera”, to name the BdT upper basin. Finally, a recent review on the formation of many erosive calderas around the world (Karatson et al., 1999) includes the BdT basin in the group of “erosional depressions”. In that respect, we suggest in this paper that the BdT basin is a major erosional landform initiated by important incision of the ravine and widened by a great number of large landslides.

3.3. Characteristics of the landslides

The upper basin of the BdT is full of large landslides (0.1–1 km³) with distinct boundaries. Field survey has shown that the slide deposits contain materials from almost all the geological formations outcropping at the cliffs of the BdT upper basin (see Table 1). At some landslide heads, thick back-tilted layers of bedrock are clearly observable (Fig. 3).
Downhill, the structure of the slide materials appears more and more weathered and broken, becoming chaotic at the landslide foot. This progressive decomposition of the slide bodies, from the head to the foot, is due to the increasing number of reactivations that they have suffered.

The geomorphological map and the geological cross-sections prepared by Lomoschitz (1995) showed at least 28 large landslides in the BdT with several generations of movement. Large initial failures of the bedrock have been followed by a succession of smaller, secondary failures as a result of the reactivation of part the main body. Indeed, it has been found convenient to divide the basin into seven sectors, each containing at least one main initial landslide and several generations of secondary movements and subsequent reactivations (Fig. 4), numbered within a given sector from 1, the oldest, to 4, the most recent (note that these numbers reflect relative movement within a given sector and cannot be directly correlated among sectors). Landslide terms used in the paper follow the recommendations of WP/WLI (1993).

Each sector has a main slide body with lengths of 1.2–3.5 km (an average of 2.5 km) and volumes ranging between 0.18 and 1.35 km³ (0.7 km³ as an average). Thus, they may be considered as very large movements (Table 2). In contrast, secondary bodies, which were detached from the main ones, are smaller: 0.3–2.3 km long (an average of 1.05 km) and with volumes ranging from $4.5 \times 10^{-3}$ to 0.45 km³ (an average of 0.1 km³).

Landslide dimensions are very variable, but all of them have lengths exceeding 150 m and therefore they belong to the category of large landslides (UNESCO, 1976). Displacement directions of the initial landslides (Fig. 4) indicate that all of them moved towards the Tirajana ravine, implying that the prevailing drainage network at that time must have been similar to the present one. In contrast, some secondary movements occurred obliquely to drainage lines.

The 28 large landslides identified cover a wide spectrum of slide types. Considering only the main movements and following the classification of Cruden and Varnes (1996), there are: 12 rock slides, 11 debris slides, 2 debris slumps, 2 earth slides and 1 debris flow (Table 3). Note that secondary slides are part of the main bodies, therefore, adding areas and volumes in Table 3 makes no sense.

Four main conclusions can be mentioned on the types and dimensions of the landslides: (1) all initial failures were rock slides; (2) rupture surfaces of these landslides followed weak layers located at great depth; (3) the majority of the reactivated slides were of rock-slide and debris-slide types, affecting 70% and 25% of...
the total area, respectively; and (4) modes of displacement were predominantly translational (rock-, debris-, and earth-slides) consisting of 89% of the total, compared to rotations and flows that comprise 11%.

Rupture surfaces developed within pyroclastic layers (tuffs, ashes, and ignimbrites), rather than within lava flows. These materials belong to the bedrock formations of Cycles I and II (Table 1). Most reactivations have occurred along the original rupture surfaces.

Regarding the aforementioned landslides (Table 2), as far as we know, only that of Rosiana is still active (Lomoschitz, 1999). In fact, the Rosiana landslide is the most important historical large landslide in Gran Canaria. Its periodic activity is known, at least, since 1879. Its most dramatic dated reactivation episode

Fig. 4. Spatial distribution of landslides within the Barranco de Tirajana basin. Arrows of different thickness indicate the three landslide activity periods. Numbers (1, 2, 3, 4) show the sequence of movements from the initial slide (1) of each sector.
Initial failures with (*).

occurred in February 1956, following a period of intense rainfall (272 mm in 24 h). Within 9 days, about 3 million m³ of material destroyed a regional road and a bridge, causing severe damage to buildings across an area of 0.3 km², and forced the evacuation of 250 people (Lomoschitz and Corominas, 1997b).

Table 3
Number and percentage of each movement type. Addition and percentage of the surface areas (km²) and material volume (km³) that were affected

<table>
<thead>
<tr>
<th>Movement type</th>
<th>Number</th>
<th>Type (%)</th>
<th>∑ Area (km²)</th>
<th>Area (%)</th>
<th>∑ Volume (km³)</th>
<th>Volume (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock slide</td>
<td>12</td>
<td>42.85</td>
<td>27.55</td>
<td>68.65</td>
<td>5.37</td>
<td>84.17</td>
</tr>
<tr>
<td>Debris slide</td>
<td>11</td>
<td>39.28</td>
<td>10.35</td>
<td>25.8</td>
<td>0.89</td>
<td>13.95</td>
</tr>
<tr>
<td>Debris slump</td>
<td>2</td>
<td>7.15</td>
<td>0.55</td>
<td>1.37</td>
<td>0.03</td>
<td>0.48</td>
</tr>
<tr>
<td>Earth slide</td>
<td>2</td>
<td>7.15</td>
<td>0.48</td>
<td>1.19</td>
<td>0.01</td>
<td>0.15</td>
</tr>
<tr>
<td>Debris flow</td>
<td>1</td>
<td>3.57</td>
<td>1.2</td>
<td>2.99</td>
<td>0.08</td>
<td>1.25</td>
</tr>
</tbody>
</table>
4. Periods of landslide activity and development of the Tirajana basin

In order to understand the evolution of the basin, the former morphology and structure of the zone were reconstructed using the data collected at bedrock formations and by back-rotating the blocks included in the slide masses (Lomoschitz, 1995).

A relative chronology among landslides has been established according to different geomorphic criteria: (a) the spatial relationships between landform features, since recent ones cut or affect older ones (landslide scarps, ravines, slide masses and sedimentary deposits); (b) spatial relationships between landslide masses and the present drainage network; (c) soil development and presence of pedogenic carbonate; (d) the evolution of the slide bodies, according to the degree of weathering of rocks (matrix content, degree of fragmentation and colour variations); and (e) both textural and morphological features of the scree deposits associated with the landslides.

As a result, three periods of landslide activity have been obtained (Fig. 5). Period I includes the ancient movements. The basal rupture surface of these landslides appears hanging above the present ravine thalweg and, therefore, the undisturbed bedrock outcrops under them. Common features of these landslides are: very eroded hummocky zones, extensive depletion zones (grabens) filled with sediments and very weathered rocks rich in silty–clayey matrix. Landslides of period I may be considered as abandoned landslides (WP/WLI, 1993). We consider failures produced during period II of activity as old landslides. The rupture surfaces of the old slides usually reach the present bottoms of the valleys. The slide masses extend along the upper half of the basin and they show a higher degree of preservation of geomorphic features than those of period I. In addition, well-developed scars, rotated rock layers and depletion zones partially covered by scree deposits are characteristic of this stage. These landslides are considered as dormant. Recent and present movements like the historic landslide of Rosiana are included in period III of activity, and they have well-preserved morphologies and distinct boundaries. They occur in relation with the present day drainage network. In some places, landslide feet override the ravine bottoms. Downstream of overridden places, braided stream channels exist, thus indicating an important contribution from the slide masses to the stream bedload. Landslides reactivated

<table>
<thead>
<tr>
<th>PERIODS OF ACTIVITY</th>
<th>GEOMORPHOLOGIC FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. ANCIENT LANDSLIDES</td>
<td>- Bedrock appears below.</td>
</tr>
<tr>
<td></td>
<td>- Hummocky surfaces and very eroded zones.</td>
</tr>
<tr>
<td></td>
<td>- Large grabens filled with deposits.</td>
</tr>
<tr>
<td></td>
<td>- High weathered rock masses, clay-silt rich matrix.</td>
</tr>
<tr>
<td>II. OLD LANDSLIDES</td>
<td>- Well developed escarpments and tilted bodies quite unweathered.</td>
</tr>
<tr>
<td></td>
<td>- Grabens partly covered with scree deposits.</td>
</tr>
<tr>
<td></td>
<td>- Obstruction deposits &gt; 51, 700 y. BP.</td>
</tr>
<tr>
<td>III. RECENT/PRESENT LANDSLIDES</td>
<td>- Well preserved forms, present drainage network invaded by landslides, clearly defined boundaries.</td>
</tr>
<tr>
<td></td>
<td>- Small landslides located at the valley bottom.</td>
</tr>
<tr>
<td></td>
<td>- The increase of bed load causes braided river channels.</td>
</tr>
<tr>
<td></td>
<td>- Active landslides in Rosiana area, open scars, tilted palmtrees, etc.</td>
</tr>
</tbody>
</table>

Fig. 5. Summary of the geomorphologic features used to mark out the different activity periods of the evolution of the Barranco de Tirajana basin.
in this period are smaller than the older slides ones, and are located next to the stream channels.

Before the occurrence of the initial landslides, from a lithologic and morphostructural point of view, the relief in this area of Gran Canaria necessarily had two different domains (Fig. 6a). One domain was formed by Miocene rocks (Cycle I) not buried by the Roque Nublo Group materials, outcropping at both NW–SW

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![Diagram](image.png)

**Fig. 6.** Idealised SW–NE cross-sections of the Barranco de Tirajana basin that show its evolution during the Quaternary. From (a) structure and relief in the Lower Pleistocene, three main periods of landslide activity have been established (b, c, d), and finally (e) shows present relief and movements.
and S sectors. Their topographic surface acted as a barrier to later eruptions. The second domain includes the formations of Cycles II and III, which buried the Miocene bedrock and filled the Central, N and NE–SE sectors. A SE–NW trending ravine marked the surface boundary of these two domains and, consequently, the Tirajana ravine erosion progressed mainly to the NW through its thalweg. The paleotopographic reconstruction prepared by Lomoschitz (1995) is consistent with the works of Pérez Torrado et al. (1995) and Pérez Torrado (2000).

Temporal evolution of the landslides within the BdT basin has been established from both absolute and relative chronology. The age of the BdT basin has been estimated from: (a) dating of bedrock formations and (b) dating of charcoal found in dammed deposits (Fig. 4).

Fragments of most of the bedrock formations appear included in the bodies of the initial landslides: Trachytic–Rhyolitic Fm. and Phonolitic Fm. (Cycle I, Miocene); Basaltic Fm., Roque Nublo breccia Fm and phonolitic domes of the Roque Nublo Group (Cycle II, Lower Pliocene); and Basanite–Nepelinite Fm. (Cycle III, Upper Pliocene–Pleistocene) whose lava flows and pyroclasts are between 2.7 and 0.6 Ma old in the BdT basin area (Balcells et al., 1992). Cycle III basanite–nefelinite lavas are found capping the volcanic series outcropping in the walls of the depression. In no case did the Cycle III lavas flow into the basin. Consequently, the BdT depression started after Cycle III eruptions.

Besides, two sedimentary deposits were formed behind the foot of the Agualatente landslide due to the damming of the ravine by the slide. This landslide belongs to the second generation of movements (Fig. 4). Some layers of the dammed deposits contain charcoal fragments and, from five 14C dating analyses, a minimum age of 51,700 BP has been obtained (samples Beta-68165 and CAMS-10273: Table 4). Since this age lies beyond the range of applicability of this method (Geyh and Schleicher, 1990), we cannot exclude that the true age of these deposits could be much older.

Fig. 6 shows the interpretative evolution of the BdT basin, from the supposed situation in the lower Pleistocene, passing through activity periods I, II and III as described above and, finally, the present situation and topography.

5. Paleoclimatic context

5.1. Climate general trends

Activity periods of landsliding in the BdT basin could be related to the more humid and wetter time intervals that occurred in the Canary Islands during the Quaternary. In a wide paleoclimatic sense, humid periods could be related to both glacial and interglacial periods. Now, the point is to choose one of these possibilities.

There is some climatic information available for the glacials in NW Africa and the Atlantic areas around the Canary Islands. Sarthein (1978) observed that, during the last glaciation, much of the land area between 30°/C176°N and 30°/C176°S was characterised by vast deserts located to the north and south of the Intertropical Convergence Zone (ITCZ). As a result, Western Sahara and the Canary Islands (like other vast areas of the Earth’s surface) were affected by a pronounced aridity. This situation contrasts with the old belief that “pluvial” wet conditions prevailed during the last glacial maximum in the Canary Islands.

Moreover, most areas of Africa during ice age winters appear to have been dominated by dry northerly and NE winds (Dawson, 1992). This resulted in the development of very stable areas of subtropical high pressure and, by inference, the occurrence of relatively cloudless conditions. Consequently, all the above indicates that climate of the last glaciation and, by extension, of previous Quaternary glaciations, did not trigger wet conditions in NW Africa nor in the Canary Islands.

<table>
<thead>
<tr>
<th>Lab. number</th>
<th>Sample no.</th>
<th>Material</th>
<th>C-14 Age years BP ± 1σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beta-65846</td>
<td>MO-1</td>
<td>charcoal</td>
<td>&gt; 39,900</td>
</tr>
<tr>
<td>Beta-65847</td>
<td>MO-2</td>
<td>charcoal</td>
<td>&gt; 45,440</td>
</tr>
<tr>
<td>Beta-65848</td>
<td>MO-3</td>
<td>carbon in silt</td>
<td>&gt; 34,300</td>
</tr>
<tr>
<td>Beta-68165</td>
<td>MO-4</td>
<td>charcoal</td>
<td>&gt; 51,700</td>
</tr>
<tr>
<td>CAMS-10273</td>
<td>MO-4</td>
<td>charred carbon</td>
<td>&gt; 51,700</td>
</tr>
</tbody>
</table>

Samples were collected from the bottom to the top of the obstruction deposit.
On the contrary, interglacials seem to be related to wet periods in the Canary Islands (around 28°N). In other words, we suggest that interglacials in the Canary Islands and NW Africa (periods of global warming) included wet and rainy episodes that could account for the occurrence of the landslide activity periods at the BdT basin.

According to Dawson (1992), NE tradewinds that cross the Canary Islands and NW Africa coasts were displaced and affected by ITCZ movements. Supporting this, Yan and Petit-Maire (1994), who studied past climatic oscillations in the Afro-Asian arid/semi-arid transitional zone for the last 140 ka, suggested that the last interglacial was associated with an increase of precipitation throughout the area considered.

If we extend the aforementioned hypothesis through the Middle and Late Quaternary, some interesting inferences can be made. According to Shackleton (1987), the warmest interglacials (with a higher sea level) occurred at isotope stages 1, 5e, 9 and 11; and formerly, at stages 15, 21, 25, 31 and 37 and some others within the Lower Pleistocene (Shackleton et al., 1990).

The beginning of the Late Quaternary, corresponding to oxygen isotope substage 5e, was characterised by an exceptional global warmth (Petit et al., 1999). This time period, considered to have lasted between 130,000 and 122,000 BP, may be associated with sea levels up to 6 m higher than present. This period of pronounced warmth appears to coincide with a period of strong Milankovitch global warming centered on 125,000 BP. The oxygen isotope record also shows that during stage 5, two periods of interstadial warmth also occurred after substage 5e. According to the oxygen isotope curve of Martinson et al. (1987) substage 5c occurred between 105,000 and 93,000 BP while substage 5a represents the time interval between 85,000 and 74,000 BP.

Another period of relative warmth occurred during isotope stage 2/1 transition. The principal period of warming began near 15,000 BP and, with the exception of the Younger Dryas, continued into the Holocene interglacial. Rates calculated by Fairbanks (1989) show that the period of maximum glacial melt took place between approximately 15,000 and 12,000 BP with a secondary peak between 10,000 and 9000 BP.

### 5.2. Regional available data

Regional paleoclimate data are concordant with the aforementioned general trends. Within the Quaternary, two episodes of marine transgression have been defined in the Eastern Canary Islands: Isotopic stage 5e and Holocene deposits (Meco et al., 1997). OIS 5e beach deposits are rich in Senegalian fauna. They reach a mean altitude of +5–6 m above present sea level. Radiocarbon ages indicate two Holocene periods of ocean highstands within 4000–2000 BP (Meco et al., 1997; Zazo et al., 1997). In the northern coast of Gran Canaria, the interglacial marine deposits of OIS 5e are at +12 m, the OIS 11c are at +35 m and the Early Pleistocene are at +85 m. These data indicate a likely uplift of that coast throughout the Quaternary.

In addition, there are extensive aeolian deposits in Fuerteventura that, being close to Gran Canaria, is the most arid island in the Canary Islands and is located about 125 km off the Saharan coast of Morocco. The dunes there contain interbedded levels of land snail shells, insect brood cells and alluvial deposits (Meco et al., 1997) that indicate humid phases within the subtropical arid climate. In general, molluscs 14C and K/Ar dating from Meco et al. (1997) fit well the warmer OIS 1, 5c and 9, but some of them do not fit so well within interglacial stages and indicate likely minor climate variations.

### 5.3. Relationship between climate and landsliding

Taking into account the likely correspondence between warming periods and precipitation periods that apparently occurred in the Eastern Canary Islands and NW Africa, we suggest that activity periods of landsliding could relate to these periods.

From the Holocene back to the Lower Pleistocene, available palaeoclimatic records are more and more scarce. As a proposal for the study area, from recent times to the past, we suggest the following. (1) Present landslides (e.g. Rosiana) correspond to the Holocene and took place within the current interglacial (isotope stage 1) and maybe from the warmest period (7000–9000 BP in the Canary Islands) to today. (2) Within the Upper Pleistocene, period III of landslide activity might have occurred in the warmest interglacial of the substage 5e (about 130 ka) or alternatively might have taken place during the two later warm interstadials,
i.e. 5c and 5a. (3) Two warm interglacials occurred within the Middle Pleistocene. They correspond to stage 9 (300,000–340,000 BP) and stage 11 (350,000–430,000 BP). Besides, according to Shackleton et al. (1990), many warm interstadials took place before them. They occurred at stage 15 (560,000–630,000 BP) within the Middle Pleistocene, but also within the Lower Pleistocene (stages 21, 25, 31, 37 and 47) and even within the Pliocene (e.g. stages 63, 89 and 95).

Nevertheless, there are insufficient data for age bracketing the landslide activity within periods I and II in the Barranco the Tirajana basin. The radiometric age (2.7–0.6 Ma) of the youngest bedrock blocks included in these landslides, suggests that the first activity period might have started in the Upper Pliocene to the Middle Pleistocene. Besides, the first activity period of landsliding had to be preceded by an important incision of the ravine, probably also related to humid periods. Only in this way is it possible to explain the erosion at the base of the slopes and the first-time failure of such a huge rocky bodies.

6. Conclusions

The Barranco de Tirajana (BdT) shows a number of specific characteristics that make it different from other ravines of Gran Canaria and of other Atlantic volcanic islands. Since four questions had been raised in Section 1, at this point we present the main conclusions we have obtained.

(1) The BdT upper basin is a major erosional landform, 900 m deep and 35 km² in extent, caused by the incision of the ravine (“barranco” in Spanish) and widened by great number of large landslides. Alluvial deposits 25 km² in extent at the valley-mouth and landslide deposits within the upper basin indicate that fluvial erosional processes and landsliding had the main role in the evolution of the ravine. In this way, the terms “depression” (Lomoschitz and Corominas, 1997a) and “erosional depression” (Karatson et al., 1999) have been proposed, rather than “caldera” to name the BdT basin.

(2) There are 28 large landslides within the BdT basin (see Table 2). Six of them correspond to initial landslide bodies of huge dimensions (an average length of 2.5 km and an average volume of 0.7 km³) and they are of rock-slide type. The remaining 22 landslides, should be considered as reactivation of the former and are smaller (an average length of 1.05 km and an average volume of 0.1 km³). One of them is episodically reactivated, the Rosiana landslide. As a whole, the main movements were of rock-slide and debris-slide types, affecting 70% and 25% of the total area, respectively. In addition, modes of displacement were predominantly translational (rock-, debris-, and earth-slides) consisting of 89% of the total, compared to rotations and flows that compose only 11%.

(3) Balcells et al. (1990, 1992) attributed an age of 3.4–2.9 Ma (Pliocene) to the slide deposits of the Tirajana basin. This is just after the emissions of Roque Nublo cycle, matching a period of volcanic inactivity in Gran Canaria. According to these authors, this may be considered as the starting age of the development of the depression. In contrast, we suggest the age of the main development of the BdT basin may be established at about 0.6 Ma, although it may extend back to 2.7 Ma. This younger determination is based on the age of the Basanite–Nephelinite Fm. lava flows whose blocks are included in the slide bodies.

Prior to the occurrence of the slope failures, an important incision of the BdT ravine through the bedrock must have taken place. This incision started along the former Tirajana ravine thalweg (Fig. 6) that flowed from the N–NW to the S–SE, because it was defined by the boundary between the two different morphostructural domains of the area. Only when the incision of the ravine was about 350 m in depth, and reached the tuff, ash and ignimbrite layers, in which the failure surfaces are located, were the first rockslides failures able to occur.

Once previous morphology and structure of the zone had been reconstructed (Fig. 6), and using absolute and relative chronological criteria, three periods of landsliding activity may be established (Fig. 5). Period I includes the ancient movements. Landslides of this period show hummocky zones, extensive grabens and completely weathered rocks and they may be considered as abandoned landslides. Failures produced during period II are considered as old landslides. They usually reach the present valley bottom and show a higher degree of preservation of geomorphic features than those of the period I. They are considered as dormant landslides. Recent and
present movements like the historic landslide of Rosiana are included in period III, and they have well-preserved morphologies and distinct boundaries. An evolutionary model has also been proposed showing the changes within the BdT basin (Fig. 6).

(4) Periods of landsliding activity in the BdT basin might have correspondence with those more humid and wetter time intervals that occurred in the Canary Islands during the Quaternary. Available paleoclimatic information (Sarthein, 1978; Dawson, 1992) shows that during the glacial periods, NW Africa and the Atlantic areas around the Canary Islands were affected by a pronounced aridity. This point of view contrasts with the old belief that “pluvial” wet conditions prevailed during the last glacial maximum. By contrast, interglacials seem to be related to wet periods in the Canary Islands. We suggest that interglacials in the Canary Islands and NW Africa (periods of global warming) included wet and rainy episodes that could account for the occurrence of the periods of landslide activity in the BdT basin.

Regional paleoclimatic data accord with the aforementioned global trends and suggest the following sequence for the study area. (1) Present landslides (e.g. Rosiana) correspond to the Holocene and took place within the current interglacial (isotope stage 1). (2) Recent landslides of period III occurred mainly during the warmest interglacial of the substage 5e. And (3) as a number of warm interglacials occurred within the Middle Pleistocene (stage 9, 11 and 15), but also within the Lower Pleistocene and even within the Pliocene (Shackelton et al., 1990), two different hypotheses can be suggested for periods I and II. These are: (a) they could have occurred within the Middle to Upper Pleistocene (stages 11 and 9) or (b) they could have taken place over a wider time interval, corresponding to the Lower to Upper Pleistocene, or even extending back to the Upper Pliocene. At the moment, both of these hypotheses are consistent with the available data.

Acknowledgements

This research was supported by the European Commission through Contract ENV4-CT97-05527 (RUNOUT project). Complementary funding was given by the Dirección General de Enseñanza Superior (DGES) of Spain, project UE98-0010. We wish to thank Francisco J. Pérez Torrado (Universidad de Las Palmas de Gran Canaria) and Christopher Kilburn (University College London) with whom we discussed some of the ideas in the manuscript.

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